# DESIGN AND IMPLEMENTATION OF DEVICE-TO-DEVICE COMMUNICATIONS IN NEXT GENERATION MOBILE NETWORKS TO COUNTER TERRORISM IN SHOPPING MALLS

Weston Mwashita

Student number: 218050828

Submitted in fulfilment of the requirements for the

Doctoris Technologiae: Engineering: Electrical

Department of Process Control & Computer Systems

Faculty of Engineering & Technology

Vaal University of Technology

Promoter: Prof. MO Ohanga

22nd February 2022

# DECLARATION

I, Weston Mwashita, student number 218050828, hereby declare that the thesis entitled:

Design and Implementation of Device-to-Device Communications in Next Generation Mobile Networks to Counter Terrorism in shopping malls

is the result of my own research and presents my own work and that all the sources that I have used or quoted have been indicated and acknowledged by means of complete references. I further declare that I have not previously submitted this work, or part of it, for examination at Vaal University of Technology for another qualification or at any other higher education institution.

22nd February 2022

## ABSTRACT

In this research study, a scheme to minimise interference in converged mobile cellular networks (MCNs) and wireless sensor networks (WSNs) was designed and implemented. The focus was the mitigation of interference that arises when proximity service (ProSe)-enabled sensors engage in a device-to device (D2D) communication to alert smartphone users upon the detection of explosives at highly crowded areas like shopping malls. D2D is a technology that academia and industry experts believe will play a prominent role in the implementation of the next generation of mobile networks, specifically, the fifth generation (5G). However, the full roll out of D2D is being impeded by the interference that the technology introduces to the cellular network. D2D devices cause a significant amount of interference to the primary cellular network especially when radio resources are shared. In the downlink phase, primary user equipment is likely to suffer from interference emanating from a D2D transmitter. On the other hand, the immobile base station is affected by interference caused by the D2D transmitter in the uplink phase. This type of interference can be avoided or reduced if radio resources are allocated intelligently under strict coordination of the base station. An NP-hard optimisation problem was formulated and finding a solution to this problem in 1 ms is not possible. 5G has a frame structure duration of 10 ms with 10 subframes of 1 ms each. Heuristic algorithms were then developed to mitigate the interference affecting the primary network that could carry out resource allocation within the fast-scheduling period of 1 ms. Smartphones have progressed into devices capable of generating massive volumes of data. The challenge is that battery technology is not keeping up with the pace of smartphone technology, so any additional feature that designers want to add, is met with a lot of contempt from customers who are concerned about their smartphone batteries depleting rapidly. In this context, the strategy must be energy-efficient for smartphone users to embrace it. A system level simulator was developed using MATLAB to evaluate the efficacy of the proposed design. Extensive simulation results showed that ProSe-enabled sensors can safely be integrated into cellular networks participating in D2D communication with smart phones, without introducing significant harm to the primary cellular network. The results showed that after implementing the proposed strategy, overall user throughput decreased by 3.63 %. In cellular networks, this is a modest figure since a reduction of up to 5% is acceptable to both users and network providers. The figure generally capped in service level agreements signed between network providers and users is 5%. The proposed technique also resulted in a 0 % reduction in SINR of CUEs in a cellular network, according to the findings. In terms of D2D link throughput for different D2D transmit levels, the method proposed in this research work surpassed a similar scheme proposed in literature by an average of 18.3%.

ACKNOWLEDGEMENTS

Firstly, and most importantly, I would like to thank Almighty God for giving me the knowledge and strength to carry out this research project. Secondly, I would like to express my profound gratitude to my academic supervisor, Prof. Marcel Odhiambo Ohanga for his excellent supervision of my doctoral studies at Vaal University of Technology. This thesis could not have been produced if it were not for his advice and guidance which I found very invaluable throughout all the phases of this research project. I feel grateful to Prof. Marcel Odhiambo Ohanga for having accepted to become my supervisor. Prof. Ohanga's in-depth knowledge and his up-lifting moral support helped me conquer the many hurdles I met along the way. His timeous feedback helped me greatly in the formulation and crystallisation of scientific ideas. I am highly privileged to have been allowed to seamlessly tap into Prof. Ohanga's philosophy of scientific research and this has helped me immensely in mastering the art of conducting scientific research. I also wish to register my appreciation of the staff at the Process Control and Computer Systems department with special mentions going to Dr. N. D. Mathaba and Mr T. E. Marie for their constructive critiquing of my research work. I also want to extend special thanks to Miss Elizabeth Adhiambo Okaka for ensuring that my initial registration and the yearly re-registrations at Vaal University of Technology went on smoothly. I am highly thankful to my wife, Ndinaani for giving me encouragement and moral support throughout the whole period of the research work. Cynthia, Samantha and Fidelity, my lovely daughters, gave me the moral support that I needed, in this doctoral journey and to them I say, thank you.

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS AND ACRONYMS

| | |
|---|---|
| 3GPP | 3rd Generation Partnership Project |
| 5G | Fifth Generation mobile networks |
| ABS | Almost-Blank-Sub-frame |
| AOI | Area of Interest |
| AP | Access Point |
| BS | Base Station |
| CH | Cluster Head |
| CIC | Centralised Interference Coordination |
| CLPC | Open Loop Power Control |
| CoMP | Coordinated Multi-Point |
| CQI | Channel Quality Indicator |
| CS/CB | Coordinated Scheduling/Beamforming |
| CSI | Channel State Information |
| CUE | Cellular User Equipment |
| D2D | Device-to-Device |
| DIC | de-centralised interference coordination |
| DL | Down Link |
| DPB | dynamic point blanking |
| DoF | Degree of freedom |
| DPS | Dynamic Point Selection |
| DUE | Device-to-Device User Equipment |
| EE | Energy Efficiency |
| FFR | Fractional Frequency Reuse |
| gNB | Next Generation Node B |
| GPS | Global Positioning System |
| H2H | human to human |
| IA | Interference alignment |
| IFFT | Inverse Fast Fourier Transform |
| ICIC | Inter-Cell Interference Coordination) |
| IMT-A | International Telecommunications-Advanced |
| IoT | Internet of Things |
| ISM | Industrial, Scientific and Medical |

| | |
|---|---|
| ITU | International Telecommunication Union |
| JT | Joint Transmission |
| KPI | Key performance indicator |
| LL | Link Level |
| LOS | Line of Sight |
| LRMC | low-rank matrix completion |
| LTE-A | Long Term Evolution-Advanced |
| M2M | Machine-to-Machine |
| MATLAB | Matrix Laboratory |
| mMTC | Massive Machine Type Communications |
| MIC | multi-stage interference cancellation |
| MTC | machine type communication |
| MCN | Mobile Cellular Network |
| MIMO | Multiple-Input, Multiple-Output |
| NAAC | Neighbour-Agent Actor Critic |
| NaCTSO | National Counter Terrorism Security Office |
| NLOS | Non-Line of Sight |
| NL | Network Level |
| NOMA | Non-Orthogonal Multiple Access |
| NR | New Radio |
| OFDM | Orthogonal Frequency Division Multiplexing |
| OFDMA | Orthogonal Frequency Division Multiple Access |
| OI | Operational Intelligence |
| OLPC | Open Loop Power Control |
| OMA | Orthogonal Multiple Access |
| OSRA | Optimal-Social-Community-Aware-Resource-Allocation |
| PAPR | Peak to Average Power Ratio |
| PDCCH | physical downlink control channel |
| PF | Proportional Fair |
| PFR | Partial Frequency Reuse |
| PHY | Physical Layer |
| PIC | Parallel Interference Cancellation |
| ProSe | Proximity Service |
| PSS | primary synchronisation signal |

| | |
|---|---|
| PUSCH | Physical Uplink Shared Channel |
| QoE | Quality of Experience |
| QoS | Quality of Service |
| RACH | random access channel |
| RATs | Radio Access Technologies |
| RB | Resource Block |
| RR | Round Robin |
| RRM | Radio Resource Management |
| SC-FDMA | Single-Carrier Frequency-Division Multiple Access |
| SDMA | Space Division Multiple Access |
| SDP | Semi-Definite Programming |
| SFR | Soft Frequency Reuse |
| SLA | Service Level Agreement |
| SONs | Self-Organised Networks |
| SUE | Smartphone User Equipment |
| SIC | Successive Interference Cancellation |
| SINR | Signal-to-interference-plus-noise ratio |
| SSS | Secondary Synchronization Signal |
| TIM | Topological Interference Management |
| TPC | Transmit Power Control |
| TTI | Transmission Time Interval |
| UCQ | Unknown Channel Quality |
| UE | User Equipment |
| UIC | Unconditional Interference Cancellation |
| UL | Uplink |
| V2X | Vehicle-to-Everything |
| WMSN | Wireless Multimedia Sensor Network |
| WSN | Wireless Sensor Networks |

TABLE OF CONTENTS

# CHAPTER ONE: INTRODUCTION

## 1.1 Introduction

With Device to Device (D2D) communication, devices that are near each other can communicate autonomously with each other making it possible for the devices to seamlessly collect and share vital information amongst themselves. This makes D2D communication an excellent candidate technology for use in Wireless Sensor Networks (WSNs). Integrating WSN and D2D into the existing or future generation of mobile networks will inevitably affect the overall network throughput of the mobile networks. Enabling D2D communication on a cellular network presents challenges of radio resource management, because D2D links utilise cellular users' uplink or downlink radio resources, which might create interference to D2D user equipment's (DUE) transmitting and receiving channels.

## 1.2 Rationale and Motivation

Quite a number of schemes have been advanced by several researchers in the mitigation of interference in D2D-enabled mobile networks. Research work that has been carried out regarding D2D communication has mostly focussed on the reduction of interference with the aim of enhancing 4G and 5G networks' spectral efficiency and overall system capacity. Not much research work has been undertaken to mitigate the interference that arises when ProSe-enabled sensors participate in D2D communication (Maraj *et al.* 2021: 68932-68965). Alnoman and Anpalagan (2017:124-127) presented an extensive review on recent advances in D2D communications with regards to public safety applications such as search and rescue missions, road safety and coverage extension. The review work by Alnoman and Anpalagan does not cover interference management schemes.  Wang and Yan (2015:1199-1204) surveyed and evaluated the effectiveness and comprehensiveness of existing security solutions in D2D communications. After an extensive review on recent works on D2D security issues, Hamoud *et al.* (2017:1-11) proposed a taxonomy on D2D security solutions. Kar and Sanyal (2018:203-208), cited interference management as a technical challenge in Prose-enabled D2D mobile networks that requires further extensive research work. A comprehensive interference management approach was cited by Li *et al.* (2019:25263-25273) as an open research area that requires further attention by researchers.

D2D communication was introduced in the Third-Generation Partnership Project (3GPP) Release 12 (3GPP 2013:1-45). Follow up work appeared in 3GPP (2014:1-50), 3GPP (2015:1-147), 3GPP (2017:1-38) and Releases 16 and 17 (3GPP 2020:1-54). The use of D2D in public safety was mostly initiated by 3GPP (Panaitopol *et al.* 2015:1-8). Academia has embraced the technology but has concentrated on the public safety that deals with use of D2D as a public safety solution after conventional communication infrastructure has collapsed following major natural or man-made disasters (Yu *et al.* 2018:70397-70425). According to Yu *et al.* (2018:70397-70425), "little work has been done toward adapting D2D from a public safety perspective". The main contributions of subsequent 3GPP releases after release 12 in relation to D2D are depicted in Figure 1.1.

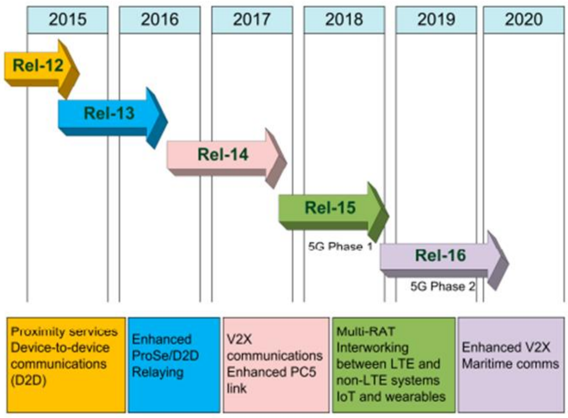


Figure 1.1: D2D communications support in 3rd Generation Partnership Project (3GPP) releases, Höyhtyä *et al.*, 2018, p.5)

The use of D2D communications for sensor networking is very promising. D2D does not overburden the existing cellular infrastructure. Sensed information can be processed quickly, locally by smart phones and other mobile gadgets, and then relayed to base stations (BSs) for further handling. Researchers from academia and industry agree that D2D will play a very pivotal role in future generation networks, specifically 5G networks (Chaaban & Sezgin 2015:15-22 and Tehrani *et al*. 2014:86-92). D2D allows devices to directly communicate with each other without heavily involving the network infrastructure though its connectivity is controlled by the network. While the public safety outlined by 3GPP deals with the continuation of the provision of communication services after disaster would have struck, this research work sought to extend this public safety to cover explosives detection by use of D2D to prevent terrorists' acts at shopping malls and other public places. The design makes use of special sensors in detecting explosives at shopping malls, involve D2D communications in processing and relaying of sensed information and prompt the cellular network to alert the responsible parties of an imminent terrorist attack.

D2D is a trending topic in the research community. Academia, industry experts and standardisation bodies are still studying the implementation of D2D (Cintron *et al.* 2021:1-82). More than a hundred research papers on D2D are available but most of the proposed schemes are still immature (Adnan *et al.* 2020:1-22). Device-to-device communication adds a new dimension to the mobile environment by simplifying data transfer between physically adjacent devices. D2D communication makes use of neighboring communicating devices to optimise the use of available resources, minimise latency, improve data rates, and extend system capacity. The development of D2D is fueled by mobile operators' actions to collect short-range communications for the maintenance of proximity-based services and to improve network performance.

Some challenges have been resolved, however the potential for ProSe-enabled sensors to cause interference in a D2D-enabled cellular network has not been satisfactorily addressed. Optimisation and mathematical techniques aren't utilised to their full potential. Most researchers, particularly those trying to solve problems in interference management, formulate NP-hard optimisation issues that are left unsolved due to the problem's NP-hardness. Numerical evaluation and simple home-grown simulators are used in most of the research that has been surveyed. There is a lack of experimental evaluation or proper modeling on interference management.
Therefore, despite its many benefits, D2D's deployment has been mostly limited to unlicensed frequency bands. The benefits of reverting to D2D are numerous with the following being the major ones (Asadi and Wang 2014:1801-1819) that emanate from the usage:

(i) Improved throughput. (ii) Increased energy efficiency. (iii) Reduced end-to-end delay. (iv) Fairness.

## 1.3 Aim of the Study

The aim of this research work was to develop new radio resource allocation and power control algorithms for machine type communication (MTC), where the same spectrum is shared by human to human (H2H) and D2D communications. The focus in the algorithm's development was interference management and energy consumption minimisation so that the scheme is acceptable to both cellular network operators and smartphone users. Cellular network operators accept strategies that do not compromise the networks' quality of service (QoS), while smartphone users generally accept schemes that do not cause their devices' batteries to deplete quickly.

## 1.4 The Problem Statement

The study sought to solve the problem of interference in D2D-enabled cellular networks in which ProSe-enabled sensors have been introduced. The concept of D2D communications has been in existence for quite a while now (Doppler *et al*. 2009:42-49), however, the challenge of interference management is impeding their full-scale materialisation (Li *et al.* 2019:25263-25273) The design of a D2D network incorporating ProSe-enabled sensors needs to include smart interference management strategies to avoid compromising the performance of an existing cellular network (Trifunovic *et al.* 2013:606-620). For users of some energy constrained devices like smart phones (Matyjszek 2021), to accept using D2D connecting to ProSe-enabled sensors, researchers need to ensure that the D2D communication incorporating sensors does not drain user devices batteries too quickly (Teherani *et al.* 2014:86-92).

## 1.5 Objectives of the Study

(i) To design a scheme for interference mitigation for use in D2D sensor networks deployable at highly crowded public places such as shopping malls.

(ii) To provide an analysis of mitigation techniques for the interference that arises from the integration of D2D and explosives detecting systems into the next generation mobile networks.

(iii) To develop a complete system level D2D communications simulation package for the evaluation of the proposed design.

## 1.6 Scope of the Study

The study intended to cover the design, implementation and evaluation of an interference management scheme developed for use in D2D-enabled cellular networks in which sensors have been introduced. A centralised scheduling strategy was developed that can be used to coordinate D2D communications among smart phones, explosives detection systems and cellular base stations. A centralised schedulinng was chosen ahead of the decentrarised strategy because it was found out that it was more effective in delealing with interference in cellular networks in which sensors would have been introduced. The scheduling strategy combines resource and power allocation, mode selection and mobile devices power consumption reduction techniques in the interference management process. Integrating sensors into a cellular network might present several challenges. Such problems include cluster creation, cluster head selection, and security. The problems of interference management and higher power consumption were the focus of this study.

## 1.7 Methodology and Research Design

(i) A rigorous review of state-of-the-art of the following was undertaken:

(a) An exhaustive literature review of existing sensors used for the detection of explosives at public places was conducted and this led to the recommendation of sensors that can work with the proposed interference management scheme.

(b) The status of D2D communication was reviewed and challenges preventing the technology from being rolled out were analysed. This was important so that the proposed interference management scheme for a hybrid sensor network could be appealing to both network operators and smartphone users.

(c) Issues surrounding the integration of sensors in D2D-enabled cellular networks were reviewed. This led to the development of a scheme that has minimum D2D-cellular interference problems.

(ii) Designed a framework that conforms to 3GPP ProSe standards of Device-to-Device communications involving sensors and smart phones exchanging harvested information about the presence of explosives at public places.

(iii) Designed an interference management scheme for D2D sensor networks deployable at highly populated areas like shopping malls.

## 1.8 Contributions of the Research Work

The following were the contributions of the study:

### 1.8.1 Contribution 1

The main contribution looks at how sensors in cellular networks can share available radio resources with no or minimal impact on existing cellular services. As a result, a spectrally efficient strategy was developed and presented. A mobile scenario with several sensors was explored, and simulations were run to investigate how the introduction of sensors might affect the network throughput and SINR.

### 1.8.2 Contribution 2

Power control of DUEs is a significant and challenging task in a D2D-enabled cellular network. A novel power control algorithm was developed in this research study. The approach considered the channel capacity, network radius, and DUE transmission power optimisation. It was concluded that the inclusion of DUEs has no detrimental effect on the QoS of an underlay cellular network, according to the simulation results of the proposed power control strategy.

### 1.8.3 Contribution 3

A state-of-the-art simulator was developed as part of this research to enable studies in converged mobile cellular networks (MCNs) and wireless sensor networks (WSNs) for the implementation and investigation of the techniques/algorithms developed to reduce interference that occurs when sensors communicate with smartphones in a D2D manner. The developed model encompasses the connections between a BS, UEs, and sensors, allowing for realistic analysis of network-related issues such as interference mitigation and network planning optimisation in urban settings such as shopping malls. The system level simulator follows the 3GPP standard for 5G network features and characteristics. Path-loss models, BS/UE standards, MIMO/ smart antenna designs, appropriate channel models such as the WINNER II model, and defined channel bandwidths are all features of the 5G network standard that were used. The system-level simulator was developed by first abstracting the link-level features (i.e., the physical layer) to a sufficient level of detail and accuracy, and then mapping the link-level to the system-level.

## 1.9 List of Publications

The research work presented in this thesis has been published in the following journals and international conferences:

(i) Weston Mwashita, Marcel Ohanga Odhiambo. Interference Management Techniques for Device-to-Device Communications. *Handbook of Research on Predictive Intelligence Using Big Data and the Internet of Things. IGI Global. 2019.* https://www.igi-global.com/chapter/interference-management-techniques-for-device-to-device-communications/219125 *ISBN13: 9781522562108, ISBN10: 1522562109, EISBN13: 9781522562115, DOI: 10.4018/978-1-5225-6210-8* pp. 219 - 245.

(ii) Weston Mwashita, Marcel Ohanga Odhiambo. A Power Control Strategy for IoT Sensors Developed for 5G Networks. *International Journal of Smart Sensor Technologies and Applications (IJSSTA).* https://www.igi-global.com/article/a-power-control-strategy-for-iot-sensors-developed-for-5g-networks/272126 Volume 1, Issue 1, January-March-2020, ISSN: 2644-1845, eISSN: 2644-1853, pp. 22-41.

(iii) Weston Mwashita, Marcel Ohanga Odhiambo. Interference Management Techniques for Device-to-Device Communications. Research Anthology titled Research Anthology on Developing and Optimizing 5G Networks and the Impact on Society. *IGI Global. 2011. ISBN: 9781799787080 (hardcover), 9781799877547 (ebook), pp383-409,* https://www.igi-global.com/chapter/interference-management-techniques-for-device-to-device-communications/270200 January 2021.

(iv) Weston Mwashita, Marcel Ohanga Odhiambo. A Power Control Scheme for Artificial Intelligence and IoT (AIoT) ProSe-enabled Sensors. *The 23rd International Conference on Artificial Intelligence (ICAI'21: July 26-29, 2021, USA)* https://www.american-cse.org/csce2021/conferences-ICAI https://www.american-cse.org/csce2021/ Springer Nature - Research Book Series: Transactions on Computational Science & Computational Intelligence. https://www.springer.com/series/11769 https://www.american-cse.org/static/2021-CSCE-BOOKLET.docx

(v) Weston Mwashita, Marcel Ohanga Odhiambo, IoT Sensors-Interference Management Through Power Control, Achieving Full Realization and Mitigating the Challenges of the Internet of Things, https://www.igi-global.com/book/achieving-full-realization-mitigating-challenges/277450

To be published in March 2022.

## 1.10 Thesis Organisation

Chapter 1 introduces the research topic, describing issues that are relevant to interference management in D2D-enabled cellular networks in which ProSe-enabled sensors have been introduced. The design challenges of integrating D2D in cellular networks for sensor networking are discussed in Chapter 2. Chapter 3 presents a discussion of the current state-of-the-art interference management techniques for D2D-enabled cellular networks. Power control, mode selection, beamforming techniques, and other novel interference management approaches that have received a lot of attention from the research community. Machine learning's role in D2D-enabled network interference reduction is also discussed in Chapter 3. The formulation of the problem is presented in Chapter 4 as well as the system model that was used in the study. A description of the development of a collaborative area monitoring framework that focuses on the management of interference introduced to a cellular network by ProSe-enabled sensors and D2D communication is also presented. Chapter 5 describes the design of the interference control method that can be utilised. Chapter 6 provides details of the development of a state-of-the-art simulator as part of this research to enable studies in converged mobile cellular networks (MCNs) and wireless sensor networks (WSNs) for the implementation and investigation of the techniques/ algorithms developed to reduce interference. Chapter 7 presents the simulation tests carried out on the proposed scheme to ensure that the design specifications are met. Chapter 7 chapter also explains the reasons for the selected tests. The simulations test results are also reported in this chapter.

# CHAPTER TWO: DEVICE TO DEVICE COMMUNICATIONS AND ITS INTEGRATION INTO SENSOR NETWORKING

## 2.1 Introduction

The background of D2D communication is covered in this chapter, with a focus on its integration in future cellular networks, particularly in the domain of sensor networks. The design challenges of integrating D2D in cellular networks for sensor networking are also discussed.

## 2.2 D2D Communications

The 5$^{th}$ generation of mobile networks brings together radical solutions to cater for the unprecedented user demand for higher data rates and bandwidth. D2D was introduced to solve the problem of heavily densified heterogeneous networks and to extend network coverage, improve spectral efficiency, increase energy efficiency, enhance system capacity, and allow for extremely low delays (Rahi and Hasan 2020:1-9). To cope with the unparalleled growth of cellular traffic, the Third-Generation Partnership Project (3GPP) Long Term Evolution Edge (LTE) and the 5G Infrastructure Public Private Partnership (5GPPP) considered D2D as one of the technologies that will connect 7 trillion wireless devices used by 7 billion people (The 5G Infrastructure Public Private Partnership 2014:4). It is generally agreed in the academia circles that D2D technology forms the cornerstone of 5G and 6G mobile networks (Ansari *et al*. 2017:3970-3984).

The Third Generation Partnership Project 3GPP has developed D2D communication as a compelling alternative for many applications requiring direct access, both with and without infrastructure. In cellular networks, D2D communication is defined as two UEs in proximity connecting directly to each other without passing via the base station (Cai *et al.* 2015:5429-5434). D2D communication in cellular networks has several advantages for both network operators and end users. To begin with, it boosts spectral efficiency by repurposing the same frequency resources that cellular users are using. Second, because of the short distance communication, it decreases communication delay and boosts network throughput. Third, D2D enhances energy efficiency by utilising less transmission power when mobile terminals communicate directly with one another. Another significant benefit of D2D is hop gain, which occurs when the uplink or downlink resources are required for the direct communication channel (Adnan *et al*. 2020:1-22).

D2D communication is not a new concept; it has been used in non-cellular (unlicensed) technologies like Bluetooth, Wi-Fi Direct, and ZigBee for a long time. These non-cellular technologies can also establish direct contact between devices, but they have low spectrum and low energy efficiency, a small communication range, and are susceptible to high interference in general (Yu-Lien *et al*. 2016:1-6). LTE-D2D technology, according to Jung *et al.* 2016:19, can be effective at addressing these issues.

Figure 2.1 shows two smartphones participating in D2D communication and one smartphone also participating in D2D communication with a sensor. For traditional networks, the BS must be involved in all communications even when communicating devices are some millimetres away from each other. This can work well for low data applications like voice and text but presents problems to modern mobile users who exchange high volumes of data especially in the form of video files. The concept of D2D communications first appeared in (Lin *et al.* 2000:1273-1282) and its first implementation appeared in (Wu *et al*. 2010:521-525).

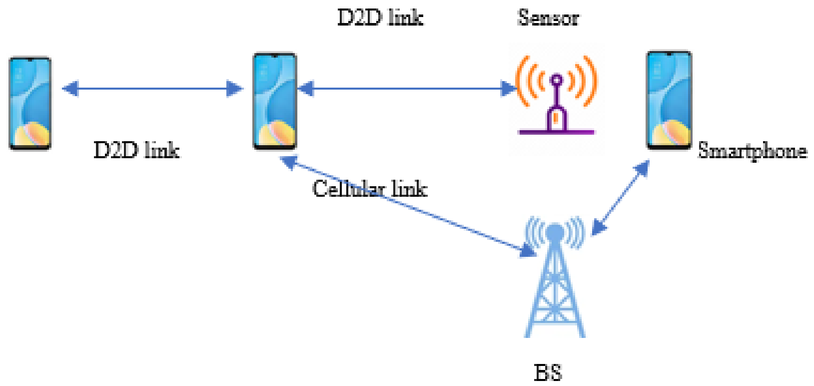


Figure 2.1: D2D communications

## 2.3 D2D Communication Modes

D2D communication can be categorised into inband (licensed) and outband (unlicensed) based on how user devices can access the licensed or unlicensed spectrum. Table 2.1 shows the different types of D2D communications.

Table 2.1: D2D communication types (Mwashita & Odhiambo 2018:222)

| | D2D communications | | | |
|---|---|---|---|---|
| | Inband | | Outband | |
| | Underlay | Overlay | Controlled | Autonomous |
| Frequency band | Licensed band | Licensed band | Unlicensed band is used | Unlicensed band is used |
| Spectrum resources | Cellular and D2D users use the same spectrum resources | Cellular users and D2D users use separate resources | Cellular spectrum is used | Industrial, Scientific, and Medical (ISM) band is used |

### 2.3.1 Inband D2D Communication

D2D and other cellular users in a cellular network share licensed cellular frequency in inband communication. The network infrastructure, such as the BS, has complete or partial control over D2D users. The BS oversees prospective D2D devices, establishing links based on channel status information, allocating radio resources either uplink or downlink, controlling power based on a pre-defined threshold level, and coordinating interference between cellular and D2D users (Mach *et al.* 2015: 1885-1922). The inband D2D communication is further subdivided into underlay (non orthogonal) and overlay (orthogonal) modes.

### 2.3.2 Underlay Inband

According to Zhu *et al.* (2018: 1148-1151) and Zhang *et. al* 2018:1-9), under underlay inband D2D, the BS allocates the same radio resources to D2D and cellular users simultaneously. Based on performance parameters such as mutual distance between D2D and cellular users, transmit power level, interference limitation area, the BS reuses either the uplink or downlink resource blocks for D2D communication. When compared to overlay, the reuse mode can achieve a higher spectrum efficiency. However, because both D2D and cellular users can use the same physical resource blocks at the same time, it creates a serious interference problem.

### 2.3.3 Overlay Inband

For this mode, the BS allocates resources for D2D communication. As a result, there is no mutual interference between cellular and D2D users, because each communication mode has its own allocated physical resource block for its own communication. However, because many D2D links can use the same RBs for their transmissions, there is still mutual interference among D2D users, which affects the overall network throughput. In comparison to underlay mode, overlay inband has a severe disadvantage of underutilisation of radio resources. This is because when there is no D2D session, the dedicated resources are kept idle, resulting in inefficient spectrum utilisation.

### 2.3.4 Outband D2D Communication

Outband D2D communication operates in the unlicensed industrial, scientific, and medical (ISM) frequency band. This is similar to the wireless local area network (WLAN) and Bluetooth technologies' working bands. Coordination and management of D2D connections in outband D2D can be controlled by the BS, or by the D2D users themselves. The key benefit of this type of D2D is that it eliminates the problem of interference between cellular and D2D networks. Additionally, resource allocation is simplified because the scheduler (i.e., BS) does not need to account for user frequency, time, or location when assigning resource blocks (RBs) to both D2D and cellular users.

Users can also use the two radio interfaces to maintain cellular and D2D connections at the same time. However, due to the availability of other communication entities such as Wi-Fi and Bluetooth devices that operate in the same unlicensed band, there is unpredictable inter-system interference. As a result, sharing unlicensed spectrum may not provide a stable, controllable environment, resulting in congestion and poor QoS, as well as a reduction in overall network throughput. Furthermore, the security of D2D transmission and coordinating communication across two bands with separate radio interfaces creates a critical power management issue. Depending on the extent of network engagement in managing and coordinating D2D communication, outband D2D communication can be classified as network–assisted (network controlled) or autonomous D2D.

### 2.3.5 Network-Assisted D2D Communication

In the network assisted mode, the BS oversees the synchronising of D2D users in time, frequency, and phase utilising primary synchronisation signal (PSS) and secondary synchronization signal (SSS). It transmits control information signals for device detection, session setup, link establishment, resource scheduling assignment, power control, and routing via the physical downlink control channel (PDCCH). In addition, the BS monitors D2D links to guarantee that D2D policies are followed. The D2D users provide a status report on the direct connection, as well as other control information about the environment, to the eNB on a regular basis via physical uplink shared channel (PUSCH), random access channel (RACH), and other channels. Channel status information (CSI), signal to interference and noise ratio (SINR), device discovery request, and scheduling request are all included in the report (Kwon *et al.* 2018:1-6).

### 2.3.6 Autonomous D2D Communication

The BS has partial control over the activities of D2D users (DUEs) or links in autonomous D2D communication. The BS manages radio resource allocation over a long period of time, limits the maximum transmit power allowed for D2D users, and so on. D2D users freely initiate communication sessions by declaring and monitoring the process between the D2D pair through direct discovery. Simultaneously, D2D users can control radio resource allocation, plan their own transmissions, and establish power control independently in a distributed manner. When there is a serving BS and no cellular network infrastructure, autonomous D2D communication can be used in both in-coverage and out-of-coverage areas. The D2D pair can establish communication with each other independently in both circumstances. The BS incurs less signaling overhead because of autonomous D2D, allowing it to service other cellular users. However, one of the primary obstacles for autonomous D2D is interference control among DUEs.

In autonomous mode, a device chooses resources at random from a resource pool that has been pre-configured or that has been identified by a BS if it is in coverage. The cellular operator determines the size of this resource pool based on traffic forecasts. Even if the devices are out of range, they can support this mode. The main problem with this mode is interference, as two or more devices may choose the same radio resource as well as significant implementation complexity on the part of D2D users. As shown in Figure 2.2, a resource pool is a collection of resources dedicated to the sidelink operation. It comprises of a subframe pool and a subcarrier pool. A bitmap in the resource pool shows which subframes will be used for the sidelink. The frequency domain setup is determined by three parameters: PRB-Start, PRB-End, and PRB-Num.

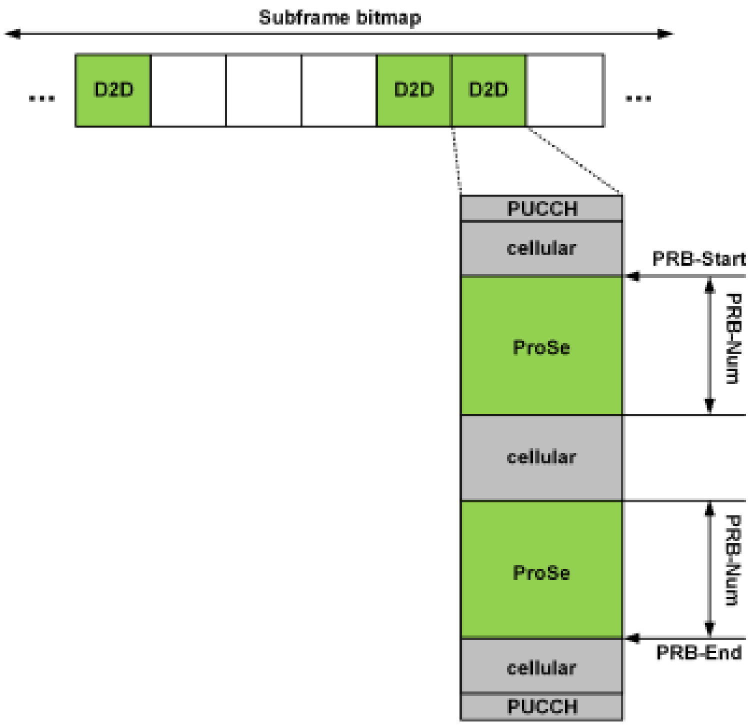


Figure 2.2: D2D Resource pool. Adapted fron (Schlienz and Roessler, 2015, pp1-36)

## 2.4 D2D Communications and Public Safety

3GPP has acknowledged the importance of having devices that are near each other to directly communicate with each other by publishing technical specifications for ProSe and D2D in LTE Release 12 of 2015 through to the publication of LTE Release 15 in 2018 as depicted by Höyhtyä *et al.* (2018:5) in Figure 2.3.

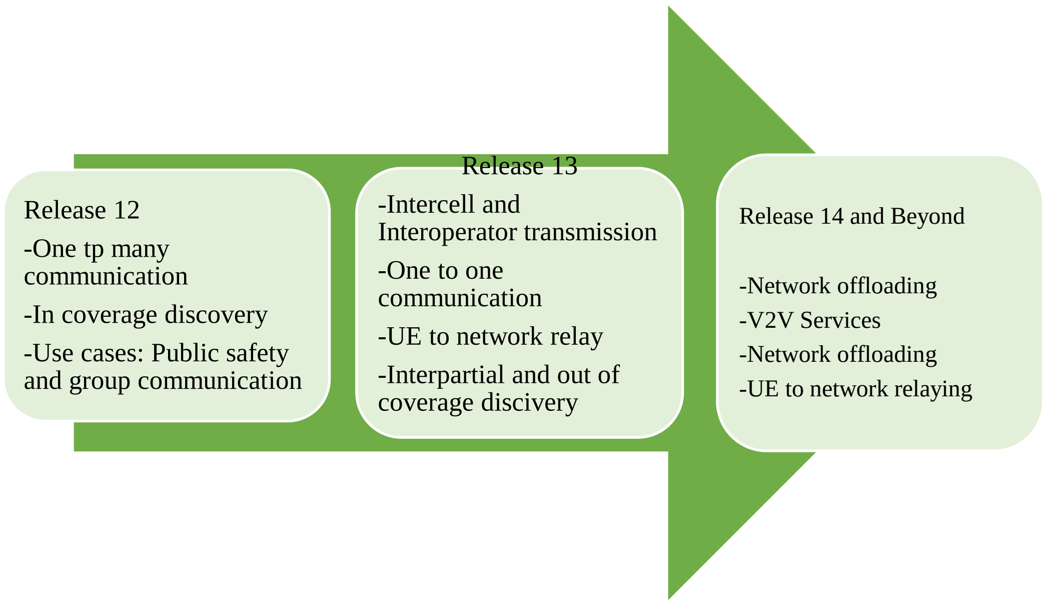


Figure 2.3: D2D communications support in 3GPP releases

The main motivation that led to the standardisation of D2D by 3GPP (2013:1-45) in LTE was for public organisations that provide firefighting services, medical emergency services and the police which are expected to intervene and render assistance after a natural disaster or in situations where ordinarily an established cellular infrastructure fails to cope with high congestion levels. Disasters like floods, fire and heavy storms can severely cripple a well-established communication infrastructure. The cellular network might fail due to damage to network infrastructure or due to an overload resulting from intense traffic. In situations like these, 3GPP proposed that D2D can be used to convey information to users who are close to each other and UEs can be used to relay information to control centres in the case of a disaster (3GPP 2013:1-45). Users with D2D-enabled devices can also use their devices to notify nearby responders of their condition and whereabouts. The 3GPP has spearheaded the standardisation process. New functions and interfaces have been introduced by 3GPP (2013:1-45) so that future cellular networks may be able to provide proximity services. LTE has been a momentous success since its inception, and this has seen many international organisations considering it for critical communications.

## 2.5 D2D LTE Architecture

The D2D architecture, which is based on the conventional LTE architecture, provides a new entity named Proximity Services (ProSe) function in the Evolved Packet Core (EPC). (Prasad *et al.* 2016:56). Figure 2.4, adapted from 3GPP (2017:13), shows the basic architecture of LTE-Advanced Pro that incorporates the ProSe functionality.

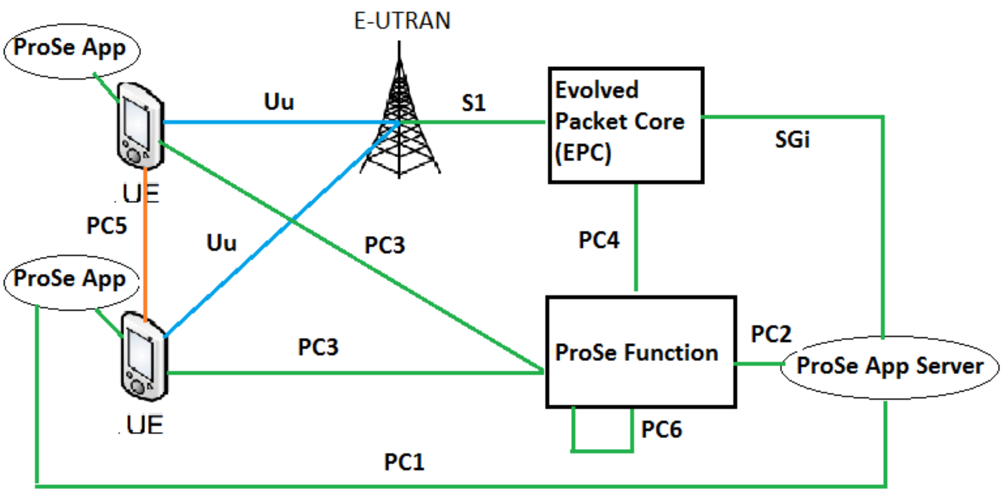


Figure 2.4: The basic architecture of the D2D LTE (3GPP 2017, p13)

As can be seen in Figure 2.4, ProSe-enabled devices have ProSe applications running on them and this allows the devices that are close to each other to directly communicate with each other. PC3 and PC5, two new logical interfaces, are introduced. A user who wants to use a Prose application must first communicate with the ProSe function via the PC3 interface.PC3 and PC5 (3GPP 2017:13). Once the UE has been authorized, it can begin the discovery process or communicate with other UEs over the PC5 interface. The term "sidelink" is used to describe direct connection over PC5. The functions of these interfaces are given in Table 2.2.

Table 2.2: Functions of PC3 and PC5

| Interface | Function |
|---|---|
| PC3 | UEs use this interface to connect to a ProSe Function |
| PC5 | UEs use this interface to connect directly to each other |

ProSe-enabled devices communicate with the ProSe Function via PC3 and through this interface, ProSe-enabled devices can obtain information for network related actions. Authorisation to participate in a D2D session is obtained from the BS via PC3.

## 2.6 Resource Management for D2D Networks

The introduction of D2D communication in cellular networks necessitates a review of current radio resource management strategies to make the most of this technology. The radio resource management strategies for D2D communication in cellular networks can be divided into three categories: (Lucas and Gozalvez, 2017:120-130)

i) Mode selection, which involves deciding whether a user pair should communicate directly or via the BS.
ii) Power control, which involves setting the transmitting nodes' power levels.
iii) Time/frequency resource allocation, which involves allocating the physical RBs for use by each interaction.

## 2.7 Performance Gains of D2D Communication

Direct connection between two mobile users without the use of a BS can result in four different types of performance gains.

(i) Short-range communication via a D2D link allows for higher data rates, shorter latency, and reduced power consumption.

(ii) The hop gain is the second benefit of D2D communications, as it only requires one hop rather than two, consisting of one UL and one DL.

(iii) The third benefit is reuse, because in an underlay mode, D2D users can share the same licensed spectrum as cellular users.

(iv) The paring gain, which enables new sorts of wireless services.

## 2.8 D2D Opportunities and Use Cases

There are a growing number of scenarios that call for data to be shared across neighbouring terminals and can therefore be facilitated by D2D technology. The key situations and services that benefit from D2D communications can be divided into the categories shown in Figure 2.5.

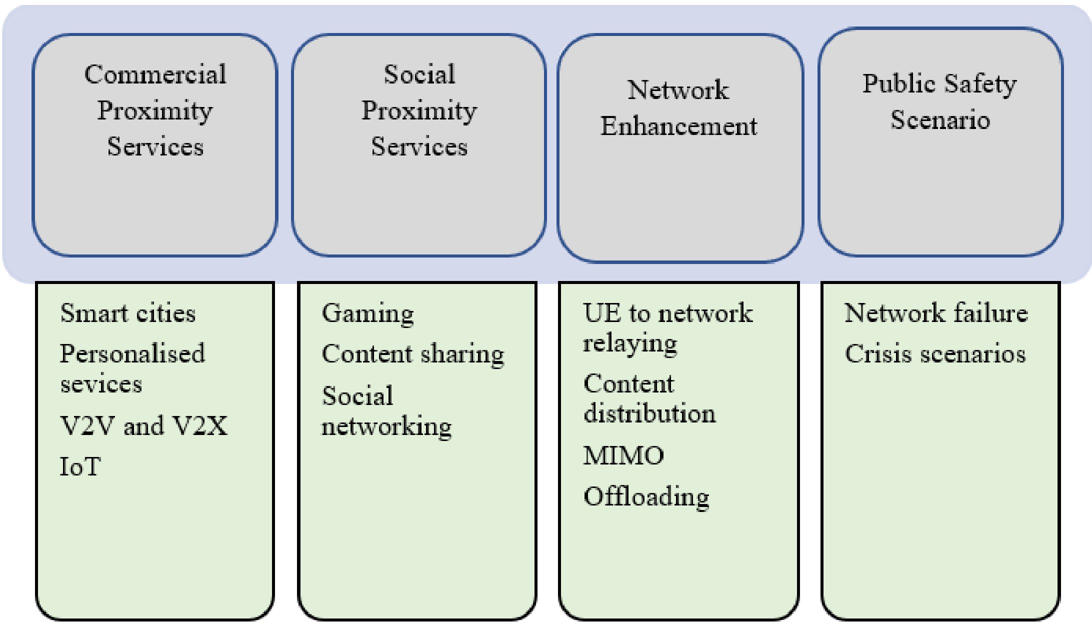


Figure 2.5 D2D communications use cases

### 2.8.1 Commercial Proximity Services

There are some promising D2D communications uses in location-aware services, both economical and social. Smart cities (Orsino *et al*. 2016:1-19), Machine-to-Machine (M2M) communications, local advertising, streaming services (Vo *et al*. 2018:209-223), and Vehicle-to-Everything (V2X) communications are among the new use cases of D2D communications for commercial proximity services. D2D communication can also be used to broadcast information regarding public transportation services, such as train schedules in subway stations or flight updates in airports, to nearby users (Kar and Sanyal 2018:203-208). Future cellular technologies are aimed to create widespread connections among different sorts of terminals, such as cameras, printers, and automobiles, in addition to human-centric communications. V2V communication intends to promote the sharing of information between automobiles in proximity to prevent accidents and enhance traffic management. For its ability to meet the tight reliability and responsiveness criteria set by V2V applications, D2D technology is a viable contender for vehicular networks (Liang *et al*. 2017:3186-3197).

### 2.8.2 Public Safety Services

In public safety scenarios, D2D communications are likely to play a significant role. Cellular infrastructure, for example, can be affected in the event of natural disasters like earthquakes, stormy weather conditions or terrorists' attacks. The cellular network may fail in these scenarios due to infrastructure damage or excessive congestion and overload caused by a heavy traffic load. D2D communications can be used to establish direct communications between mobile users to ensure public protection, disaster assistance, and public safety services (Fodor *et al.* 2014:1510-1520). D2D communications were introduced by the 3GPP specifically for public safety scenarios. Public safety agencies such as the police and firefighters, have traditionally established their own communication technologies, which are based on standalone infrastructure and devices, utilise different standards based on the geographical location, and mostly provide voice services. There are several reasons to assume that providing new network innovations could be beneficial in an emergency. In the case of broadband data transfer, real-time video, and geolocation, for example, it would be possible to track the exact location of first responders or injured persons (Câmara and Nikaein, 2015).

### 2.8.3 Network Enhancement

Due to D2D connections, user to network relaying is possible. The fundamental benefit of this scenario is that it increases capacity, expands cellular network coverage, and reduces the energy consumption of low-power devices (e.g., IoT and wearables) (Liu *et al.* 2014:2304-2308). Secondly, the D2D approach can be used to optimally distribute the network load in the following scenarios: content delivery (Biswash *et al.* 2017:995-997, multicasting (Santana *et al.* 2018), and direct communications (voice, messages, content sharing). Thirdly, the BS takes advantage of D2D-based localization to improve user placement accuracy. Finally, the D2D approach can help with the administration of various cellular procedures, such as handover (Lai *et al.* 2020:1-6). D2D relaying is a technique that involves employing a UE as a relay to assist another nearby device in communicating with a BS. The UE-relay-BS setup allows base station coverage to be extended. Furthermore, the devices participating in D2D communication constitute a virtual cellular infrastructure, which takes advantage of spatial diversity. Smartphones that maybe close to sensors can act as relays. The D2D capability must be enabled on a smartphone for it to function as a relay. The sensor then sends its data over a D2D link to a nearby smartphone, which subsequently sends the aggregated data to a BS via cellular connectivity. Using UEs as relays has the advantage of not requiring additional deployment expenditures. One disadvantage of this setup is that it is difficult to estimate the areas covered by UEs because they move about according to their owners' patterns. Several research papers have investigated the feasibility of employing a UE as a relay to connect sensors via D2D networks. Rigazzi *et al*. (2014:1-15) devised a multi-hop D2D communication technique to reduce energy consumption and interference when sharing radio resources across cellular and D2D networks incorporating sensors.

### 2.8.4 Social Proximity Services

D2D communications can also enhance a variety of social proximity services, including social networking (Nitti *et al.* 2019:1-5), gaming, content sharing, and video delivery. Cellular networks have recently been significantly overburdened by social-based services such as YouTube, Facebook, and Twitter, in which thousands of users subscribe to a single content provider (for instance, a famous artist) and receive his/her material updates on a regular basis. Offloading such traffic to alternative networks, such as a delay-tolerant network made up of D2D interactions between mobile users, is a feasible way to mitigate cellular constraints (Wang *et al*. 2020:1-10).

## 2.9 Integrating D2D in Cellular Networks for Sensor Networking

The use of D2D communications for sensor networking is very promising. Sensed information can be processed quickly, locally by smart phones and other mobile gadgets, and then relayed to BSs for further handling. Researchers from academia and industry agree that D2D will play a very pivotal role in future generation networks, specifically 5G networks (Chaaban & Sezgin 2015:15-22 and Tehrani *et al*. 2014:86-92). According to a report by 3GPP (2013:1-45), Massive Machine Type Communications (mMTC) is commonly regarded as a significant service that is provided by 5G cellular networks in the provision of wireless sensing services. mMTC is an Internet-of-Things (IoT) scenario in which many static sensors are placed and report irregularly to cloud-based application servers. D2D communication, as one of the key technology enablers for 5G networks, offers a cost-effective way to meet the demands of mMTC services.

Massive machine-type communication is being explored to support communication among many devices. This provides a feasible solution for future industrial IoT (IIoT) (Al-Sakran *et al*. 2018:291–297). Massive devices can access a wireless network in a spectrum-sharing mode, in which several devices are allocated to the same spectrum at the same time, due to limited spectrum resources in the cellular system. This limits the number of devices that can connect to the cellular system because of co-channel interference.

Studies have been conducted to see how D2D can be used to improve mMTC services. (Pratus and Popovski, 2014:423-428) and Kar and Sanyal (2018:203-208) proposed that a single cellphone can operate as a relay for other sensors via D2D connectivity. Packets generated by those sensors can be sent to a BS via a relay. Because the D2D pairing operation is carried out in a scattered fashion without the assistance of BS, there is a loss of global awareness. As a result, the proposed approach has a limited applicability.

Wireles Sensor Networks have been in existence since the 1950s, Singh *et al.* (2020:1-24). Environment monitoring, home automation, healthcare, agricultural, military, smart grids, smart autos, and explosive detection are just a few of the applications for wireless sensor networks (WSN). Sensors having wireless radio interfaces are used in these applications to create a wireless network and communicate with other sensors or a data aggregator. Kundaliya (2020:1-5) pointed out that WSN will be critical in launching the early Internet of Things (IoT) sector though there are some technical hurdles that must be addressed before WSN may be used as a network infrastructure for the early IoT. The autonomous communication among sensors is a typical open problem. Controlling all sensors in a WSN using a central node is inefficient (Kundaliya 2020:1-5).

According to Mumtaz and Rodriguez (2014), D2D communication can be a solution in WSNs in resolving this problem. Instead of being routed through a controller or central node, sensor nodes in proximity can establish a direct link with each other employing D2D communication. The network coverage expansion and interworking with heterogeneous networks is an emerging field of study of WSN to improve IoT. Cellular networks could be a great contender for resolving this issue. Most countries are covered by cellular networks, which interoperate with other networks. As a result, there is a rising trend to combine WSNs and cellular networks.

According to Meng *et al.* (2017:2694), a large number of devices, including monitoring sensors and execution control units, will be deployed to enable factory automation and industry control systems in the future industrial Internet of Things. Large amounts of periodic and non-periodic data, such as video monitoring data, sensing data, and operation instructions, will be sent to a centralized control unit or neighboring devices via an industry wireless network. The current cellular system, however, should embrace D2D communication for it to serve future IoT applications with many devices and heterogeneous data flow (Park 2019:1-6).

## 2.10 Design Challenges of Integrating D2D in Cellular Networks for Sensor Networking

Integration of D2D capabilities in cellular networks creates new technological and architectural challenges.

### 2.10.1 Mode Selection

In the context of D2D communication, a natural design problem is determining the conditions under which two users should create a direct link (D2D mode), rather than connecting via the BS. The mode selection problem entails determining whether to use D2D or cellular mode for a D2D pair. The decision on the performance metric to optimise, what channel state information is required, and how frequently this information should be updated are all design concerns tied to the mode selection problem. Another key decision is how frequently the users' communication mode should be updated. On the one hand, the mode selection time frame cannot be too broad because the wireless channel may swiftly change, rendering the assigned modes ineffective. Adapting the communication mode to channel fluctuations, on the other hand, can be impracticable and costly due to additional signalling overhead. Finally, because of the mutual effects that they have on each other, the communication mode of a transmitter should be allocated jointly with the radio resources (e.g., power and frequency channels) to realise the full potential of D2D communication, particularly in the case of shared channels where interference can become an issue (Hou and Chen, 2020:244-251).

### 2.10.2 Neighbor Discovery and Synchronisation

Neighbour discovery and synchronization, according to Bagheri *et al.* (2015:591-595), are two crucial first steps in building dependable D2D connections. The process of neighbour discovery involves the searching for devices that are geographically adjacent to each other, representing possible D2D users. User synchronisation aids in the efficient use of available energy and spectrum. Neighbour discovery, according to Mumtaz and Rodriguez (2014), can be accomplished via asynchronous scan/search algorithms based on beacon sequences. Users looking for peers, broadcast their identification on a regular basis so that other users in the area can recognise them and determine whether to initiate a D2D communication. Due to a lack of synchronisation, the receiver must constantly monitor the channel to avoid missing the transmitters' discovery signals. Because the listening phase can greatly deplete the battery of mobile devices, this constant monitoring becomes an essential issue in terms of energy usage.

When D2D connections are established with the help of a cellular network, the cellular infrastructure's underlying synchronisation can be exploited to improve the D2D discovery phase. In this scenario, however, new discovery signals must be developed and integrated into existing cellular mechanisms. The functionality of the cellular network in which the D2D technology is embedded can also dictate the type of D2D synchronisation. For example, to coordinate interference in a cellular operation like OFDMA multi-carrier modulation, time and frequency synchronization is required.

### 2.10.3 D2D Channel Modelling

When compared to regular cellular channels, D2D radio channels have different propagation qualities (Nurmela and Kyosti, 2014:1-5). First, in D2D communications, both the transmitter and receiver have modest antenna heights, resulting in more interaction with objects in the terminals' immediate vicinity. This is especially problematic in urban settings, where devices are placed in roadways with moving shadowing items such as vehicles (Vannithamby and Talwar, 2017).

In open space or indoors, however, the D2D pairs' short-range communication is likely to cause line-of-sight (LoS) propagation. Unlike cellular communication, where the base station is fixed in place, both endpoints of a D2D link can move. This double motion necessitates the development of novel Doppler models. D2D communications may operate in the mm-wave bands as well. Other propagation properties of transmissions at these frequencies must be considered. It's critical to have access to the CSI between mobile devices while planning and analysing the performance of D2D-enabled networks. This is a more difficult operation than in traditional cellular networks, where all that is necessary is the CSI between the devices and the base station. The collection and possible sharing of such data can add an unacceptably high amount of overhead to the system. In D2D-enabled networks, the trade-off between CSI accuracy and signalling overhead must be considered.

### 2.10.4 Matching Performance, Computational Complexity and Signalling

It's difficult to come up with optimal resource allocation methods that are both low in computational complexity and low in signalling overhead (Zhou *et al.* 2017:5256-5268). In many circumstances, algorithms for resource allocation policies must tackle nonconvex, combinatorial, and other optimisation problems. This can be time-consuming, inefficient, and unmanageable in real-world systems. Furthermore, optimal solutions frequently rely on the complete CSI of all relevant links and/or the flow of a large amount of data among nodes. Due to the associated communication overhead, this may be unworkable. As a result, the difficulty is to strike a good balance between optimality and application, as well as to choose between joint versus separate resource allocation optimisation and centralised versus distributed solutions.

### 2.10.5 Interference Management

The expense of obtaining additional licensed bandwidth is high for network operators. As a result, the available spectrum must be effectively utilised using adequate interference control strategies. Interference management is a difficult problem to solve, particularly in networks where D2D communications use cellular spectrum (Wenjun *et al.* 2019:4530). In this case, intra-cell interference is added to the typical inter-cell interference due to frequency reuse amongst users in the same cells. Interfering transmissions in D2D networks can operate at any distance, hence the presence of D2D links can have a significant impact on system performance. By lowering the signal-to-interference-plus noise ratio, interference can impede successful transmissions.

According to Mwashita and Odhiambo (2018:219-245), there are three approaches that can be employed in tackling the interference in D2D-enabled cellular networks:

(i) Centralised approach.

(ii) Distributed approach.

(iii) Hybrid approach.

Table 2.3 presents the general characteristics of these capproaches.

Table 2.3 Characteristics of interference management classes

| Criteria | Centralised Approach | Distributed Approach | Hybrid Approach |
|---|---|---|---|
| Controlling Entity | The Base Station | DUEs make their own decisions | BS and DUEs participate in a well-defined manner in the controlling of interference |
| Where used | Can be used in small networks | Can be used in large networks | Can be used in moderately large networks |
| Attributes that can be used for controlling | Channel State Information (CSI) QoS, Feedback, etc. | Spectrum utility maximization | Beamforming, power |
| Control actions | Power, Resource allocation | Power, Linear optimisation | Power, resource allocation |
| Disadvantages | Requires huge amount of signalling | Interference coordination is difficult | Computationally intensive |

## 2.11 Conclusion

Today's wireless broadband access systems face a considerable challenge of providing high-speed data rates while also performing well in a variety of geographical and landscape scenarios. Mobile communication systems have been extensively researched to provide solutions that allow users to convey useful information. In this context, the Third Generation Partnership Project (3GPP) has introduced D2D communication as a viable alternative for a variety of applications that require direct access, both with and without infrastructure. This chapter has presented the background of D2D communication with a focus on its integration in future cellular networks, particularly in the domain of sensor networks. D2D opportunities and use cases have been outlined. The design challenges of integrating D2D in cellular networks for sensor networking have also been discussed. The design issues that academics and industry professionals are facing in trying to progress technologies using D2D use cases have been identified as mode selection, neighbour discovery, and synchronisation, D2D channel modelling, and interference management. Interference management has been noted as a particularly challenging problem to handle, particularly when aspects such as computing complexity and signaling are critical in the desired outcome. The need for robust interference management techniques to deal with the interference that is introduced by D2D has also been discussed. The next chapter presents a literature review of interference management techniques for D2D-enabled cellular networks.

# CHAPTER THREE: LITERATURE REVIEW OF INTERFERENCE MANAGEMENT SCHEMES IN D2D-ENABLED NETWORKS

## 3.1 Introdruction

The purpose of this chapter is to discuss the current state of the art in interference management techniques for D2D-enabled cellular networks. Power control, mode selection, beamforming techniques, and other novel interference management approaches have gotten a lot of attention from the research community. Machine learning's role in D2D-enabled network interference reduction is also discussed in this chapter. The current approaches' drawbacks are also noted. This is being done to provide an effective technique for reducing interference in D2D-enabled cellular networks where sensors would have been deployed to participate in a D2D communication arrangement with smartphones.

## 3.2 Categories of interference management techniques

According to Adnan *et al.* (2020:1-22) interference avoidance, interference cancellation, and interference coordination are the three main categories of methods that have been advanced by many researchers to mitigate the interference that exists in D2D-enabled mobile networks. The categories and the methods are presented in Table 3.1.

Table 3.1: Categories of Interference Management Techniques

| D2D Interference Management Techniques | | |
|---|---|---|
| Interference Cancellation | Interference Coordination | Interference Avoidance |
| (i) Successive interference cancellation<br>(ii) Parrallel interference cancellation<br>(iii) Multi-stage interference cancellation<br>(iv) Full Duplex-Based Interference Cancellation<br>(v) Unconditional Interference Cancellation<br>(vi) Non-Orthogonal Multiple Access | (i) InterferenceAilgnment<br>(ii) Enhanced inter-cell interference coordination<br>(iii) Coordinated multipoint<br>(iv) Network assisted interference cancellation and Suppression | (i) Spectrum splitting<br>(ii) Power control |

## 3.3 Interference Avoidance

Interference avoidance approaches involve manipulating signals to prevent interfering nodes from interacting (Ansari *et al.* 2017:3970-3984). The main goal of this interference mitigation technique is to enhance the SINR, which allows all system UEs to share the same frequency channels regardless of how severe the interference is. Interference avoidance is a frequency, timing, and power control technique that coordinates network resources and reallocates them to UEs (López-Pérez *et al.* 2009:41-48). Interference avoidance approaches have been extensively studied using various network resources such as radio frequency, user interaction, power distribution, and so forth. Although these approaches are referred to as "interference" avoidance, they have also been used to reallocate resources to address a variety of network challenges, including UE offloading, handover, and so on. As a result, approaches in this area should be categorised based on whether the distribution of network resources is static or dynamic.

To properly present how interference avoidance works on D2D networks in this thesis, Viering *et al.* (2006:2095-2100)'s proposal of categorising the strategies into two groups based on how they interact with network resources was adopted. The two groups are static channel allocation and dynamic channel allocation techniques.

### 3.3.1 Static Channel Allocation Techniques

The most significant resource that must be pre-allocated for static channel allocation approaches is frequency (Amirteimoori and Tabar, 2010:3036-3039). For the method of static channel allocation, each cell will have its own exclusive portion of the frequency resource and will not share it with its neighbours. Frequency reuse systems include traditional frequency planning schemes (Reuse-1 and Reuse-3), partial frequency reuse (PFR), and soft frequency reuse (SFR):

#### (i) Conventional Frequency Schemes

The perfect scenario is to utilise a frequency reuse factor of one (Reuse-1), which means that all available frequency resources are shared and reused across network cells. However, considerable interference will certainly result from this technique, particularly for cell edge users with low received power. To reach Reuse-1, a trade-off must be made while using static channel allocation. To directly decrease the interference caused by reuse-1, Viering *et al.* (2006:2095-2100) and Navaratnarajah *et al.* (2013:37-43) proposed a replacement technique, Reuse-3, that divides the entire frequency resource into three equal but orthogonal sub-bands, allowing adjacent sectors to be assigned to different sub-bands without interfering with neighboring sectors. The results reveal that interference can be significantly reduced, but there is a drawback: spectrum efficiency is sacrificed in favour of this tight interference avoidance technique. As a result, when compared to Reuse-1, two-thirds of frequency resources are not fully utilised.

(ii) Partial Frequency Reuse (PFR)

The Reuse-3 approach is relatively simple: it is a basic static resource allocation methodology that involves trading off spectrum efficiency. PFR systems have been used to increase the frequency factor from Reuse-3 to minimise the disadvantages of traditional planning. The general concept behind this plan is to reserve the same band and power level for all sectors. Khan (2019) proposed using two separate frequency reuse factors to create reduced inter-cell interference for all UEs and other devices participating in D2D communication within a cell. For a reduced interference, full frequency reuse is used for cell centre users and low frequency reuse is used for cell edge users. Rahman and Yanikomeroglu (2010:1-6) improved the concept by limiting the use of some frequency resources in certain sectors. Furthermore, the reuse factors for cell edge users ought to be variable for each individual cell, as determined by the prevailing interference scenario. Chang *et al.* (2019:3993-3998) extended the PFR concept by defining adaptive spectral sharing for different cell loads. This design considers the fact that traffic loads in different cells can change in terms of content and request timing. Because this condition is identical to the problem of graph colouring, the authors used the graph colouring algorithm to address the resource allocation problem.

Porjazoski and Popovski (2010:160-164) developed an analytical method based on static inter-cell interference coordination (ICIC) for calculating inter-cell interference and applying coordination based on numerical results for cells sharing the same frequency channels. This inter-cell interference coordination technique focuses on reducing interference from cell-edge UEs and other D2D-enabled devices. Instead of merely selecting a universal reuse factor, it analyses the interference level of various CUEs and D2D-enabled devices before deciding on the amount of reserved frequency reuse. The researchers then analysed inter-cell interference using three different schemes: uniform frequency reuse factor, Reuse-3, and static inter-cell interference coordination. According to simulation data, the interference level for cell-edge users utilising partial frequency reuse ICIC was found to be around two times lower than those using Reuse-3 schemes, and about three times lower than those using universal frequency reuse situations. Since PFR provides a strict non-sharing policy for reserved parts of the frequency resources, spectrum efficiency for large scale networks is underutilised.

Some studies suggest incorporating flexibility to PFR's stringent no-sharing restriction, sometimes known as Soft Frequency Reuse (SFR), to improve spectrum efficiency (Jiming *et al.* (2013:45-55). As a result, the term "soft" refers to the ability to achieve frequency reuse by altering power control strategies between the cell centre and peripheral regions. Jiming *et al.* (2013:45-55 increased the frequency reuse factor for centre DUEs and CUEs to 1, allowing these users to take advantage of all available frequency resources. The researchers then employed a power control strategy to keep cell CUEs and DUEs at a minimal level of interference. To distribute transmission power to DUEs and CUEs, the needed reuse factor is applied: the centre DUEs and CUEs group is assigned high power due to the high interference level of applying Reuse-1, while the peripheral DUEs and CUEs are allocated low power to keep the overall transmission power constant.

Doppler *et al*. (2009:42-49) employd the interference awareness concept and determined the SINR for active DUEs and DUEs. Instead of centre or peripheral devices, the researchers split the groups by actual SINR of DUEs and CUEs and assigned high power to the high SINR group. However, inter-cell interference coordination's concept of SFR may differ from traditional schemes. Since cell edge DUEs and CUEs suffer from more severe inter cell interference than those in the centre, Liu *et al.* (2014:2304-2308) proposed that those peripheral devices be given higher power. Centre DUEs and CUEs will still have a greater frequency reuse factor and access to cell peripheral devices' frequency bands, but their allocated power should be reduced to keep the total transmission power unchanged. Inter-cell interference coordination focuses on total devices' interference balance inside the cell and neighboring cells, whereas traditional systems primarily focus on the current cell's centre DUEs and CUEs with high frequency reuse factors.

Static channel allocation methods do not aim towards Reuse-1 for all DUEs and CUEs in the system. Static channel allocation can increase the reuse factor of certain

DUEs and CUEs by up to 1 by reserving a portion of the frequency resource. Inter-cell interference coordination may outperform existing algorithms by considering the precise cell-edge interference condition as well as the level of interference between neighboring cells. This approach, however, necessitates intelligent recalculation and optimisation of inter-cell interference coordination settings whenever the condition of cell edge CUEs and DUEs changes. Furthermore, because of their low received power, cell edge DUEs and CUEs may be more susceptible to QoS deterioration. As a result, the static channel allocation reserving frequency resource strategies may not be suitable for deployment in D2D-enabled networks with sensors participating in D2D communication.

Shah *et al.* (2015:137-152) proposed a scheme that uses fractional frequency reuse (FFR) based architecture for the allocation of the available resources to deal with interference that results from D2D communications. The scheme utilises proportional fair (PF) scheduling algorithm in the allocation of RBs. The researchers designed a smart power control technology that enables DUEs and CUEs to achieve an acceptable minimum SINR. The proposed scheme outperformed schemes that use strict and soft FFR. One major drawback of the proposed scheme is the issue of out-of-bound emission problem that is caused by peak-to-average power ratio (PAPR).

### 3.3.2 Dynamic Resource Allocation Techniques

Coordination systems are used in dynamic resource allocation techniques to allocate resources depending on the overall network planning. They are divided into three categories: centralized, semi-distributed, and autonomous-distributed (Hamza *et al*. 2013:1642-1670):

(i) Centralised Resourse Allocation Technique

The term 'centralised' refers to the fact that the network is managed by a single controller. This controller will evaluate all network CUEs and DUEs for interference and then distributes available resource blocks to these devices. The central controller must receive every channel quality indicator (CQI) from network BSs and give back coordination signals to accomplish specified network metrics such as total throughput, CUEs' and DUEs' fairness, and interference levels. Das *et al.* (2013:786-796), proposed that interference avoidance and dynamic load balancing coordination be controlled using a centralised architecture, with coordinated cells clustered according to their location. The researchers assumed that comprehensive CQI information from all cells, as well as coordination signals back to cells, would be unaffected, and that large total throughput gains would be realised through real-time traffic offloading. Koutsimanis *et al.* (2013:2524-2530) developed a technique to address the centralised topology's delay problem. To achieve optimum total throughput, the authors used a centralised coordination architecture to allocate RBs to each cell. The authors then presented a distributed technique to provide inter-cell interference coordination power adjustment among neighboring cells, reducing central controller coordination signaling and allowing for local fine tuning. The authors focused solely on the benefit of placing a high-speed operating central controller in the network, ignoring the massive additional backhaul signaling caused by coordination information between central controllers and all BSs.

(ii) Semi-Distributed Topology

Massive backhaul signaling will unavoidably result from centralised cell coordination techniques. As a result, semi-distributed technologies have been proposed to address this issue. Unlike centralised topologies, semi-distributed topologies typically divide algorithms into two parts: the first is centrally based, like all centralised schemes, and installs a central controller to manage network BSs. The second part is based on BSs, and instead of directly distributing RBs to DUEs and CUEs, the central controller merely provides resources to BSs. As a result, at frame level, BSs will be responsible for controlling their own DUEs and CUEs (Park and Choi, 2015:1-6).

(iii) Autonomous-Distributed Schemes

Autonomous-distributed methods decentralise the network even more by minimising central coordination as well as coordination among BSs. Each BS is very independent, assigning channels solely based on its own DUEs' and CUEs' information, reducing overhead signaling between BSs even further (Cicalo *et al.* 2011:1-9).

Kim *et al.* (2018:1-21) designed an interference management scheme that can be used to deal with intercell interference that emanates from sensors and UEs sharing resources in the uplink and downlink. For their study, the researchers, considered a converged wireless multimedia sensor network (WMSN and cellular networks. According to Porambage *et al*. (2016:1-6) and Usman *et al.* (2016:590-597), a multimedia sensor is a special sensor that can collect multimedia data. The multimedia sensors are useful in the transmission of multimedia, checking of traffic and in the monitoring of environment, machines, and people. Compared to conventional WSNs, WMSNs handle very large amount of traffic. The proposed scheme involved the division of a cell into six equal zones and the division of the allocated frequency into six fractional portions. The researchers proposed a resource allocation scheme that they called Fractional Frequency Reuse-3 (FFR-3). In the scheme, cellular links within the same cell are allocated fixed orthogonal resources.

The researchers evaluated the performance of their scheme by use of a simulator. The NLOS Winner Bf path loss model was used with a carrier frequency of 2 GHz. For the performance evaluation, it was assumed 50% of the sensors use the cellular link and 50% using the D2D link. They conducted each experiment 1000 times with the results being averaged by using the Monte Carlo method. Performance evaluation of the proposed scheme was achieved by comparing it to a semi-static scheme.

The researchers admitted that optimal power control of transmit powers of D2D sensors and UEs participating in D2D communication is very crucial in managing interference that arises when sensors are made to communicate directly with nearby devices. Their design, however, did not incorporate a rigid power control strategy of the devices engaged in D2D communication. This is likely to affect the QoS of the underlying cellular network. Furthermore, the high complexity of the proposed interference management scheme is likely to increase UE power consumption and the authors made no effort to come up with a strategy that compensates the increased power consumption.

Any communication by devices that are very close to the BS is likely to severely degrade the SINR at the BS. The proposed scheme proposed by Kim *et al.* (2018:1-21) does not limit D2D transmissions in the uplink using distance from the BS as a parameter. It was crucial to check the performance of the proposed scheme for distances that are very close to the BS. The proposed scheme does not make use of the downlink.

Kim *et al.* (2017:1-18) proposed an interference management technique in D2D-enabled cellular networks in which sensors would have been introduced for countering terrorism or other applications. The researchers proposed a joint Almost Blank Sub-Frame (ABS) and fractional frequency reuse (FFR) to deal with intercell interference that affects DUE receivers coming from CUEs. Their study sought to increase the SINR by reducing intercell interference. For their scheme, the researchers, considered a seven-cell hybrid network with CUE and DUE communications taking place. Cells are divided into two regions: centre region (inner region) and cell edge (outer region). The proposed scheme has three phases. The results obtained showed that the proposed scheme can improve system throughput and QoS. However, there was no attempt by the researchers to address intra-cell interference that come from co-channel DUEs.

### 3.3.3 Power Control Strategies

A power control strategy is one technique that can be used to reduce co-tier as well as cross-tier interference. According to Song *et al.* (2015:1-388), power control can be realised using two methods:

(i) Self-organised. With D2D pairs controlling their transmit powers at the local level without involving the BS. They achieve this by making use of a pre-defined SINR to meet a pre-defined QoS. CUEs are not involved in this process. This scheme is not so efficient, but the implementation is simple.

(ii) Network managed. DUEs and CUEs constantly modify their transmit powers according to the prevailing SINR conditions. The iterative procedure halts when all users have met the prescribed SINR requirements. Compared to the self-organised scheme, this method though very complex, is more efficient.

In 3G cellular networks, power control is used to deal with the near-far problem. The near-far problem is a result of UEs transmitting to a BS using the same transmit power irrespective of their locations in the cell. This results in weak transmissions from the cell edges being obliterated by strong signals from UEs located very close to the BS. 4G on the other hand is not affected by intra-cell interference as orthogonal resources are used in the uplink. However, power control is still needed for the compensation of path loss and shadowing. New strategies such as fast scheduling have been introduced to supersede power control schemes in 4G (Lin *et* *al.* 2019:1-19). Power control strategies have however been rekindled in 5G as an innate method of D2D interference management. According to Alsharif *et al.* (2020:1-21), instead of using traditional methods, 6G mobile networks will use operational intelligence (OI), a technology that efficiently allocates power to accomplish satisfactory network operations. Due to its heterogeneity, density, and scalability, operational intelligence requires multi objective optimisations that can function in the highly complex and dynamic nature of 6G.

Lee *et al.* (2015:1-13) proposed centralised and decentralised power control strategies. The centralised power control approach involves D2D communication links being managed centrally by a BS which uses normalised channel gains received as feedback from the DUEs. The BS computes the DUEs' and the CUEs' uplink transmit powers. The authors used stochastic geometry to develop a centralised power control scheme that works by collecting global CSI from DUEs and CUEs. The major problem with this centralised power control approach is the very high CSI feedback overhead that can easily disrupt the efficient running of the cellular network. In a bid to fix the high CSI feedback overhead, Lee *et al.* (2015:1-13) proposed a distributed ON-OFF power control strategy which avoids the sharing of CSI information. DUEs select transmit powers from a decision set making use of a pre-defined threshold that is used in conjunction with the D2D pairs' direct link information. The DUEs use these two pieces of information to select their best transmit powers. The researchers found out that the centralised power control scheme results in an improved network throughput performance that comes with a drawback of increased complexity. The distributed power control strategy outperformed the centralised power control strategy overall at a much lower complexity.

Janis *et al.* (2009:169-179) proposed a scheme that can be used in interference management for a D2D system operating as an underlay network in an LTE-Advanced mobile network. In the proposed scheme, the BS manages allocation of orthogonal frequency division multiple access resource blocks. D2D transmitters have their powers limited using the cellular uplink power control information as a way of containing the interference on the BS. The authors modelled and simulated the proposed scheme and the results showed that D2D communication can be implemented in cellular networks without adversely impacting the network operations. However, the scheme only dealt with interference from D2D pairs to CUEs and not vice versa. In as much as D2D communications should not affect the QoS of a cellular network, devices engaged in D2D communications also need to enjoy interference-free communication sessions.

Wen *et al*. (2012:542-547) proposed a strategy that maximises system's throughput as a way of managing interference in D2D-enabled cellular networks. The proposed strategy focuses on resource allocation, power control and a self-optimisation system. D2D receivers estimate the interference that exists in the whole band. This information is then used by D2D pairs to select a suitable resource block set for spectrum sharing. The BS then broadcasts resource block information and D2D property messages. The broadcast messages should contain UEs' locations and priorities amongst other things. UEs then use the broadcast information to discover partners that they can pair up with. D2D pairs then decide on the best transmit resource block group that introduces the least interference to the nearby cellular users.

A priority mechanism is used to ensure that D2D pairs within the same cluster do not transmit on the same channel, thus avoiding interference in the process. Once a pair has started using a new resource block set, SINR level is detected to decide whether a power increase request can be made to a BS. The BS can only allow a power increase if that action does not affect other users. The researchers evaluated the proposed scheme through extensive simulations. They observed a 220%-430% gain in system capacity. This was made possible by the interference reduction brought about by the proposed scheme. The proposed scheme however failed to handle a big number of D2D pairs intending to share resources in a small area. The scheme was not designed for heterogeneous networks and since the next generation mobile networks will be heterogeneous networks, the proposed scheme might not post satisfactory results where such networks are involved.

Xu *et al*. (2014:1-84) developed joint power control and beamforming strategy in the mitigation of interference in a D2D-enabled cellular network. The BS at the centre of a cell can have multiple antennas and the UEs can have a single antenna each. The strategy is centralised with the BS controlling the transmit powers as well as the beamforming. By use of extensive simulations, the researchers were able to show that the proposed joint power control strategy and beamforming strategy results in an improved system throughput with reduced interference. Beamforming requires a comprehensive precoder design which increases the computational overhead. The proposed design requires an accurate CSI feedback of all the DUEs and CUEs involved in the links. This can be problematic in large cellular networks that incorporate ProSe-enabled sensors.  The multiple antenna system substantially increases the cost of hardware implementation.

Hongnian and Hakola (2010:1775-1780) evaluated the impact of power control strategies in managing interference resulting from D2D communications. The researchers concluded that power control schemes should not be used alone in those networks. Power control schemes must be complemented by schemes like resource scheduling or mode selection. Fodor *et al*. (2013:6008-6013) also established that power control schemes can be effective in a cellular incorporating D2D communications and they came to the realisation that CUEs benefit more than the DUEs.

### 3.3.4 Spectrum Splitting

Spectrum sharing allows DUEs to share the spectrum bands of the licensed users (Mandeep & Amandeep 2015:3089-3091). Figure 3.1 shows various network systems that can be made to dynamically share spectrum.

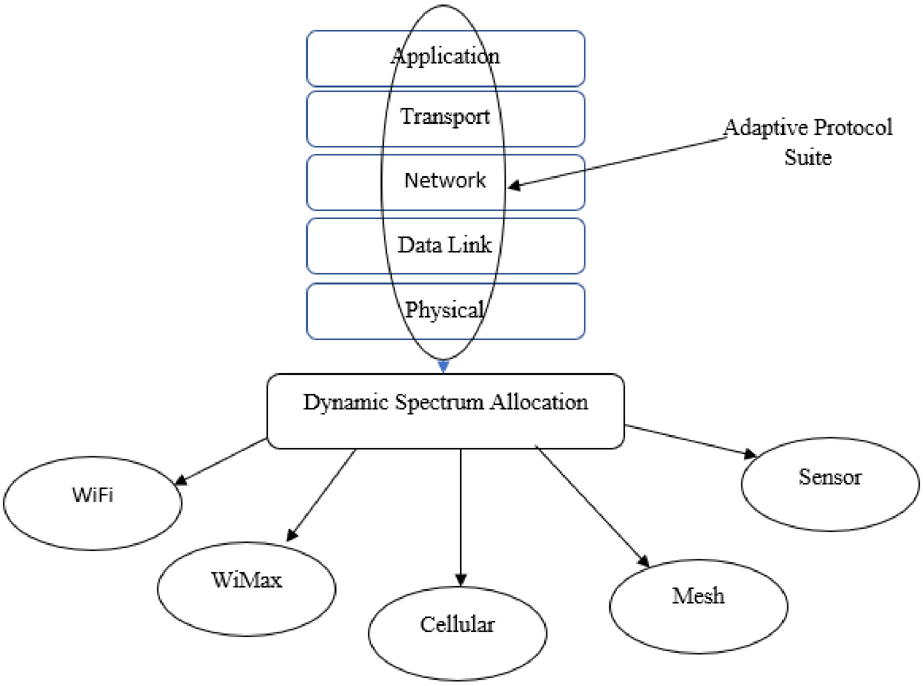


Figure 3.1: Dynamic spectrum sharing (Mandeep & Amandeep, 2015, p.3089)

Nouran and Nordin (2016:130-150) claim that spectrum splitting is the simplest method which can be used in the reduction of cross-tier interference in a D2D-enabled cellular network. An analytical approach to tackle the spectrum splitting optimisation problem was used by Lin *et al.* (2014:1273-1282) to effectively reduce interference in a D2D-enabled cellular network. The authors designed a tractable hybrid network model which could drop mobiles using a random spatial Poisson process.

They used the model to capture important characteristics like mode selection and went on to design an analytical framework which they used to produce analytical rate expressions. These expressions were used in the optimisation of spectrum sharing parameters. The researchers then derived an optimal D2D mode selection threshold that is used in the reduction of DUEs' transmit powers to lowest levels which could allow communication to occur at minimum interference. The authors split the uplink into two portions which are orthogonal to each other. They reserved one portion of the spectrum for DUEs and the other one for CUEs overlay in-band D2D communication. For the underlay in-band D2D communication, the authors allowed DUEs to make use of frequency hopping in the reduction of interference on other communicating devices. The researchers concluded that for the underlay mode, an increase in spectrum resources leads to an increase in sum rate. The rate of D2D connections is however affected by interference. The rate is sensitive to a spectrum reduction for CUEs, in the overlay but it is more robust to the D2D interference existing in the underlay. Lin *et al.* (2014:1273-1282) successfully identified the trade-off between the underlay D2D spectrum access and the mode selection by use of the model they designed. They achieved this by using traditional homogeneous cellular networks consisting of 5 macro-BSs. Though the authors posted good results in enhanced sum rate and reduced interference, the performance of the scheme has not been tested in heterogeneous networks.

## 3.4 Interference Cancellation

Intelligent cancellation techniques enable the receiver to decode the message by limiting the influence of interference. Advanced signal processing techniques, such as spatial diversity techniques and multiple-input multiple-output (MIMO), are used in interference cancellation. An intelligent interference cancellation method enables a receiver to decode messages by limiting the influence of interference (Hu and Yuan, 2015:1-12). Adaptive beamforming strategies can be employed to reject interfering signals that come from a direction which is different from the anticipated direction. A beam finder can be used to control the phase and amplitude of a beam into a highly directional beam that points in the direction of the intended recipient with zero signal in the direction of interference. This beam forming concept can be adapted and utilised in D2D-enabled mobile networks to manage interference. Interference cancellation is further categorised into parallel interference cancellation (PIC), successive interference cancellation (SIC) and multi-stage interference cancellation (MIC).

### 3.4.1 Successive Interference Cancellation

Successive interference cancellation is a promising interference cancellation technology for wireless networks and has been widely investigated by many researchers. The primary idea behind SIC is to regenerate interfering signals and then cancel them from the received composite signal to increase the target signal's signal-to-interference ratio (SIR). The SIC receiver decodes the strongest interfering signal first, dismissing all other signals as noise. The analogue signal is then generated from the decoded signal and cancelled from the received signal. The remaining transmission is free of interference from the strongest interfering signal after this stage. After then, the SIC receiver decodes, regenerates, and eliminates the second most powerful interfering signal from the remaining signal, and so on, till the desired signal is recovered (Iswarya and Jayashree, 2021:1057-1059).

For each stage, Varanasi and Aazhang, (2018:509-519), used the SIC approach to detect only one UE. The first stage is to look for the signal with the highest receiving power, and the second stage is to look for the signal with the second highest receiving power. The stages are repeated until all the received signals have been processed. Then, from the entire received signal, each signal will be reformed, reconstructed, and isolated. In the end, this cancellation process benefits all UEs; UEs in the early stages suffer little interference due to the high received power, while UEs in the later stages suffer less interference due to the cancellation of high-power signals in the early stages. Since interference cancellation does not act on the physical layer but on the composite signal itself, it is no longer limited to control signals. However, there is one big drawback that prevents this technology from being used in D2D networks: high latency. The computing complexity and delay of SIC are proportional to the number of users, and this latency is particularly severe for users and devices that require real-time transmission of data.

Tao *et al.* (2013:452-458) proposed a resource allocation strategy based on a greedy algorithm blended with a sequential interference cancellation scheme. The SIC technique was employed at the receiver to cancel mutual interference between users. The proposed system has problems in terms of added computing overhead and energy usage, according to the authors. 5G networks are projected to be energy efficient, with minimum overhead at the BS. To implement the proposed technique, the constraints must be considered when building future D2D networks.

3.4.2 Parallel Interference Cancellation and Multi-Stage Interference Cancellation

Though parallel interference cancellation and successive interference cancellation are two different types of interference cancellation, the gap is becoming less with the advent of new approaches (Andrews, 2017). Sawahashi *et al.* (2016:433-449) used the PIC concept to identify all UEs at the same time, allowing the first initial report to be generated quickly. Severe interference can be identified and cancelled using this report, and detections on several UEs can be run in parallel to analyse interference further. PIC also can also be referred to as multi-stage interference cancellation because this method is conducted in parallel with several UEs. Soft interference cancellation in subsequent parallel detections is required because the initial detection only gives large scale interference cancellation. PIC contains a finite number of cancellation steps following the detecting phase, even though users are detected in parallel, which may reduce latency. A PIC receiver eliminates interference from signals in parallel units in consecutive phases. As interfering signals are eliminated from each received signal, related changes to a data correlation matrix's root matrix are represented as computationally efficient rank-one updates. Processing of signal and/or correlation information can be initiated, halted, or continued at any time, for example, because of signal or data quality. With root matrix updates, the PIC receiver can apply a variety of demodulation methods.

Wijk *et al.* (2015:1-6) developed a multi-stage SIC model for determining a flexible trade-off between the two methods. The UEs are divided into groups, each of which is probed individually before having their signals cancelled as a group from the composite received signal, and other groups are detected in parallel. The results obtained demonstrated that this approach works effectively for a limited number of UEs because detecting UEs in groups reduces the time spent on the detection stages. However, because the difficulty of parallel cancellation remains proportionate to the number of UEs, latency remains a severe concern for D2D networks, especially when each stage is now a group of devices near each other rather than a single UE.

### 3.4.3 Unconditional Interference Cancellation

Unconditional interference cancellation (UIC) is a simplified interference cancellation approach that assumes powerful interferers with received strengths larger than a particular threshold can be totally (unconditionally) eliminated (Lee, *et al.* 2013:78-86). UIC does not relate to a specific IC technique, but rather models the effect of IC approaches using a cancellation-power threshold-based estimate. This model is analytically tractable and provides a broad overview of IC performance.

### 3.4.4 Full Duplex-Based Interference Cancellation Technique

As part of 5G D2D communications, full duplex (FD) communication between D2D users is being investigated as a new technology. The capacity to transmit and receive data at the same time could open new research possibilities (Giatsoglou *et al.* 2016:1-6). Han *et al.* (2014:851-856) presented an FD-based interference cancellation method. The DUE can use its FD capability to transmit both the required signal and the interference from the BS in the presented manner. This technique uses fewer resources for interference control because it avoids the large overhead required for D2D and CU coordination. This technique is especially useful in situations where CSI is unknown.

Ali *et al.* (2014:45-61) used the FD approach to cancel self-interference. Lower D2D distances are found to provide better performance in uplink transmission conditions due to lower transmit powers. However, a comparison of half duplex and FD for downlink indicates that FD operation results in higher throughput.

### 3.4.5 Non-Orthogonal Multiple Access

One of the most promising radio access strategies in 5G networks and beyond is non-orthogonal multiple access (NOMA) (Kizilirmak, 2016). Compared to the existing de facto standard orthogonal multiple access (OMA) approach, orthogonal frequency division multiple access (OFDMA), NOMA offers several desirable potential benefits, including higher spectrum efficiency, low latency with excellent reliability, and huge interconnectivity. The basic concept of NOMA is to service several users simultaneously, using the same frequency, and at the same location. NOMA has the potential to be used in a variety of fifth generation (5G) communication scenarios, including D2D communications and the Internet of Things, according to recent research (IoT). NOMA is made up of two different techniques: Power-Domain NOMA and Code-Domain NOMA. Superposition Coding (SC) at the Base Station (BS) and sophisticated Successive Interference Cancellation at the User Equipment are used to achieve non-orthogonal resource allocation in Power-Domain NOMA (Kizilirmak, 2016:1-11).

Zhao *et al.* (2016:1-6) investigated how NOMA could be used in device-to-device communications to manage interference introduced by D2D network elements. In the proposed NOMA-based D2D framework, a novel algorithm based on many-to-one matching theory was presented to solve the sub-channel allocation problem. The proposed technique was shown to have an acceptable complexity when a stable matching between the D2D groups and subchannels was attained. When compared to the upper bound obtained by the exhaustive-search approach, numerical results demonstrated that the suggested algorithm achieved near-optimal performance. The proposed NOMA-based D2D framework was also shown to outperform the traditional OMA-based D2D framework.

Instead of successive interference cancellation, Gandotra *et al.* (2018:1006-1017) presented an enhanced NOMA-based system that leverages multiple interference cancellation (MIC) techniques (SIC). The results suggest that MIC outperforms SIC in terms of performance and complexity. The proposed MIC system demonstrates its usefulness by reducing the total circuit's power usage. The authors, on the other hand, did not discuss the network's reduced latency.

### 3.4.6 NOMA Implementation Challenges

There are still some problems to overcome to successfully implement NOMA. NOMA requires a lot of computational power to perform SIC algorithms, especially when there are a lot of users and a lot of data. Power allocation optimisation is still a difficult problem to solve, especially when UEs are moving quickly around the network. Cancellation issues, which are prevalent in fading channels, are particularly sensitive to SIC receivers. It can be used in conjunction with other variety of approaches such as multiple-input-multiple-output or coding schemes to improve reliability and, as a result, reduce decoding problems (Iswarya and Jayashree, 2021:1057-1059).

## 3.5 Interference Coordination

Interference coordination methods become increasingly relevant in network situation s with inband D2D communication. With centralised interference coordination (CIC), the BS supervises the interference management in the cell. In decentralised interference coordination (DIC) schemes, the D2D nodes participate in the coordination mechanism with limited supervision from the BS. Wen *et al.* (2012:542-547) developed a CIC technique that combines mode selection, power control, and resource allocation into one system. The proposed multi-pronged technique could be used to construct more intricate 5G D2D networks in the future. Yang *et al.* (2014:242-247) introduced another CIC technique for minimising intra-cell interference in the uplink mode that uses genetic algorithm based joint resource allocations and user matching schemes. Alvarez *et al.* (2016:505-510) presented a DIC architecture in which D2D nodes alter the allocation of physical resource blocks (PRBs) dynamically to reduce interference. The D2D nodes conduct periodic PRB sensing, and PRBs that experience interference are not chosen for transmissions. The proposed decentralized method aligns with the vision of future 5G networks with a significant D2D node density. Yin *et al.* (2015:2626-2631) proposed another DIC approach in which the BS manages D2D-to-CU interference and the D2D nodes control inter-D2D node interference. Game theory is used to formulate the inter D2D interference coordination problem. The proposed scheme improves performance at the BS by lowering signaling overhead.

### 3.5.1 Interference Alignment

Interference alignment (IA) is a cooperative interference management approach that uses several time slots, frequency blocks, or antennas to offer various signaling dimensions (Ayach *et al.* 2013:35-42). The TXs collaborate to generate their transmitted signals in multi - dimensional space, thus the interference seen at the RXs is limited to a small section of the total signaling space. IA maximises the amount of non-interfering symbols that can be sent over the interference channel at the same time by doing so. IA enables multiple interfering users to communicate over a limited number of signaling dimensions by condensing the space spanned by interference at each receiver into a small number of dimensions while trying to keep the desired signals separable from interference so that they can be projected into the null space of the interference and recovered free of interference.

Zhao *et al.* (2019:3347-3365) proposed a design that provides a D2D coordinated multi-point transmission system based on interference alignment technology that allows several D2D service pairs to use the same "frequency-time slot" resource block at the same time. The technique first determines an area for performing interference alignment using a cellular system's time-frequency synchronisation and satellite positioning approach, and then implements time-frequency synchronisation of the receiving and transmitting stations of several D2D service pairs. A BS and a receiving station estimate the channel state information between the base station and a transmitting terminal, as well as between the transmitting terminal and the receiving terminal of each D2D service pair, by measuring reference signals successively transmitted by transmitting terminals of the plurality of D2D service pairs. Through base station calculation, the terminals of a plurality of D2D service pairs obtain the power control factor, transmitting terminal pre-coding matrix, and receiving terminal interference suppression matrix, and transmit on an assigned frequency-time slot resource block using interference alignment technology. In-depth simulations by the researchers revealed that their design can greatly improve spectral efficiency (SE) for cell-edge users. Under a better signal-to-noise ratio, the method substantially increases the capacity compared with a traditional frequency and time slot orthogonal multiplex scheme. interference.

### 3.5.2 Enhanced Inter-Cell Interference Coordination

The access nodes of a typical heterogeneous network (HetNet) are a mixture of pico, femto, and macro. The high-power macro-cell network nodes are used to provide blanket coverage of urban, suburban, and rural areas, whilst the pico-cell and femto cells which have smaller RF coverage areas, are used to augment the macro network nodes by filling coverage gaps and increasing throughput. As a result, high-power macro-cell BS transmissions could severely interfere with downlink pico-cell transmissions to related UEs (Pederson *et al.* 2013:120-127).

Enhanced inter-cell interference coordination approaches, according to 3GPP (2011:1-208), are featured in Release 10 of the third-generation partnership project (3GPP) LTE advanced (LTE-A) and fall into three categories: time-domain techniques, frequency-domain techniques, and power control techniques.

(i) Time-domain techniqus- The basic idea underlying time-domain enhanced inter-cell interference coordination approaches is to schedule transmission to susceptible UEs in time-domain resources where other nodes' interference is minimised.

(ii) Frequency-domain techniques-The primary objective underlying frequency-domain eICIC approaches is to arrange control channels and physical signals in a restricted bandwidth to achieve completely orthogonal transmission between cells. The BS uses the UE's measurement reports to assess whether a UE has unacceptable amounts of interference in frequency-domain orthogonalization. The macro cell BS signals the pico cell BS across the backhaul when a victim

UE is identified. After that, the BSs plan their transmissions across the full spectrum.

(iii) Power control techniques- Primary objective is to increase the performance of target macro-cell UEs, this strategy relies primarily on lowering the radiated power of pico-cells, which are employed for throughput enhancement.

### 3.5.3 Coordinated Multipoint

The basic goal of Coordinated Multipoint (CoMP) is to allow geographically dispersed BSs to work together to serve UEs. In CoMP, multiple transmitter points provide coordinated transmission in the downlink, and multiple receiver points allow coordinated reception in the uplink. (Lopez-Perez *et al.* 2011:22-30). A TX/RX-point is made up of a group of co-located TX/RX antennas that cover the same sector. CoMP's TX/RX points might be in distinct places or co-located but provide coverage in various sectors. They could be from the same or different BSs. CoMP can be done in a variety of methods, and in both homogeneous and heterogeneous networks, the synchronisation can be done for both the downlink and the uplink. Downlink CoMP transmission is divided into four categories according to the 3GPP: dynamic point selection (DPS), joint transmission (JT), dynamic point blanking (DPB), and coordinated scheduling/beamforming (CS/CB) (Sun *et al.* 2013:56-66).

In DPS, the connection quality between the BSs and the UE is assessed per-subframe, and the BS with the best channel circumstances is dynamically selected. In other words, DPS takes advantage of channel variations opportunistically to increase selection variety. However, in compared to the already established frequency and spatial diversity gains, the attainable selection diversity gain may be modest. The objective of IDPB is to identify and mute the prominent interferers in the coordinating region in real time. The number of dominant interferers diminishes, resulting in a considerable increase in the UE's instantaneous SINR. Muting a BS may lessen interference in the UE, but it also causes the BS's performance to deteriorate. Before muting a BS, it's crucial to evaluate the beneficiaries' performance gains to the BS's performance loss. If the gains in performance outweigh the losses, the BS can be turned off; otherwise, it should be kept active.

By beamforming and scheduling over different BSs, the CS/CB CoMP transmission method aims to reduce interference. By utilising channel knowledge, a judicious beamforming weight selection may help to boost the SINR of a specific UE, allowing for directional support. It can improve transmission across a single UE while reducing interference to other UEs. Furthermore, by using a coordinated scheduling technique to pick the UE for transmission, interference at the UEs can be reduced even further.

As uplink CSI is available in the network without resource-intensive transmission and the UE terminals require almost no modification, uplink CoMP is easier to implement than downlink coordination. Uplink CoMP includes joint reception (JR) of the received signal at multiple BSs and/or CS decisions among UEs to manage interference levels and improve coverage (Marsch and Fettweis, 2011:1730-1742). JR's core concept is to combine many copies of a signal received by antennas at different locations to produce a final output signal. The operation in JR is like that in JT; however, in JR, the received data must be transported between the BSs, necessitating the need of a backhaul infrastructure. How much the received signals are pre-processed before being transmitted determines the quantity of information delivered between collaborating BSs. Even though quantised baseband samples give the most extensive information for joint processing, their processing places the most strain on the backhaul. CS tries to reduce interference by properly aligning UE scheduling and precoding decisions among BSs in the coordination region. In comparison to JR, CS only requires the sharing of CSI and resource allocation information among the BSs, reducing the burden on the backhaul network significantly.

Using the zero-forcing technique, CoMP can eliminate inter cell interference between D2D users and CU. A processing unit in a centralised CoMP processes information such as the Pre-coding Matrix Index (PMI) and the Rank Indicator (RI) to determine the adequacy of the D2D operation (Mumtaz *et al.* 2014:718-723). The developed method was tested in a multi-CUE and DUE pair environment, making it particularly useful for 5G D2D networks. The efficacy of the developed technique in a heterogeneous environment with dense node deployment could be studied in the future to gain insight into the effects of interference.

## 3.6 Other Interference Management Technigues in D2D-enabled Networks

### 3.6.1 Topological Interference Management

Topological interference management (TIM) works based on network topology information rather than instantaneous CSI (Yi and Gesbert, 2015:6107-6130). The interconnectivity pattern in the TIM approach is represented by an adjacency matrix that is shared by all devices in the network and is dependent on 1-bit interference data (weaker or stronger than the noise level), depending on the network's propagation physical processes (Jafar 2014:529-568). As a result, the matrix entries depict the interference relationship between the transmitters (columns) and the receivers (rows). The TIM problem has been shown to be identical to the index coding problem with linear techniques, where the received signals are linear combinations of the transmitted ones in terms of degrees of freedom (DoF). DoF is specified as the pre-log factor of the bandwidth when the signal-to-noise ratio (SNR) is high (Veeravalli and Camal 2018). This is predicated on the concept that the smallest rank of a matrix that matches the side information graph is equal to the optimal linear index code length. This graph is a directed graph with the vertex set representing the users and the edge set containing an edge *(i, j)* if and only if user *i* has packet *j* as side information. As a result, the TIM problem can be solved by solving an equivalent matrix completion problem over a bounded or real field based on a few specified elements of this array (Candès and Recht 2009:717).

Salam *et al.* (2019:7856-7871) developed a device-to-device (D2D) network clustering and topological interference management framework. The method divides the entire network into distinct groups, each serviced on a separate frequency, and TIM manages the interference within each group based solely on connectivity patterns rather than on CSI. To this end, TIM is modelled as a low-rank matrix completion (LRMC) problem that is addressed using a novel and simple semi-definite programming approach (SDP). The authors devised a clustering method that is suitable for the LRMC approach to solving TIM, based on the SDP relaxation of the maximum-*k*-cut algorithm, and extended to account for each cluster's capacity. This clustering problem is shown to be a constrained maximum-*k*-cut algorithm, for which they derived a relatively tight upper limit that aids in determining the performance guarantee of various clustering methods. The joint clustering-TIM can help enhance the system DoF in some instances, according to simulation studies, notably in big D2D networks. The proposed scheme also decreases the LRMC-based TIM approach's computational complexity.

A problem with using TIM for D2D is that it can't handle very strong interference that's even stronger than the desired signal and cache it: this scenario is common in D2D communications that take place in proximity (e.g., in crowded D2D networks like shopping malls, live shows, or sports arenas) and ignores signal strength differences due to propagation path loss, which is a significant physical phenomenon in D2D (Veeravalli and Camal 2018, Zhang and Tian 2018:1-9).

### 3.6.2 Mode Selection

The point at which any two devices near each other should start communicating with each other is very important after discovering each other. It does not always mean that it would be always optimal for the two nearby devices to switch to D2D mode. SINR and channel quality condition are the most used metrics to determine whether nearby devices should be allowed to engage in D2D communication. For network assisted D2D communications, the BS can choose the mode that can be used by a D2D pair. For this task, the BS makes use of channel quality information that is obtained from CUEs and DUEs to decide. For autonomous D2D systems, the DUEs themselves get to decide at what point to change from one mode to the other. Interference can affect the communication process if mode selection is not handled properly (Safdar *et al.* 2016:7967-7987).

### 3.6.3 Mode Selection Decision Based on Availability of Orthogonal Resources.

Huang *et al.* (2016:1-8) proposed a mode selection method that chooses the overlay method if devices are near each other and there is availability of orthogonal resources. The BS then gets to decide whether the nearby devices can participate in D2D communication. Ues can connect and communicate if the agreed conditions are met. Ues can be made to use dedicated or other resources otherwise they can remain in cellular mode. The strategy that Huang *et al.* (2016:1-8) devised also ropes in resource allocation and power control techniques to effectively minimise interference. Once the BS has decided a mode that has to be used, the BS then controls the transmit powers of the D2D pairs to meet a specified QoS requirement for all receivers in the area. The BS then allocates available RBs to CUEs and DUEs in a way that reduces interference. Reuse of the available resources can only be allowed if a D2D pair is not within an interference zone. Results from extensive simulation showed that the proposed scheme can deliver a higher sum rate when D2D pairs are closer to each other and are quite far from the BS. The scheme is somewhat restrictive in that D2D communication can only be allowed if there is availability of orthogonal resources. This might be good for effective interference management but might result in spectrum underutilisation.

### 3.6.4 Optimal Social-Community-Aware Resource Allocation

Li *et al.* (2015:293-296) proposed a technique that CUEs, and DUEs can utilise in the sharing of spectrum resources to minimise interference in the next generation mobile networks where D2D is used. The researchers called the scheme, Optimal Social-Community-Aware Resource Allocation, shortened to OSRA. The algorithm the authors proposed capitalises on the fact that in D2D, the devices are normally carried around by human beings who exhibit well defined social structures. The algorithm exploits this human behaviour in solving the resource allocation problem. The gathered social information about users is used to form social characteristics of the community and divides a network into communities.

Simulations were conducted in a bid to evaluate the performance of the proposed technique. The results obtained showed that the system performance was substantially enhanced in terms of D2D transmission time. Implementation of the scheme at highly populated shopping malls might give problems since the only regular visitors who frequent these places are the shop attendants of which their number is insignificant compared to the many irregular visitors who go to the shopping malls.

### 3.6.5 Social Interaction Resource Allocation

Wang *et al.* (2015:342-349) proposed a different version of social interaction that should be taken into consideration when allocating network resources. It is not always the case that devices that are geographically close to each other connect directly to form a D2D pair for the sake of sharing information. The authors argued that social properties should also be taken into consideration when figuring out whether any two nearby devices should participate in D2D communication. Not only should the decision be based on the distance between the devices and the link quality, but the social side of things should be considered.  A D2D communication link that is instituted between two colleagues is likely to last longer than a communication link established between strangers. Figure 3.1 shows the connection of DUEs based on the personality traits of the users. Dashed arrows on Figure 3.1 denote D2D links which are intermittent due to human mobility from a social network perspective. A longer communication link between DUEs ensures that more information is delivered. This means that the social traits and the geographical separation should be considered when allocating RB resources to DUEs.

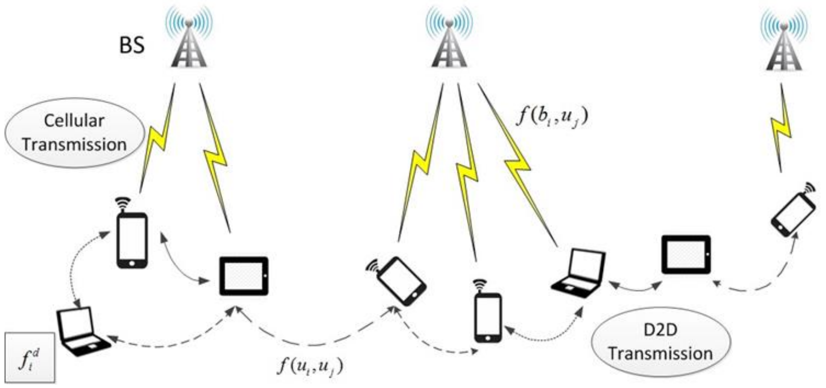


Figure 3.2: System architecture (Wang *et al.*, 2015, p.345)

A D2D communication link established between friends who are in proximity with each other will be a more reliable link compared to users who are not friends. This is so since the contact time is most likely to be longer in comparison to a D2D communication link between strangers. The researchers went on to use contact time to model the sociality traits of D2D communication links in a bid to maximise the RB resource utilisation. With numerical results, the researchers concluded that both the user's social traits and the geographical position affect the performance of a network and the resources allocation.  The researchers went on to propose a sociality-based network framework which they used to establish a mean contact time between any two users within a time slot. The established mean contact time of each DUE was then used to come up with resource allocation constraints. The authors used CPLEX Interactive Optimizer to solve the formulated linear optimisation. CPLEX Interactive Optimizer is an executable program that can read a problem interactively or from files in certain standard formats, solve the problem, and deliver the solution interactively or into text files. They were able to conclude that social-aware optimisation strategies outperform schemes that do not consider the sociality aspect.

### 3.6.6 Network Coding-based Interference Management Scheme in D2D Communications

A novel scheme by Shuang *et al.* (2017:48-54) that makes use of helper nodes and network coding to manage interference was proposed. The researchers described helper nodes as those nodes not participating in D2D communications. Any idle node within a coverage area can be chosen as a helper. The helper's link conditions are noted. Links can only be chosen as candidate links provided the packet error rate for that specific link is above a prescribed value. Helpers buffer packets from nodes participating in the transfer of packets. If it so happens that some packets do not get to the BS, the helper is requested to forward these packets that it would have encoded and in this way the BS is guaranteed to get all the packets from UEs including those that get lost along the way. The evaluation of the performance of the proposed scheme was achieved by taking note of the number of packets received against packets sent and the strength of the signal against distance travelled. Results showed that the proposed scheme extends the area of D2D communications and at the same time improves system throughput. The system however is designed to only deal with the interference from D2D communications to cellular users. Interference from cellular to D2D users is not considered. The concept of relaying messages in the network is very likely to increase end to end delay and an unnecessary overhead.

### 3.6.7 Beamforming Techniques

Adaptive beamforming strategies can be employed to reject interfering signals that come from a direction which is different from the anticipated direction. A beam finder can be used to control the phase and amplitude of a beam into a highly directional beam that points in the direction of the intended recipient with zero signal in the direction of interference. This beam forming concept can be adapted and utilised in D2D-enabled mobile networks to manage interference. Xu *et al*. (2014:1-84) developed joint power control and beamforming strategy in the mitigation of interference in a D2D-enabled cellular network. A BS with multiple antennas is placed at the centre of a cell with UEs having a single antenna each. The strategy is centralised with the BS controlling the transmit powers as well as the beamforming.

By use of extensive simulations, the researchers were able to show that the proposed joint power control strategy and beamforming strategy results in an improved system throughput with reduced interference. Beamforming requires a comprehensive precoder design which increases the computational overhead. The proposed design requires an accurate CSI feedback of all the DUEs and CUEs involved links. This can be problematic in large cellular networks that incorporate ProSe-enabled sensors. The multiple antenna system substantially increases the cost of hardware implementation.

## 3.7 Interference Management Techniques Using Machine Learning

Machine learning is being used in a variety of applications in mobile networks because of recent advances in the field. Machine learning (ML) is an artificial intelligence (AI) discipline that lets machines to learn from examples and data without having to be explicitly programmed (He and Ding, 2019). ML algorithms can uncover hidden patterns in large amounts of complicated data by employing a variety of training approaches, which are often divided into the following categories (Hashima *et al*, 2021:1-14):

(i) Supervised Learning- The ML model in this category seeks to learn a function that maps an input (x) to an output (y) based on a set of historical data used to train the model.

(ii) Unsupervised Learning- Unsupervised-learning models, in contrast to supervised-learning models, discover and explore hidden structures in raw data without the use of data labels.

(iii) Reinforcement-Learning- RL is a great tool for dealing with real-time stability issues where supervised and unsupervised learning methods are ineffective. RL's learning technique is built on observation and experimentation, just like humans.

### 3.7.1 Mode Selection Using Machine Learning

In dense networks, the resource allocation and mode selection processes in D2D communications exhibit high levels of complexity. For mode selection, machine learning approaches can provide more extensive flexibility in dealing with network dynamics. Ban and Lee (2019) developed a deep learning-based transmission technique for D2D networks. They designed a convolutional nueral network (CNN) that picks D2D connections for data transmission, with 90% of the selected sub-optimal data used to train the CNN-based algorithm and 10% used for validation. The neural network provided 85-95 percent accuracy, according to their numerical data. Zaky *et al.* (2020:14-29) developed an auto-encoder that pairs underlay D2D transmitters to reuse the spectrum of CUEs using a supervised learning approach, with the effective pairing in a dataset obtained using the traditional Hungarian algorithm that reduces the overall cost of selection through optimization algorithms formed as a bipartite graph. The basic concept is to apply a deep learning approach that can convert the cost matrices of matching different DUEs-CUEs to the corresponding optimal solutions described by the assignment matrix generated by the Hungarian algorithm in a less complex and time-consuming manner.

### 3.7.2 Power Control Using Machine Learning

Power control is an important interference management related topic that machine learning can handle in D2D. Fan *et al.* (2017:558-563) proposed two supervised and unsupervised learning-based power control methods. By comparing the two machine learning algorithms to traditional power control approaches in terms of computational complexity, throughput, and energy efficiency, the authors demonstrated the importance of machine learning in D2D communication. To achieve a near-optimal result, Kim *et al*. (2020:1-12) devised a technique in which D2D devices memorise the appropriate transmit power with position information. For D2D links, they employed the proposed approach to solve a distributed power allocation problem. They devised a distributed algorithm that trains the devices as a group yet allows each device to operate autonomously, resulting in near-optimal performance.

### 3.7.3 Resource Allocation Using Machine Learning

Li and Guo (2019:1-14) proposed neighbour-agent actor critic (NAAC), a distributed spectrum allocation method based on multi-agent deep reinforcement learning. NAAC leverages neighbor users' historical knowledge for centralised training but executes without it in a dispersed manner, which not only eliminates signal interference during execution but also makes use of user collaboration to improve system efficiency. The simulation results show that the proposed framework successfully reduces cellular link outage probability, improves D2D link sum rate, and has good convergence.

### 3.7.4 Problems Asscicated with Machine Learning

Fast speed learning is required for the implementation of machine-learning based algorithms, especially for fast-moving devices. It's also a good idea to learn and update models for high channel versatility. However, modelling in practice is not always possible, which creates a bottleneck in D2D communication networks. Proposing an optimal/sub-optimal ML-based approach with quick inference time in mmWave D2D is a difficult task, especially when considering multiple D2D use cases, because of the intrinsic complexity of priority-based algorithms. In worst-case scenarios, most machine learning approaches have theoretical performance guarantees. These strategies, on the other hand, do not perform better in reality since the environments are not always so hostile, and they do not fully exploit the settings' simplicity.

## 3.8 Conclusion

Researchers have developed interference control strategies in D2D-enabled cellular networks since the technology's inception in the early 2000s. Most techniques have been designed to manage interference in D2D-enabled mobile networks, where D2D would have been implemented largely to boost spectrum utilisation. Off-loading cellular data onto the D2D network increases spectrum use in these designs. There has been very little study committed to attempting to alleviate interference caused by the addition of sensors to D2D enabled cellular networks. The limited research available has not sufficiently addressed resource sharing in the uplink to efficiently deal with interference, nor has it considered the issue of device power consumption throughout the interference management process. Machine learning-based solutions have also been discussed. It has been noticed that for the implementation of machine-learning based algorithms, particularly for fast-moving devices, quick speed learning is essential. Learning and updating models for high channel flexibility is also important. In practice, however, modelling is not always achievable, resulting in a bottleneck in D2D communication networks. The problem that this research project aims to address will be described and discussed in the following chapter.

## 4.1 Introduction

The formulation of the problem is discussed in this chapter, as well as the system model that was used in the study. A description of the development of a collaborative area monitoring framework that focuses on the management of interference introduced to a cellular network by ProSe-enabled sensors and D2D communication is also presented.

## 4.2 The System Model and Assumptions

A system of sensors for the detection of a cocktail of explosives is placed at strategic points at a crowded area like a shopping mall to form a wireless sensor network as depicted in Figure 4.1

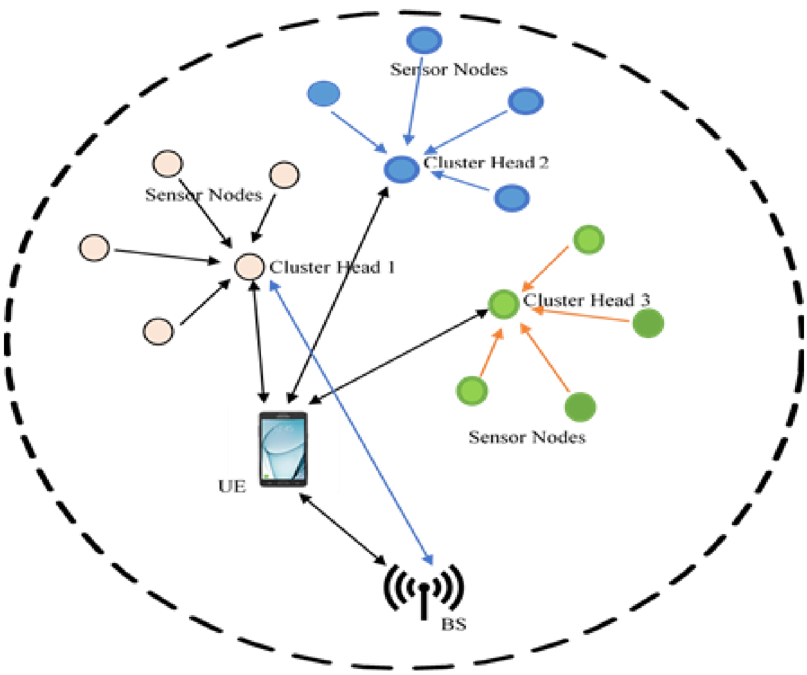


Figure 4.1: The system model

Sensors are deployed to monitor an area of interest (AOI) and are grouped into clusters. An AOI can be monitored independently by three clusters with each cluster having a cluster head (CH). CHs are pre-selected and are ProSe-enabled devices that can be smoothly integrated into a cellular network according to the 3GPP standardisation process (3GPP 2013:1-45). The cluster heads have special capabilities like synchronisation and D2D communication participation. For the proposed interference mitigation scheme, it is not all the CHs that get to communicate with the BS at the same time. The CH with the best channel conditions communicates with the BS. Limiting the number of CHs that communicates with BSs ensures that the BSs' traffic does not escalate to untenable levels.

## 4.3 Critical Communications and Public Safety

The main problem in incorporating sensors into cellular networks by allowing D2D communications between the sensors and UEs is the interference that arises. Two types of interference would result from such an action. There is interference from cellular communications to the CH-UE communications. This is shown in Figure 4.2.

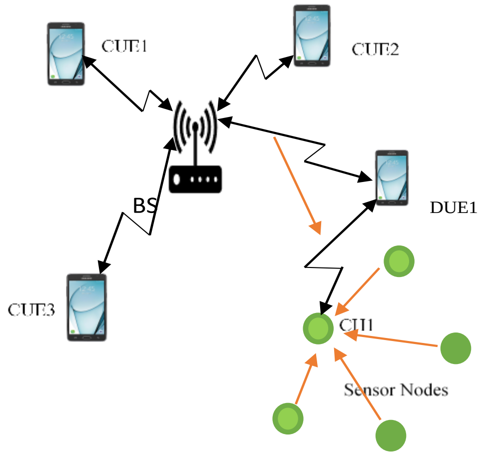


Figure 4.2: Interference from cellular to D2D

Then, there is interference from CH-UE communications to the cellular network as shown in Figure 4.3.

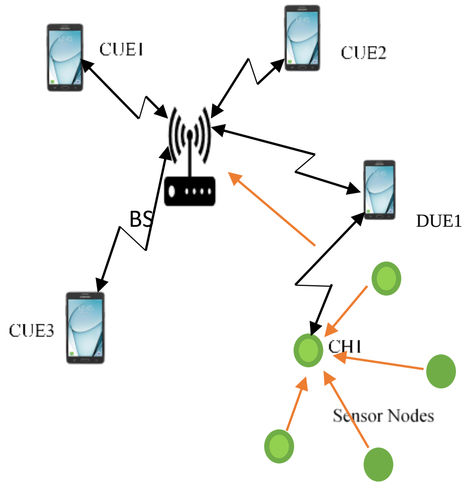


Figure 4.3: Interference from D2D communications to cellular communications

The sensors must be positioned at strategic points at shopping malls or public places. Sensed data is sent to cluster heads which then analyse the patterns that appear to be suspicious.

Chemicals are the main constituents of explosives (Kumar *et al*. 2016:1-7). An elaborate analysis of the chemical signatures makes it highly probable to predict the explosivity of materials. The proposed strategy sought to exploit more than one type of sensor to confirm the presence of explosives. A single type of sensor is just not good enough. Amongst the sensors should be those capable of detecting vapour traces of explosives. The principle used by these sensors is anchored on the fact that very minute quantities of detectable gaseous molecules of explosives will always be emitted due to the finite vapour pressure of the materials used in the manufacture of the explosives.

According to Patel (2010:1), sensors like nanowire arrays which are more sensitive than sniffer dogs, can detect extremely minute quantities of the most used explosives within seconds. Such sensors can be used in conjunction with smartphones to warn the smartphone users of impending danger at shopping malls. Mcdermott (2016:1), reported that a Rhode Island professor, Otto Gregory, developed a sensor capable of detecting the kind of explosives that were used in the Paris bombings of November 2015 that killed 130 people and injured several others.

## 4.4 Problem Formulation

In this section, the interference management problem that arises when ProSe-enabled sensors are included in a D2D-enabled cellular network is formulated and discussed. The proposed scheme was developed in such a way that it can work with 5G networks and beyond. Release 12, 3GPP (2013:1-45) and follow up work that has appeared in 3GPP (2014:1-50), 3GPP (2015:1-147), 3GPP (2017:1-38) and 3GPP (2018:1-130) have indicated that 5G has a frame structure duration of 10 ms with 10 subframes of 1 ms. 5G supports multiple orthogonal frequency division multiplexing (OFDM) numerologies as shown in Table 4.1.

Table 4.1: OFDM supported transmission numerologies (3GPP, 2018:9)

| $\mu$ | $\Delta f = 2^{\mu} \cdot 15[\text{kHz}]$ | Cyclic prefix |
|---|---|---|
| 0 | 15 | Normal |
| 1 | 30 | Normal |
| 2 | 60 | Normal, Extended |
| 3 | 120 | Normal |
| 4 | 240 | Normal |

The 5G frame structure supports a multi-antenna scheme which helps in beam management and uses OFDM. OFDM is a multiplexing technique that is used to transmit many parallel subcarriers as opposed to using a single wideband carrier. 3GPP has adopted OFDM as a multiplexing technique for 5G because of its ability to work with exceptional robustness to signal impairments on the air interface. As can be seen in Figure 4.4, the 5G resource block is almost identical to that of LTE with the difference in the physical dimension (i.e., number of OFDM symbols within a radio frame and the subcarrier spacing). For 5G, a radio resource covers:

(i) Duration of transmission.
(ii) Transmit power.
(iii) Antenna configuration.
(iv) Modulation/coding scheme.
(v) Type/number/configuration of antennas.
(vi) D2D capability.

.

According to Conceição *et al*. (2020:1-26), OFDM falls short of meeting some of the needs for future wireless communication, and more advancements in this area are possible. This has necessitated the development of new approaches to replace OFDM that were more spectrum and power efficient. Many OFDMA versions have been proposed in the context of 5G and future generations of wireless communications, including Filtered-OFDM (F-OFDM) and Time Interleaved Block Windowed Burst Orthogonal Frequency Division Multiplexing (TIBWB-OFDM) (Conceição *et al*. 2020:1-26)

Since OFDMA and the proposed OFDMA variants support use of multiple antennas, the interference mitigation scheme developed in this research work sought to exploit the use of space division multiple access (SDMA) technology to deal with the interference that sensors are likely to introduce to cellular networks. A BS that has enough information of the multiple antenna radio propagation channels, can easily establish non-interfering links to the different users. A beamforming technique can be employed to take advantage of the spatial channel dimensions by focussing the radiated signal into a narrow beam that is pointed to the intended recipient. In a SDMA/OFDMA environment, there is need for a sophisticated strategy for assigning radio resources to UEs and sensors for minimum interference. Using CSI available at the BS, SDMA can be used to place UEs and sensors in the same group.

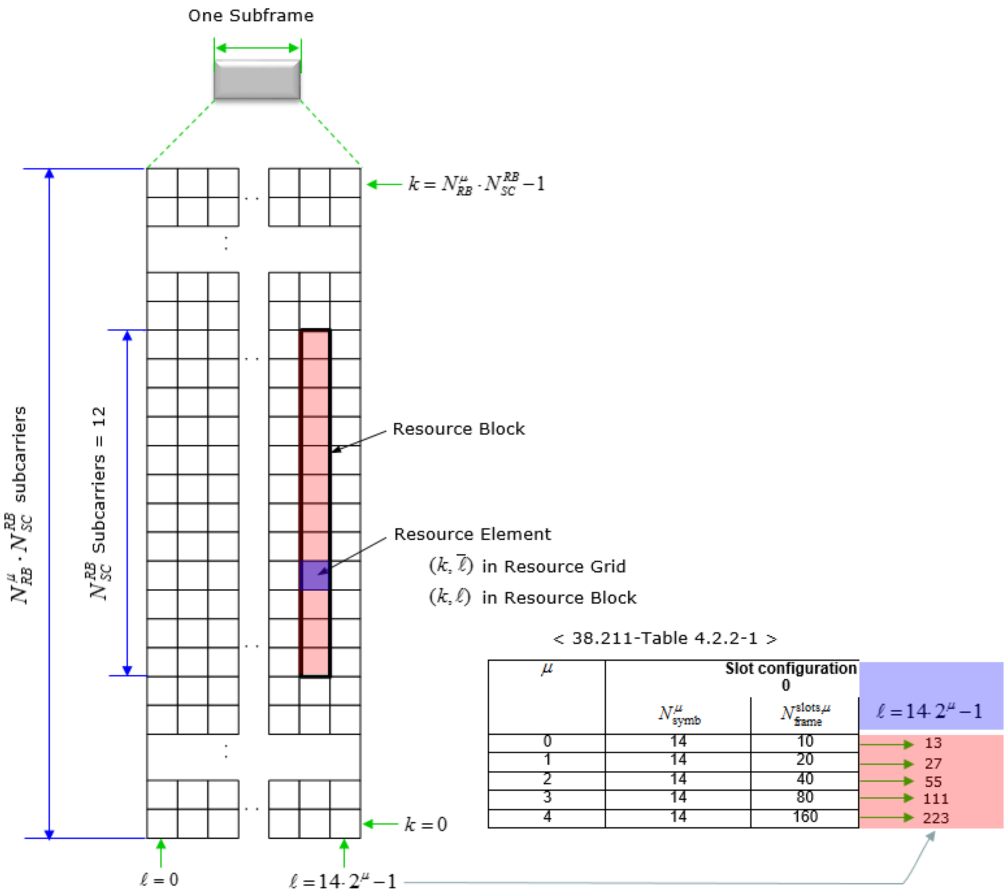


Figure 4.4: The 5G resource block (3GPP, 2018:9)

For the proposed scheme, it is assumed that there are *L* transmission links scheduled in a frame with *N* slots all allocated to *K* SDMA groups as shown in Figure 4.8.

| Slot 1 | Slot 2 | Slot 3 | Slot 4 | …… | Slot N |
|---|---|---|---|---|---|
| SDMA group 1 | | SDMA group 2 | | | SDMA group K |
| Link 1, 2 | | Link 3, 4, 5 | | | Link M |

Figure 4.5: A SDMA frame structure

The total number of slots in an SDMA group $k$ is denoted $n^k$. With SDMA, it is possible for frequency resources to be reused concurrently by UEs and sensors that are separated by use of multiple inputs and multiple output precoding techniques. A group of CUEs and DUEs sharing a subcarrier is termed a SDMA group. SDMA groups are made up of consecutive time slots. They are mutually orthogonal in time and frequency. Within the groups, multiple links can be slated simultaneously on identical time slots. The data rate of link *i,* in a SDMA group *k,* of local D2D communications (i.e., communications between CHs and UEs) is given as $c_i^k$.

For the proposed scheme, CHs and UEs can directly communicate with each other using the cellular downlink and uplink resources depending on their location with respect to the BS. According to Chaaban *et al.* (2015:1-7) and Wang *et al.* (2013:1148-1151), cellular uplink utilisation is far lower than the downlink utilisation hence it is more efficient for the nearby devices to use the uplink resources.

## 4.5 Notations and Assumptions

Table 4.2 summarizes the key mathematical symbols and notations used throughout this sub-section.

For a transmission scenario depicted in Figure 4.1, the network consists of one BS, 3 cluster heads and set of *m* cellular UEs, i.e., $U^M$ = {1, 2, .........., *M).* The BS transmits to the devices within the cell using a fixed power given by:

$$p_m^r > 0\,, \quad \forall r \tag{4.1}$$

For each DUE transmitter, $t \in U^{d_T}$, transmit power over the available resource blocks is determined by the vector:

$$P_t = \left[p_t^{(1)}, p_t^{(2)}, \dots \dots p_t^{(T)}\right] \tag{4.2}$$

where $p_t^{(r)} \geq 0$ represents the the transmit power level of a DUE transmitter *t* over RB *r*. This transmit power must be chosen from a limited set of power levels given by:

$$U^{PL} = \{pl1, pl2, \dots\dots\dots PL\} \tag{4.3}$$

Within the network, sensors can participate in D2D communications forming up to a maximum of *D* pairs of DUEs. The set of D2D pairs is denoted by:

$U^D$ = {1,2, ..........., D}. The set of the total devices in the network is $U$ and is given by = $U^D \cup U^M$.

The set CUEs and DUEs, i.e., $U^D$ *and* $U^M$, use the same set of orthogonal RBs. This set of the orthorgonal RBs is denoted by $U^r$ = {1, 2, ..........., $R$}. The $d$-th element of the sets $U^{d_R}$ and $U^{d_T}$ representing the receiver and transmitter of the DUE pair $d \in U^D$ respectively.

Table 4.2: A summary of mathematical symbols and notations

| Notation | Interpretation |
|---|---|
| $D$ | The total number of D2D pairs. |
| $U$ | The total number of CUE links. |
| $N$ | The total number of allocated slots. |
| $U^M$ | Set of CUEs |
| $U^D$ | Set of DUEs |
| $P_t$ | Total power |
| $U^r$ | A set of resource blocks |
| $K$ | The total number of SDMA groups and links |
| $U^{d_T}$ | A set of DUE transmitters |
| $U^{d_R}$ | A set of DUE receivers |
| $x_t^{(r,pl)}$, $X$ | Indicator of allocation, transmitter *t* using resource *{r, pl}* and the indicator vector X, respectively |
| $T$ | Total number of underelay transmitters (DUE and CUE transmitters) |
| $Ga$ | Represents the Gaussian noise power on a specific link |
| $p_{cue}$ | Represents the transmit power of CUE |
| $p_{D2D}$ | Represents the transmit power of D2D (CH to UE transmission) |
| $G_{D_t\, D_r}$ | Represents channel gain between D2D transmitter (*Dt)* and D2D receiver (*Dr)* |
| $\delta_i^k$ | Represents the scheduling factor for link *i* within *k* SDMA group. |
| $G_{cueBS}$ | Represents the channel gain between CUE and the BS |
| $G_{CUE.D_r}$ | Represents channel gain between CUE and D2D receiver |
| $G_{D_t.BS}$ | Represents channel gain between D2D transmitter and the BS |
| $SINR_{cue}^r$ | SINR for any arbitrary CUE in a cell over RB *r* |
| $P_{BS}\ G_{CUE}$ | Represents macro tier interference |
| $SINR_{D2D}^r$ | SINR for any arbitrary D2D in a cell over RB *r* |
| $R_{cue}$ | Represents the maximum achievable data rate over RB *r* for CUEs |
| $B$ | Represents the available bandwidth. |
| $R_{D2D}$ | Represents the maximum achievable data rate over RB *r* for DUEs. |
| $n^k$ | Number of slots distributed to a SDMA group k. |
| $pl$ | Power level |

| | |
|---|---|
| $\delta, n, p$ | Represent the sets of $\delta_i^k, n^k$ and $p_i$ respectively. |
| $I^r$ | Aggregated interference on RB *r* |
| $I_{max}^r$ | Threshold interference limit for the RB *r* |

For UEs and CHs using a resource block (RB) *r*, the SINR over RB *r* at the BS is given by:

$$SINR_{cue}^r = \frac{\delta_i^k G_{cueBS.}p_{cue}}{Ga + \sum p_{D2D} G_{D_t.BS}} \quad (4.4)$$

And the SINR over RB *r* at the D2D receiver is given by:

$$SINR_{D2D}^r = \frac{\delta_i^k G_{D_t\, D_r} p_{D2D}}{Ga + \sum p_{cue}\, G_{CUE.D_r}} \quad (4.5)$$

To address the issue of the unprecedented increase of mobile data traffic, the next generation mobile networks will incorporate heterogeneity into the networks and will be heavily densified. According to Hu *et al.* (2013:66-73), to cater for the heterogeneity nature of those networks, the adjusted SINR of the D2D receiver or a mobile user connected to a micro BS is given by:

$$SINR_{D2D-adjusted}^r = \frac{\delta_i^k G_{D_t\, D_r} p_{D2D}}{Ga + P_{BS}\, G_{CUE}\, [macro\ tier\ interference] + \sum p_{cue}\, G_{CUE.D_r} [underlay\ tier\ interference]} \quad (4.6)$$

The Shannon formula (Peterson and Davie, 1996:94-95) can then be used to calculate the maximum achievable data rate of any arbitrary CUE over RB *r* as:

$$R_{cue} = B.log_2(1 + SINR_{cue}^r) \quad (4.7)$$

The maximum achievable rate of an arbitrary D2D device over RB *r* is given by:

$$R_{D2D} = B.log_2\left(1 + SINR_{D2D-adjusted}^r\right) \quad (4.8)$$

The objective of the resource block and transmit power allocation problem is to find the RB and power level that optimises the possible sum data rate for underlay devices (e.g., DUEs and CUEs). A binary decision variable, $x_t^{(r,pl)}$ denotes the RB and power level allocation indicator for any underlay transmitter where:

$$x_t^{(r,pl)} = \begin{cases} 1, & \text{if transmitter } t \text{ is transmitting over RB } r \text{ with power level } pl \\ 0, & \text{otherwise} \end{cases}$$

If the decision variable, $x_t^{(r,pl)} = 1$, this means that $p_t^{(r)} = pl$

To determine the total interference, $I^r$ on RB *r* for this research project, (Son *et al.* 2011:1260-1272)'s concept of calculating the overall interference was adopted.

$$I^r = \sum_{t=1}^{T} \sum_{pl=1}^{PL} (x_t^{(r,pl)} g_{t,m_t^{(*)}}^{(r)} p_t^{(r)}) \text{ where } m_t^{(*)} = argmax\, g_{t,m}^{(r)}, \forall m \in U^M \quad (4.9)$$

For this research work, a sensor is only allowed to communicate with a nearby smartphone only when it does not violate a pre-defined interference threshold to the CUEs ie., $I^r < I_{max}^r$.

The overall interference in a cellular network where sensors and UEs can communicate directly with each other for the purposes of sharing sensed information can be minimised for maximum system throughput by utilising an efficient scheduling of available resources. It was proposed that the scheduling of available resources be treated as a constrained optimisation problem. The network optimisation problem can then be formulated as:

$$\max_{\delta,n,p} \sum_{t=1}^{T} \sum_{r=1}^{R} \sum_{pl=1}^{PL} \{x_t^{(r,pl)} \{\{R_{cue} + R_{D2D}\} \frac{n^k}{N}\}\} \quad (4.10)$$

Subject to:

$$\sum_{t=1}^{T} \sum_{pl=1}^{PL} (x_t^{(r,pl)} g_{t,m_t^{(*)}}^{(r)} p_t^{(r)}) < I_{max}^{(r)}, \forall r \in R \quad (4.11)$$

$$\sum_{r=1}^{R} \sum_{pl=1}^{PL} \{x_t^{(r,pl)}\} \leq 1, \forall t \in U^T \quad (4.12)$$

$$(x_t^{(r,pl)} \in \{0,1\}, \forall t \in U^T, \quad \forall r \in U^R, \quad \forall pl \in U^{PL} \quad (4.13)$$

The aggregated interference introduced to the CUEs by DUEs on each RB is limited by a pre-defined threshold with the restriction in Equation (4.11). The constraint in Equation (4.12) states that each underlay transmitter can only select one RB at a time and that each transmitter can only select one power level at each RB. The restriction in Equation (4.13) represents the binary indicator variable for transmission alignment selection.

The formulated problem is a combinatorial non-convex non-linear optimization problem whose complexity to solve using an exhaustive search is of $O((R(PL))^T)$. Using an example of 5 resource blocks (R= 5), 5 power levels (PL =5) and 2 DUEs plus 3 CUEs (T= 3+2=5), the search space contains 9 765 625 $O\left((5(5))^{(3+2)}\right)$. As can be observed in this example, the number of feasible solutions may be extremely large such that taking a Brute force approach is computationally impracticable. Obtaining an optimal solution within a scheduling interval of one millisecond is not possible especially for places like shopping malls with a high number of people, a high number of sensors and and high number of available power levels. 5G has a frame structure duration of 10 ms with 10 subframes of 1ms (Segura *et al.* 2021:1-11). Because of this, it was proposed that a sub-optimal greedy heuristic algorithm be used in the allocation of resources to CUEs and CHs for the devices to participate in D2D communication.

The objective of the formulated problem is to allocate power and RB resources intelligently to the CUEs and DUEs. This is achieved by maximising network throughput during instances when sensors would have requested for one-to-one communication with UEs in the vicinity in a bid to issue a warning of the presence of explosives. The maximum throughput is achieved having taken interference into consideration.

In this study, CHs and UEs can share resources in the UL as well as the DL. The UL is preferred for the greater part of the cell due to heavier traffic which is experienced on the DL. This is common with Internet data traffic which is characterised by heavier download traffic compared to the upload traffic (Wang *et al*. 2013:1148-1151). Using the UL for the greater part of the cell also has the advantage of having the BS effectively coordinating the interference between sensors, specifically CHs and Ues. In this study, CHs can communicate with nearby UEs using the same radio resources as those allocated to CUEs in the DL as well as UL if the imposed interference does not adversely affect the QoS requirements of the CUEs.

## 4.6 The Proposed Interference Management Scheme

This section outlines the proposed scheme. The proposed scheme is decomposed into two major components:

(i) Proposed scheduling strategy.

(ii) Power control strategy.

The major components were further decomposed into sub-components:

(i) D2D permission request.

(ii) D2D links resource allocation.

### 4.6.1 The Proposed Scheduling Strategy

For the proper allocation of radio resources, the BS must determine the channel quality between UEs and the BS, CHs and the BS and between the UEs and CHs. This is achieved by sending pilot signals on special subframes. In receiving the pilot signals, UEs and CHs calculate their path losses between the BS and themselves. The Ues and CHs in turn transmit pilot signals to the BS that it uses to determine the channel gains between the Ues, CHs and itself. The proposed scheduling strategy is made up of two parts: D2D permission request and D2D links resource allocation.

#### (a) D2D Permission Request

Cellular network service providers have SLAs they sign with their internal and external end users. Service providers are obliged to indemnify their customers in case of breaches of warranties. The proposed solution takes the issue of SLAs into consideration. The BS must decide whether to accept requests from CHs to initiate D2D communications. The decision is based on how the inclusion of D2D communications would affect the overall QoS of the network. Permission is granted or denied after going through the following steps:

(i) Estimate the resulting interference.

(ii) Will the interference be tolerable by the network?

Figure 4.5 shows the flow diagram of the proposed scheme.

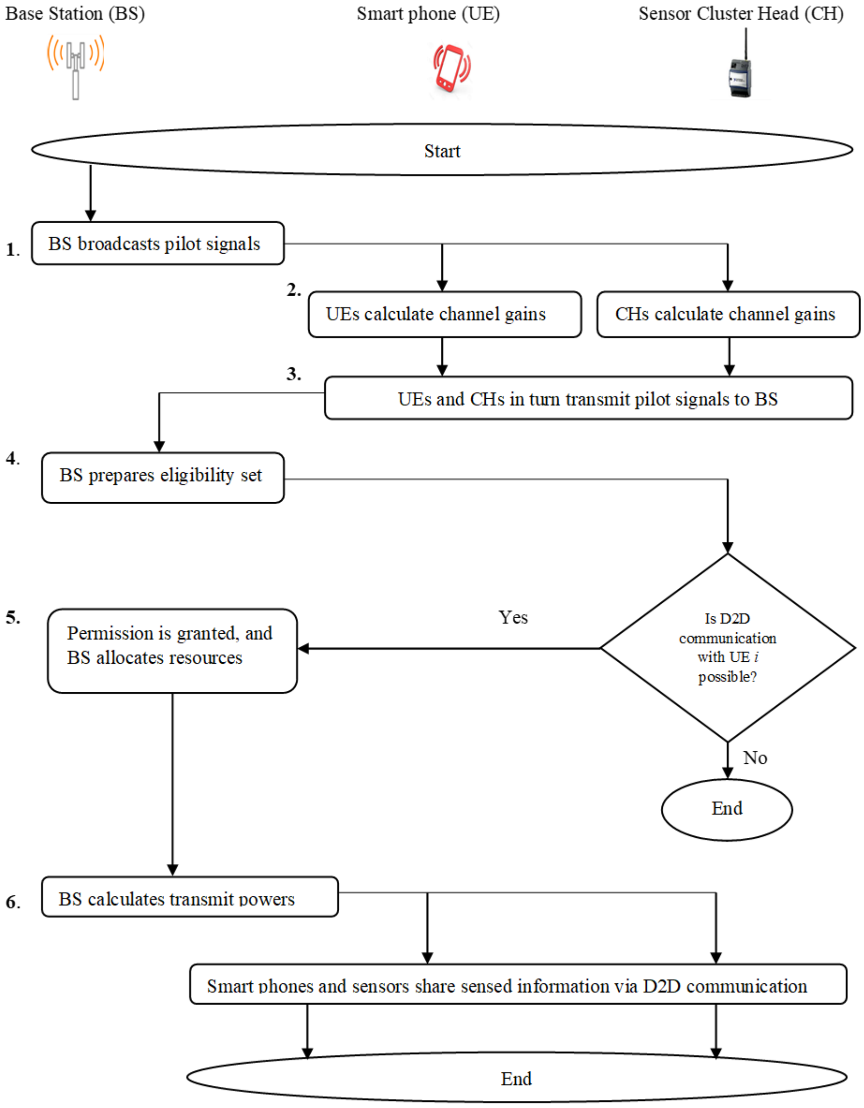


Figure 4.6: Flow diagram of the proposed scheme

The BS estimates the total interference plus noise using equation (4.14):

$$I_t = Ga + P_{BS}\, G_{CUE}\, [mti] + \sum p_{cue}\, G_{CUE.D_r} [uti] \qquad (4.14)$$

Where:

$I_t$ total interference.

Mti macro tier interference

uti underlay tier interference

If the resultant interference does not degrade the network's overall quality of service, resources can be allocated to CHs for sensor networking; otherwise, D2D connection will be rejected.

(b) D2D Links Resource Allocation

The main objective of the strategy is to implement frequency reuse that has a limited impact on the CUEs' data rate. This means that CUEs can take as many resources as possible so that a specified threshold on the CUEs' data is not compromised. This gives a constraint on the number of resources that can be availed to sensor networking devices at any given point in time. Once it has been ascertained that a CH can directly communicate with a UE, then the next step is the allocation of RBs for the D2D session. There might be one or more UEs that the CH might want to simultaneously get connected to, so that sensed information can be relayed to these UEs. The location information of UEs within a cell is known to the BS. This information is vital in the allocation of resources for D2D communication. The flowchart in Figure 4.6 outlines how RBs are allocated to the CH and UEs to participate in D2D communication.

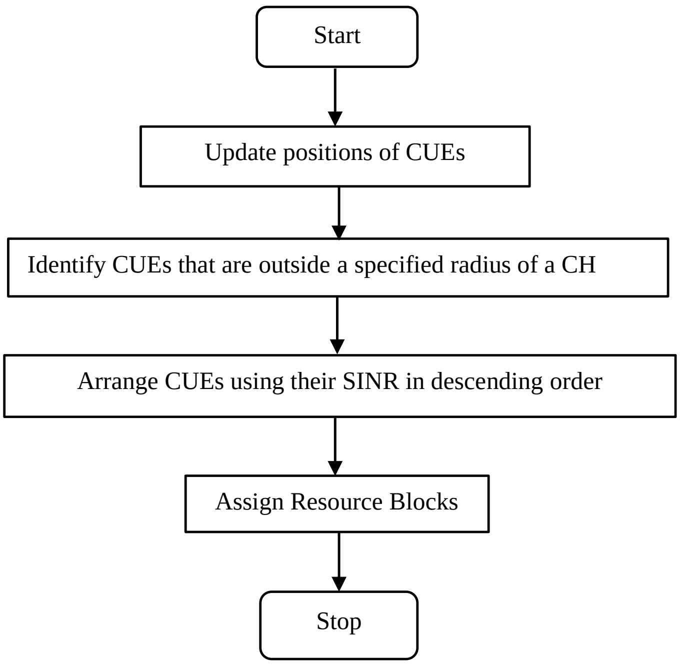


Figure 4.7: RBs allocation flow diagram

## 4.6.2 Power Control

Once the BS has decided which resources have to be allocated to which sensors and UEs, the next step is to decide at which power level those devices must transmit at as a way of managing the resulting interference. An elaborate power control mechanism can be used to effectively deal with cross-tier as well as co-tier interference in a cellular network where sensors are used. Song *et al*. (2015:135) pointed out that there are basically two methods that can be used to implement an effective power control mechanism:

(i) Self-organised. For static power control, a fixed power scheme utilises some parameter as a reference. The transmit powers of DUEs are then limited to a specific threshold. Devices connecting directly to each other make power changes without involving the BS following a predetermined SINR to meet a predefined QoS. The devices that are connected directly to base stations do not take part in the process. This method is simpler on implementation but lacks on efficiency.

(ii) Network managed. Both devices connect directly to each other and those only connected to BSs dynamically change their transmit powers following a SINR report. The process only stops when all the active users have fulfilled their SINR requirements. This method is complex but more efficient. Dynamic control uses a feedback mechanism that utilises the prevailing conditions in real time to control the DUEs transmit powers. The power control strategy is chiefly dependant on the distance between the D2D pairs. The power control for the proposed solution involves the BS as the central entity collecting global CSI. DUEs forward their normalised channel gains and target SINR figures to the BS. The BS then calculates the power that the DUEs must transmit at for minimum interference amongst the communicating devices.

Power control is a critical component in 3G in dealing with the near-far problem. The near-far problem emanates from devices connecting to a central BS in such a way that weaker transmissions from the cell boundaries become obliterated by stronger signals coming from devices that are very close to the BS. 4G does not experience intra-cell interference because resources utilised in the uplink are orthogonal. 4G still requires power control to take care of path loss and shadowing. Fast scheduling has however been introduced in 4G to replace power control techniques (Sesia *et al*. 2011:45).

Transmit powers of the devices to be involved in a D2D communication can be controlled according to the prevailing SINR. Power control has been rekindled in 5G as an intuitive strategy of reducing interference that is introduced by D2D communications. 5G, just like 3G and 4G, makes use of two types of power control:

(i) Open loop power control (OLPC).

(ii) Closed loop power control (CLPC).

These two power control strategies are shown in Figures 4.7 and 4.8.

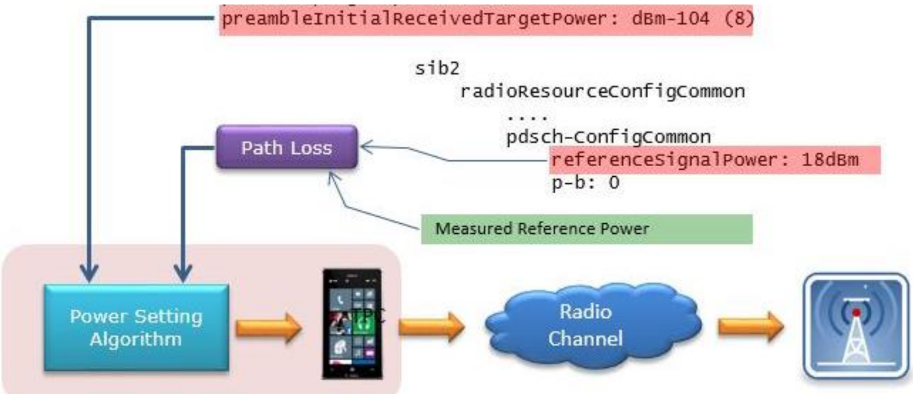


Figure 4. 8 Open loop power control (5G NR LTE 2020)

The open-loop method utilises a pre-determined level that is arrived at having considered path loss estimation between the transmitting and receiving stations. For current LTE systems, the UL transmissions within individual cells are orthogonal which means that interference management is not critical. For this reason, interference management schemes that must be utilised should be able to deal with intercell interference.

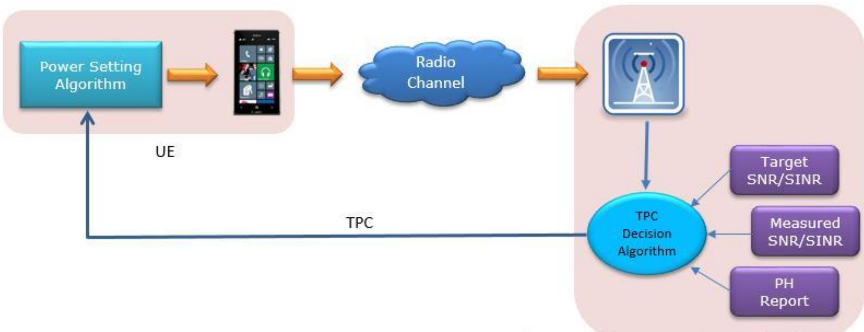


Figure 4.9 Closed loop power control ((5G NR LTE 2020)

To design a strategy for controlling the transmission power of sensors and UEs participating in D2D communications, it was important to undertake an evaluation of the current LTE power controls. The evaluation sought to determine whether the existing power control strategies are enough for sensor networking. The current LTE systems make use of a combination of closed-loop and open-loop control systems.

(a) CUE Power Control

According to Penda (2018:61), equation 4.15 can be used for the purposes of controlling CUE transmission power.

$$P_i = \{P - \rho G_i + \Delta_{TF} + \emptyset(\Delta_{TPC}) + 10log_{10}M, P^{max}\} \text{ [dBm]} \quad (4.15)$$

Where:

| | |
|---|---|
| $P - \rho G_i$ | Represents the operating point. |
| $\Delta_{TF} + \emptyset(\Delta_{TPC})$ | Represents the dynamic offset. |
| $10log_{10}M$ | Represents the bandwidth factor. |
| $M$ | Represents the number of RBs assigned to the user. |
| $P^{max}$ | The maximum power that can be transmitted by CUEs. |
| $\rho \in [0,1]$ | Represents the path loss compensation factor. |
| $G_i$ | Represents the path gain between the BS and user *i*. |
| $\rho G_i$ | Represents the path loss compensation factor. |
| $P$ | Represents the power level that is used to control the SINR target. |
| $\emptyset(\Delta_{TPC})$ | Represents the transmit power control (TPC) command that is given by the network. |

According to 3GPP (2007:1-125), the power level that is used to control the SINR target is obtained by making use of equation 4.16:

$$P = \rho(SINR_{cue}^{target} + P_{in}) + (1-\rho)(P^{max} - 10log_{10}M) \quad (4.16)$$

Where:

| | |
|---|---|
| $P_{in}$ | Represents the estimated noise and interference power for every resource block. |
| $SINR_{cue}^{target}$ | Represents the SINR target for CUEs. |
| $M$ | Represents the number of RBs assigned to the user. |

The path compensation factor, $\rho$, is used to compensate for attenuation between the receiver and the transmitter. Full compensation which is given to users operating at the cell edges maximises fairness for those users but has the disadvantage of increasing intercell interference. An acceptable trade-off between cell edge data rate and system capacity is normally found in the range of 0.7 to 0.8.

(b) Power Control for the CH- UE D2D Communication

If a cluster head is made to share an uplink resource with a CUE, then SINR over RB *r* at the BS is given by:

$$SINR_{cue}^{r} = \frac{\delta_i^k G_{cueBS}.p_{cue}}{Ga + p_{D2D}G_{D_t.BS}} \quad (4.17)$$

To meet predefined QoS requirements, this SINR over RB *r* should be equal or higher than a target SINR, $SINR_{cue}^{target}$ that is required at the BS for successful communication.

$$\frac{\delta_i^k G_{cueBS.} p_{cue}}{Ga + p_{D2D} G_{D_t.BS}} \geq SINR_{cue}^{target} \tag{4.18}$$

If the interference that a CH transmitter adds on RB *r* over subframe *s* is given by:

$$I_s^r = p_{D2D} G_{D_t.BS} \tag{4.19}$$

Then:

$$\delta_i^k G_{D_t D_r} p_{D2D} \leq \frac{\delta_i^k G_{cueBS.} p_{cue}}{SINR_{cue}^{target}} - Ga \tag{4.20}$$

$$p_{D2D} \leq \frac{\delta_i^k G_{cueBS.} p_{cue}}{SINR_{cue}^{target} \delta_i^k G_{D_t D_r}} - \frac{Ga}{\delta_i^k G_{D_t D_r}} \tag{4.21}$$

Lemma 1. For optimality, the transmit power for a CH transmitter should be:

$$p_{D2D} = \frac{\delta_i^k G_{cueBS.} p_{cue}}{SINR_{cue}^{target} \delta_i^k G_{D_t D_r}} - \frac{Ga}{\delta_i^k G_{D_t D_r}} \tag{4.22}$$

Proof: If $p_{D2D}$ is more than the specified value, then the predefined SINR would not be met and if it is less, then maximum achievable rate over the RB in question will not be attained.

### 4.6.3 The Proposed CH-UE Discovery Process

For a ProSe-enabled UE device to be alerted of the presence of explosives in the vicinity, it must periodically broadcast device information which includes its identity. This is a standard procedure in LTE and LTE-A. A CH does not need to be communicating with nearby Ues all the time. If this was the case, the cellular infrastructure would fail to cope with the ensuing traffic leading to network providers not accepting the co-option of WSN into their networks. Under the proposed strategy, a CH will seek to pair up with a nearby UE if sensors within the cluster have detected the presence of explosives in the AOI. The CH then listens for identification signals coming from nearby ProSe-enabled UEs. If there is a nearby UE, then the CH must request for RBs from the nearest BS so that the CH may participate in D2D communication with the UE. Focus is placed on controlling the interference from D2D communication with the discovered ProSe-enabled UE to the cellular network. If this interference is not controlled to acceptable levels, cellular network operators will be hesitant in the incorporation of some WSN add-on applications into their networks since it compromises QoS. The following signalling steps were proposed:

Step 1: A CH sends a request message to the BS to establish D2D links between the CH and the ProSe-enabled UE and between the UE and two other cluster heads.

Step 2: On receiving the request, the BS sends a discovery message to the UE, and schedules the UE to listen to discovery messages from the CH and to send acknowledgement signals to the BS.

Step 3: Upon receiving the discovery message from a BS, the UE sends discovery and acknowledgement signals to the CH using resources allocated by the BS.

Step 4: On receiving the discovery message, the UE measures SINR which it sends to the BS.

Step 5: The BS allows the CH and the UE to start a D2D communication and at the same time allocating resource blocks to the UE for it to further establish D2D communication with two other CHs serving the same AOI as the first CH that initiated the D2D communication.

Step 6: If the two other CHs upon interrogation by the UE, confirm that there indeed are some explosives in the vicinity, the UE notifies the BS.

Step 7: The BS then sends an emergency evacuation plan to the UE and sends a notification message to the responsible authorities like the police, premises owners etc.

Step 8: On receiving the emergency evacuation plan, the UE displays the evacuation plan, highlighting the escape route to be taken whilst vibrating in a unique way to alert the holder of the smartphone.

## 4.7 Attributes of the Proposed Interference Management Scheme

The proposed scheme ensures that the transmission power of the CHs is properly controlled so that there is very minimum interference that is introduced to cellular communications. The permitted CH transmit power should be such that the minimum SINR requirements are met. Interference is further managed by allocating resource blocks that are not in use by other nearby CUEs. The proposed solution does not force UEs to wake up too often to listen to requests from CHs to pair up and receive sensed information or for the UEs to be constantly transmitting discovery messages so that pairing with CHs might take place. If this can take place, the UEs' battery would be depleted too quickly. Smart phones have evolved to become gadgets that can generate a large amount of data. The problem is that battery technology is not keeping up with the pace of the smartphone technology and hence, any additional service that designers might want to add, is met with a high resentment by users fearing a rapid deterioration of their smartphone batteries.

## 4.8 Conclusion

The chapter has discussed the formulation of the problem and presented the system model that was employed in the study. A description of the development of a collaborative area monitoring framework focussing on the management of interference that ProSe-enabled sensors and D2D communication introduce to a cellular network has also been furnished. The solution to the combinatorial optimisation problem was decomposed into two fundamental components, which were then subdivided into sub-components, with each sub-component outlined and analysed separately. A description of the proposed CH-UE discovery procedure has been provided as well. The design specifics will be presented in the next chapter.

# CHAPTER FIVE: DESIGN OF THE PROPOSED SCHEME

## 5.1 Introduction

This chapter describes the design of the interference control method that would be utilised in cellular networks with ProSe-enabled sensors. The scheme's summary is covered in Section 5.2. The allocation of resources to D2D devices in both the uplink and downlink is discussed in Section 5.3 with the aim of determining the optimal alternative for the proposed system. The proposed method is broken down into two primary components in section 5.4: the proposed scheduling strategy and power control. D2D permission request and D2D links resource allocation are two of the key components that are further broken down into sub-components. The top-down technique was chosen so that the sub-components may be sufficiently detailed for later practical validation of the proposed solution. The operational procedure for CHs seeking to communicate with UEs is described in Section 5.5. Section 5.6 brings the chapter to a close.

## 5.2 Overview of the Proposed Interference Management Scheme

Deployed sensors monitor an AOI in real-time and report any suspicious targets to CHs that process received information and in turn collaborate with other CHs to confirm the existence of explosives in the vicinity. This should be done in a manner that does not introduce excessive interference to the primary network. The CHs must seek permission from cellular network BSs so that the sensed information can be passed to smartphones to alert the users of the presence of explosives. The detection is carried out by independent sensors of different types simultaneously to reduce false alarms as any false alarm can render the system ineffective and unusable. For a false alarm-free network, an AOI is divided into zones with each zone being scanned by appropriate types of sensors. Three clusters of the same type of sensors are installed in an AOI with each cluster having a CH. All three clusters operate independently, and they share their sensed information. If it so happens that two or three CHs have positive results about the presence of explosives in the AOI, a pre-selected CH initiates communication with CHs of other types of sensors. If the presence of explosives is confirmed by at least two pre-selected CHs of different types of sensors, the process of notifying smartphones is then then initiated. Figure 5.1 shows an AOI in which the proposed scheme is implementable with examples of different types of sensors shown. As can be observed in Figure 5.1, the design shows some convergence of wireless sensor networking and cellular networking. According to Swain *et al.* (2020:39-49), Saranya *et al*. (2013: 961-965) and Kumbhar *et al.* (2017:664-672), the convergence of cellular networks is still in the research stage and there has not been any large-scale implementation.

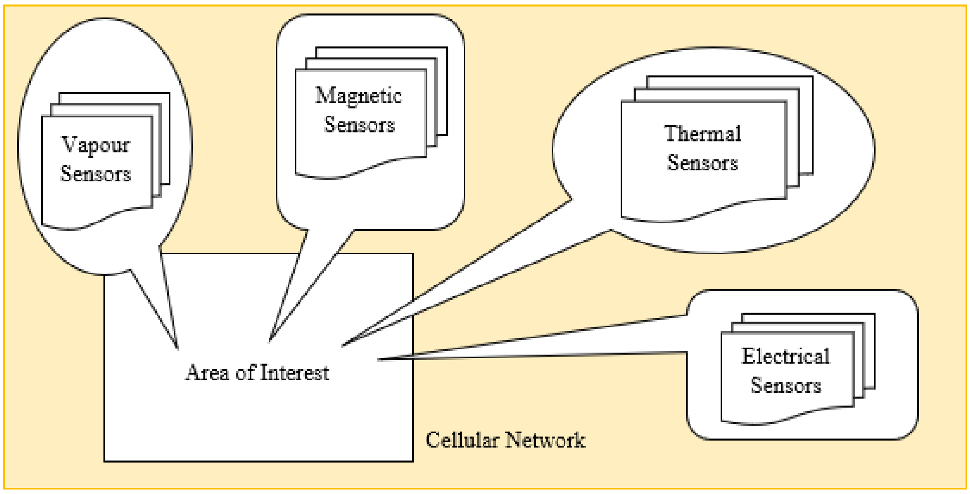


Figure 5.1: Convergence of WSN and cellular networks

## 5.3 Sharing of Resources

New Radio (NR) is the new air interface earmarked for 5G radio systems. The multiple access technology for 5G is orthogonal multiple access (OMA) for both UL and DL transmissions. With NR, the BS which is named the next generation Node B (gNB) performs scheduling procedures by assigning RBs to devices at every transmission time interval (TTI).

Devices that are near each other can be made to share resources or they can make use of dedicated resources in the UL or DL or in both. The allocation of resources to devices can be BS-assisted or BS-controlled. Under the BS-assisted resource sharing scheme, the devices involved in D2D communication allocate resources to themselves using pre-determined strategies. There is limited signalling between the devices and the BS. Under the BS-controlled resource allocation, resources are controlled solely by the BS. With this resource allocation method, management of the interference that arises as a result of D2D communication is easier to handle. The BS, as a central controller can terminate communication between sensors and smartphones the moment the QoS of a cellular network is threatened.

### 5.3.1 Sharing of Uplink Resources

Figure 5.2 shows the sharing of UL resources by CHs and UEs. In this type of sharing, CH transmitters introduce undesirable interference to the BS as they use the same resources Ues use to communicate with the BS. An acceptable SINR is a requirement if communication between sensors and cellular networks is to be allowed in the UL. Distance of sensors in relation to the BS is also crucial. Any communication in the UL by D2D devices that are very close to the BS severely degrades the SINR at the BS and should thus be avoided. However, Doppler *et al*. (2009:1-6) demonstrated that using the UL is less difficult in implementation and more effective in operation compared to using the DL for a fully loaded cellular network.

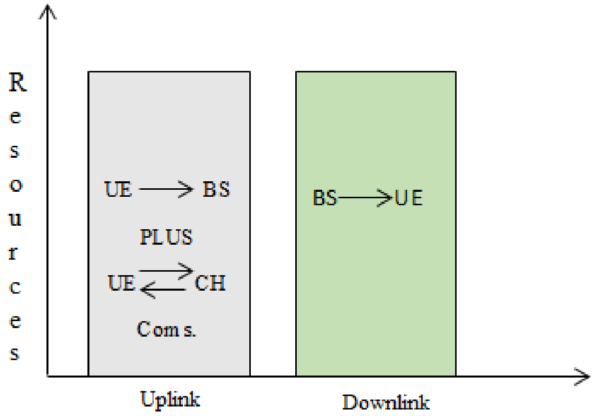


Figure 5.2: Uplink sharing

### 5.3.2 Sharing of Downlink Resources

Figure 5.3 shows the sharing of DL resources. In this case, the D2D communication that is undertaken by devices close to each other does not introduce interference to the BS.

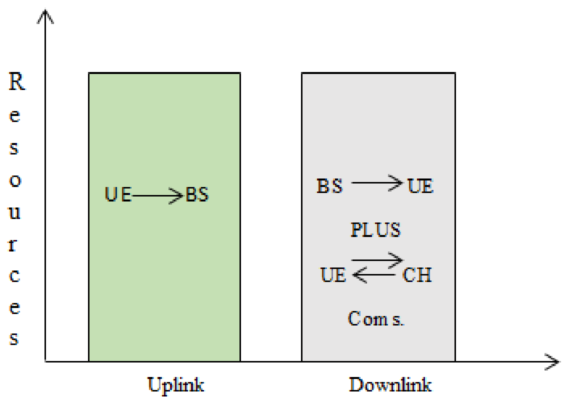


Figure 5.3: Downlink sharing

In fact, the BS is the one that can introduce interference to the devices engaged in D2D communication especially to those devices that are very close to the BS. This does not affect the overall QoS of the cellular network if the DL is used by sensors to communicate with Ues.

### 5.3.3 Sharing of Both the Uplink and Downlink Resources

Sharing of both UL and DL is shown in Figure 5.4. If the devices are to share both the UL and the DL, an increased bandwidth is enjoyed by the devices participating in the D2D communication. The three cases (uplink shared, downlink shared and the case where both the uplink and downlink are shared) result in high spectral efficiency.

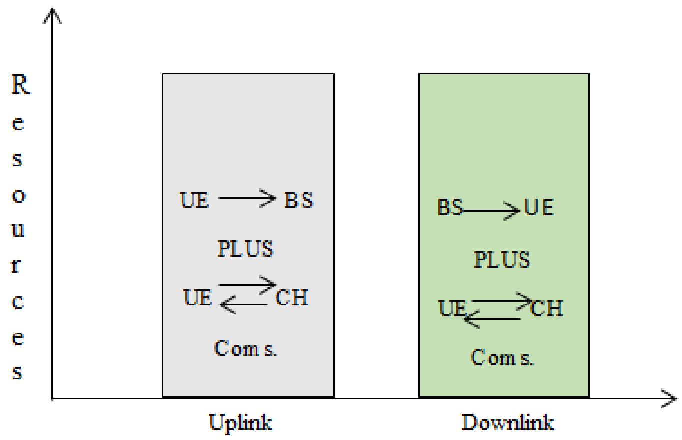


Figure 5.4: The sharing of RB resources in both the uplink and downlink

### 5.3.4 Reservation of Resources

The other techniques of resources allocation involve the reservation of resources for D2D communication either in the UL, DL or in both. Where separate resources are allocated to Ues and sensors, there is some very little interference between DUEs and CUEs. However, there is no spectral efficiency gain that is achieved in the network. With future networks aiming to deliver extremely high data rates in order to fulfil the many services that come with the Internet of Things, technologies that do not make use of resource sharing are fast being side-lined.

### 5.3.5 Sharing of Resources as Prescribed by 3GPP

According to the 3rd Generation Partnership Project (3GPP 2013:1-45) standardisation process, D2D communication for the purposes of ProSe, should make use of the UL resources. The LTE standards making body, introduced side link interface as shown in

Figure 5.5 and the resources for the 3GPP-proposed interface are supposed to be taken from the UL.


Figure 5.5: D2D communication utilising the 3GPP-introduced interface (Schlienz & Roessler, 2015:7)

LTE recommends that SC-FDMA modulation scheme be used for the PC5 interface. The channels for the side-link interface are defined by 3GPP (2015:1-267), 3GPP (2015:1-35), 3GPP (2015:1-43), 3GPP (2015:1-79) and 3GPP (2015:1-38). The channels are shown in Figure 5.6.

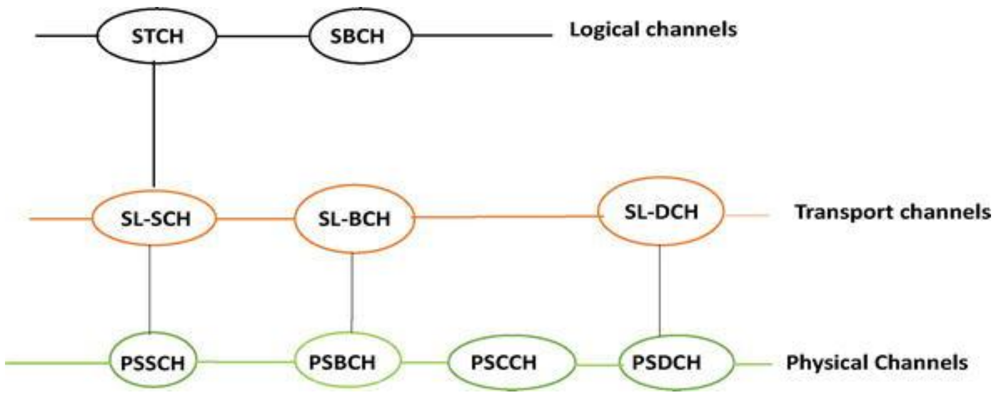


Figure 5.6: PC5 Sidelink channels for the air interface (Schlienz & Roessler, 2015, p8)

With D2D devices sharing resources with UEs in the UL, the D2D transmitters are likely to introduce interference to the BS especially from the devices very close to the BS. For network providers to allow D2D communication into their networks, a minimum SINR must be achieved so that the overall network QoS is not compromised. This results in devices that are very close to the BS not being allowed to engage in D2D communication since they would cause higher interference to the BS compared to the ones that are further from the BS.

For this research project, it was therefore proposed that UEs that are close to the BS use DL resources and the ones further from the BS make use of UL resources. CHs that utilise the DL do not introduce interference to the BS. In cellular communication, the UL and the DL are normally used asymmetrically since a higher number of users tend to upload less data than to download. This explains why it was proposed to allocate a wider spectrum in the UL compared to the DL. UL comes with easier implementation but become problematic when used very close to the BS (Doppler *et al*. 2009:1-6).

## 5.4 Decomposition of the Proposed Scheme

This section outlines the actual decomposition of the proposed solution. The proposed solution is decomposed into two major components:

(i) Proposed scheduling strategy.

(ii) Power control.

The major components are further decomposed into subcomponents:

(i) D2D permission request.

(ii) D2D links resource allocation.

### 5.4.1 The Proposed Scheduling Strategy

For the proper allocation of radio resources, the BS must determine, the channel quality between UEs and the BS, CHs, and the BS and between the UEs and CHs. This is achieved by sending pilot signals on special subframes. In receiving the pilot signals, Ues and CHs calculate their path losses between the BS and themselves. The Ues and CHs in turn transmit pilot signals to the BS that the BS uses to determine the channel gains between the UEs, CHs and itself. The proposed scheduling strategy is made up of two main parts: D2D permission request and then D2D link resources allocation.

#### (a) D2D Permission Request

Cellular network service providers maintain SLAs with their internal and external end users. Service providers are obliged to indemnify their customers in case of breaches of warranties. The proposed solution naturally takes the issue of SLAs into consideration. The BS must decide whether to accept requests from CHs to initiate D2D communications. This decision is based on how the inclusion of D2D communications would affect the overall QoS of the network. Permission is granted or denied after going through the following steps:

(i) Estimate the resulting interference.

(ii) Will the interference be tolerable by the network?

The BS, according to Hu *et al*, (2013:66-73), estimates the total interference plus noise using equation 5.1:

$$I_t = Ga + P_{BS}\, G_{CUE}\, [mti] + \sum p_{cue}\, G_{CUE.D_r} [uti] \quad (5.1)$$

Where:

| | |
|---|---|
| $I_t$ | total interference |
| mti | macro tier interference. |
| Uti | underlay tier interference. |

Resources can only be availed to CHs to perform sensor networking only if the overall interference that they add to the network does not result in an unacceptable network's overall quality of service.

(b) D2D Link Resources Allocation

The location information of all the UEs and CHs within a specific cell is known to the BS by use of the Global Positioning System (GPS). Since UEs are mobile, their locations must be updated regularly. The positions of CHs are fixed since the sensors are placed at strategic positions at crowded places like shopping malls. A cell is divided into two: the inner and outer sections. For this research project, it was proposed that, for the inner section, DL resources are shared, and UL resources are used in the outer section as depicted in Figure 5.7.

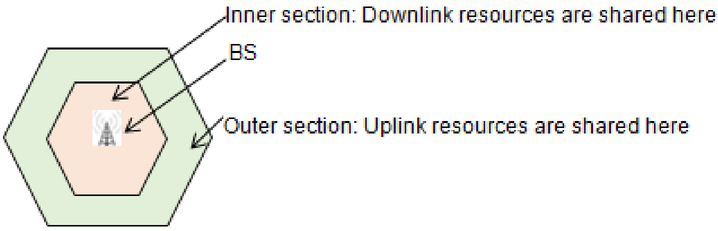


Figure 5.7: The resources that are shared in the uplink and downlink

The flow diagram in Figure 5.8 outlines the cell sectorisation procedure by the BS. For a sensor to be allowed to connect with a UE, it's transmit power is rigidly controlled so that the transmissions may not degrade other transmissions taking place in the vicinity.

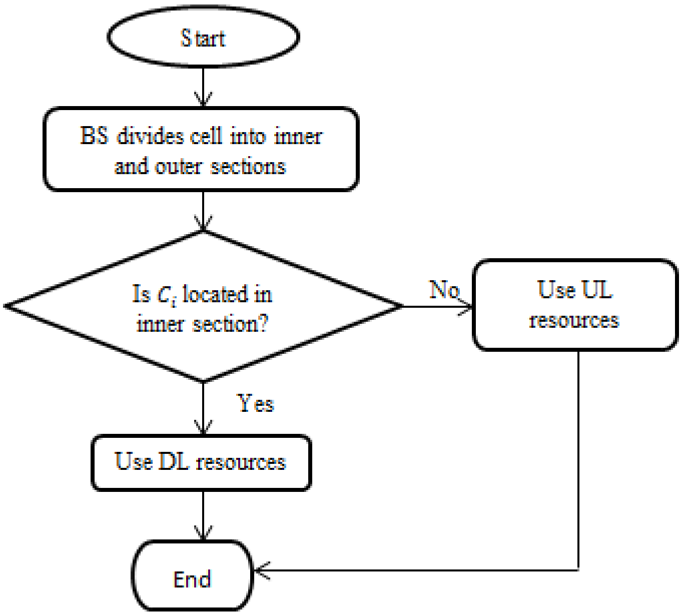

Figure 5.8 Cell sectorisation procedures

For sensors to participate in D2D communications there is need to limit the distance between the participating devices. Since a BS knows the positions of all UEs and CHs within the cell, distances between UEs and CHs can be calculated using the location information.

The BS then groups the UEs around CHs using the distance information for possible communication. Hakola *et al.* (2010:1-6), through extensive numerical analysis and simulations, concluded that, fixing a maximum distance between communicating ProSe devices can prevent the degradation of the QoS of D2D communications. Devices that are close to each other need not transmit at high power. Not exceeding a prescribed power level is good for CUEs and the BS. Devices that are transmitting at low power do not introduce significant interference especially to the BS.

Figure 5.9 shows grouped potential D2D devices in which pairing have not taken place. The BS sorts UEs and CHs according to their locations into inner and outer sections of the cell using Algorithm 1. The algorithm uses the distance information to group potential D2D devices.

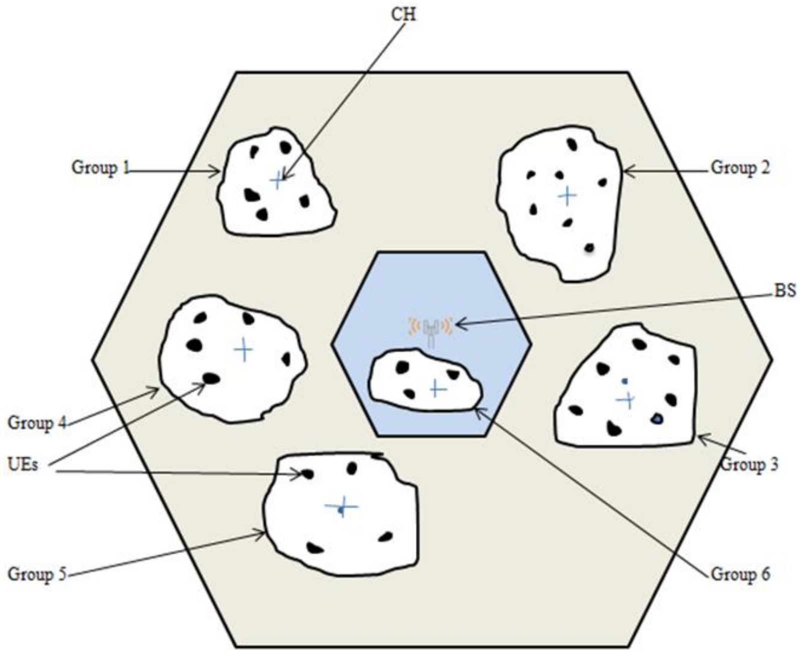


Figure 5.9: Potential D2D devices grouped

Algorithm 1: UEs grouping for possible UE-CH communication

1: Inputs: $U = \{U_i\}_{i=1,2,\ldots\ldots N}$; $C = \{C_i\}_{i=1,2,\ldots\ldots K}$; $D_{max}$;

2: Output: $G_1, G_2, G_3 \ldots\ldots\ldots$

3: Given that $i = 0$;

4: **for** inner **and** outer sections of the cell

5: **while** ($U \neq \emptyset$ **and** $C \neq \emptyset$) **do;**

5.1: Find $U_i$ in $U$ such that ($U_i - C_i\ distance$) $\leq D_{max}$; // distance between a sensor and smart phone should not go above a specified value.

5.2: Place ($U_i - C_i$) pair into group $G_{i+1}$.

5.3: **if** size($G_i$) = 0 **then**

5.4: **Break;**

6: **end while**

7: **end for**

The complexity of the algorithm for a system that has $K$ CUEs and $M$ DUEs is 0($MK$^2) which is not prohibitive even for a dense network.

Kang and Kim (2017:9924-9930) proposed an algorithm that uses distance between CUEs and DUEs to select UL resources allocated to CUEs that can be reused by devices that are close to each other. The authors argued and proved that shorter distances between CUEs and DUEs result in minimum interference resulting from direct communication between the devices even if resources are shared. However, the authors did not consider the effect of D2D communications on a BS that takes place very close to the BS using UL resources.

Rodziewicz *et al.* (2015:1-6) designed a strategy that utilises devices' locations to decide on which UL resources can be availed for reuse by devices close to each other. The authors failed to take into consideration the effect on a BS, of devices close to each other engaged in D2D communication whilst being very close to a BS using UL resources.

According to Duong and Shin (2013:776-779), the SINR at the BS is not affected by the location of CUEs since CUEs follow a rigid power control to avoid the near-far problem but is chiefly affected by the distance between DUEs communicating amongst themselves and the BS. The smaller the distance, the higher the impact on BS's SINR. It is therefore very important when designing schemes of allocating resources to devices close to each other engrossed in D2D communication to consider this distance.

(i) Downlink Resource Allocation

The algorithm that was developed for the downlink allocates resources to Ues and CHs based on the devices' spatial separability properties. 5G allows the use of multiple antennas at the BS. SDMA can then be used to increase system capacity. The SDMA technology enables the reuse of RB resources by utilising spatial properties of the different users with respect to the BS. Different users can be spatially separable in a subcarrier if, after sharing the subcarrier, the SINR requirements at their respective receivers are satisfied. The spatial separability of users depends on the angular and multipath characteristics of different users. The multiple antennas available at the BS are used in such a way that channel reuse is made possible for as long as the co-channel users are spatially separable.

The developed scheme sought to take advantage of the fact that the SDMA technology with its adaptive smart antennas, can be made to reuse downlink resources by making use of the adaptive antennas at the BS. If sensors that are very close to the

BS have registered their intention to communicate with nearby smart phones, downlink resources can be made available by having some CUEs release resources and availing them to the sensors. The algorithm that was developed works by first identifying CUEs whose spatial signatures are highly correlated. Once CUEs are identified, they are made to reuse specific resources and to release their current resources for use by sensors. Having CUEs and sensors using separate resources eliminates any form of interference that may emanate from D2D communication. However, the system must be capable of dealing with the co-channel interference coming from the CUE users. Algorithm 2 outlines how resources are allocated in the downlink for this research project.

Algorithm 2: Allocation of resources in the downlink

1: Inputs: $U = \{U_i\}_{i=1,2,\ldots\ldots N}$; $C = \{C_i\}_{i=1,2,\ldots\ldots K}$;

2: Output: $R = \{R_i\}_{i=1,2,\ldots\ldots P}$; //set of CHs paired with CUE $i$.

3: Randomly allocate orthogonal resources to CUEs

4: **for** each CH request for resources **do**

5: **if** there are two spatially separable CUEs

5.1: Make the two share the same resources and release the other set of resources for use by the CH

5.2: **else** deny the request

6: **end if**

7: **end for**

(ii) Uplink Resource Allocation

For the sensors to be allowed to share CUE resources in the UL, the sensors should not cause severe interference to CUEs. Network operators would never allow a scenario that results in a compromised QoS of their networks. The algorithm developed for the UL ensures that the QoS of the network is not degraded by only allowing the sensors to share uplink resources if a specified interference level is not violated as shown in algorithm 3. The pairing process is premised on the strength of D2D links. Since the D2D communication is allowed for CHs and smart phones that are in proximity, it is assumed that D2D links are always very strong, and the pairing process should be based on interference thresholds. Pairing is permitted if interference levels satisfy specified thresholds for both CHs and the smartphones. If the number of devices wishing to participate in D2D engagement with nearby devices is too large, the algorithm is designed such that some devices can be made to share resources with CUEs in the downlink.

Algorithm 3: Allocation of Resources in the Uplink

Inputs: $U$ = $\{U_i\}_{i=1,2,\ldots\ldots N}$; // a set of CUEs already allocated with resources
$C$ = $\{C_i\}_{i=1,2,\ldots\ldots K}$; // a set of CHs requesting for resources
$Q$ = $\{CUEs_i\}_{i=1,2,\ldots\ldots R}$; // CUEs already utilising the downlink that can still accommodate some sensors.
Output: $R$ = $\{R_i\}_{i=1,2,\ldots\ldots P}$; //set of CHs paired with CUE *i*.
**for** all $U_i \in U$ and $C_i \in$ C
    calculate SINR levels;
    **if** $SINR_{D2D}^{r} \leq SINR_{D2D}^{target}$ **and** $SINR_{cue}^{r} \leq SINR_{cue}^{target}$ **then**
        Pair up $U_i$ link with $C_i$ link: $R_i$ = $R_i$ + {k};
    **end if**
**end for**
    **if** D2D link *k* is not paired with any CUE in the uplink
        Pair up D2D link *k* and $Q_i$ in Q: $R_1$ = $R_1$ + {k};
    **end if**
**end for**

### 5.4.2 Power Control for the CH- UE Direct Communication

The maximum transmit power of devices that are engaged in direct communication with each other should be rigidly controlled not only in a bid to manage interference but also to guarantee successful D2D communication. The objective of the developed power control is to ensure that a network prescribed SINR target for CUEs, $SINR_{cue}^{target}$, and a network prescribed SINR target for DUEs, $SINR_{due}^{target}$ are met.

Where a CH is to share a UL resource with a CUE, then SINR over RB *r* at the BS is given by:

$$SINR_{cue}^{r} = \frac{\delta_i^k G_{cueBS}.p_{cue}}{Ga + p_{D2D} G_{D_t.BS}} \tag{5.2}$$

And for the downlink, the SINR over RB *r* at the CUE is given by:

$$SINR_{cue}^{r} = \frac{\delta_i^k G_{cueD2D}.p_{D2D}}{Ga + p_{D2D} G_{D_t.BS}} \qquad (5.3)$$

To meet predefined QoS requirements, this SINR over RB *r* should be equal or higher than a target SINR, $SINR_{cue}^{target}$ that is required at the BS for successful communication.

$$\frac{\delta_i^k G_{cueBS}.p_{cue}}{Ga + p_{D2D} G_{D_t.BS}} \geq SINR_{cue}^{target} \qquad (5.4)$$

If the interference that a CH transmitter adds on RB *r* over subframe *s* is given by:

$$I_s^r = p_{D2D} G_{D_t.BS} \qquad (5.5)$$

Then:

$$\delta_i^k G_{D_t D_r} p_{D2D} \leq \frac{\delta_i^k G_{cueBS}.p_{cue}}{SINR_{cue}^{target}} - Ga \qquad (5.6)$$

$$p_{D2D} \leq \frac{\delta_i^k G_{cueBS}.p_{cue}}{SINR_{cue}^{target} \delta_i^k G_{D_t D_r}} - \frac{Ga}{\delta_i^k G_{D_t D_r}} \qquad (5.7)$$

Algorithm 4 is used to control transmit powers of devices involved in D2D communication.

Algorithm 4: Power Control Algorithm

1: Input: Matrix P // Paired CH- UE devices

2: Output: A set of transmit powers, $p = (pl1, pl2, \ldots, PL)$;

3: **for** all pairs,

3.1 calculate transmit powers for the D2D transmitters using Equation (4.21);

3.2 allocate powers accordingly

4: **end for**

5: $P = (p1, p2, \ldots, pL)$

5.5 The Operational Procedure of CHs Seeking to Communicate with UEs

For a ProSe-enabled UE device to be alerted of the presence of explosives in an AOI, it must periodically broadcast device information which includes its identity. This is a standard procedure in LTE and LTE-A. A CH does not need to be communicating with nearby UEs all the time. If this were the case, the cellular infrastructure would fail to cope with the ensuing traffic leading to network providers not accepting the co-option of WSN into their networks. Under the proposed strategy, a CH will seek to pair up with a nearby UE if sensors within the cluster have detected the presence of explosives in the AOI. The CH then listens for identification signals coming from nearby ProSe-enabled Ues. If there is a nearby UE, then the CH must request for RBs from the nearest BS so that the CH may participate in D2D communication with the UE. Focus is placed on controlling the interference emanating from the D2D communication with the discovered ProSe-enabled UE to the cellular network. Failing to control this interference to an acceptable level would lead cellular network operators to reject the integration of WSN into their networks as the integration leads to a compromised QoS. Figure 5.11 outlines the operational procedure that CHs use to connect wirelessly to nearby Ues to warn them of presence of explosives.

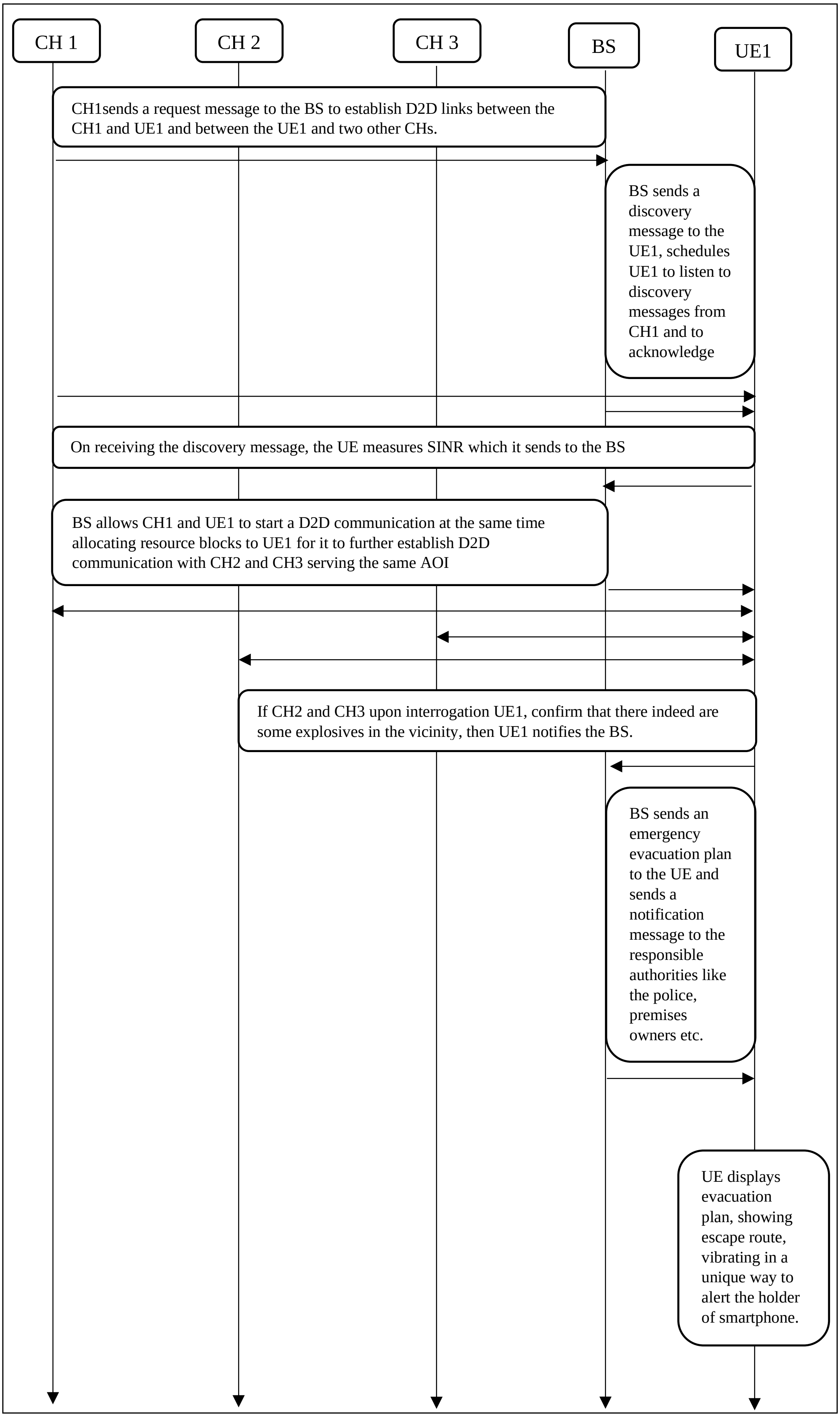


Figure 5.10: The operational procedure for connection

## 5.6 Conclusion

The details of the proposed interference management scheme's design have been presented in this chapter. The concept has been split down into two primary components: the proposed scheduling strategy and power control, which have been further subdivided into D2D permission request and D2D links resource allocation. Four algorithms have been presented: an algorithm for grouping UEs for probable UE-CH communication, algorithms for resource allocation in the uplink and downlink, and finally a power control technique. The algorithms' pseudocodes have been presented. The next chapter presents the details of the system level simulator that was developed for the evaluation of the proposed design.

# CHAPTER SIX: SYSTEM LEVEL SIMULATOR DEVELOPMENT

## 6.1 Introduction

A state-of-the-art simulator was developed as part of this research to enable studies in converged mobile cellular networks (MCNs) and wireless sensor networks (WSNs) for the implementation and investigation of novel techniques/ algorithms developed to reduce interference that occurs when sensors communicate with smartphones in a D2D manner. The developed model encompasses the connections between a BS, UEs, and sensors, allowing for realistic analysis of network-related issues such as interference mitigation and network planning optimisation in urban settings such as shopping malls. The system level simulator follows the 3GPP standard for 5G network features and characteristics. Path-loss models, BS/UE standards, MIMO/ smart antenna designs, appropriate channel models such as the WINNER II model, and defined channel bandwidths are all features of the 5G network standard. The system-level simulator was developed by first abstracting the link-level features (i.e., the physical layer) to a sufficient level of detail and accuracy, and then mapping the link-level to the system-level. A 5G heterogeneous network was employed in the simulation. For macrocells and femtocells, OFDMA transmission technology was used. Subcarriers are used to divide the frequency spectrum. A single RB is made up of twelve consecutive subcarriers and is the smallest unit that may be assigned to a single UE or sensor. The channel bandwidth in this study is 20 MHz, and there are 100 RBs in the channel.

## 6.2 Simulation of Mobile Communication Systems

There are basically three types of simulators that can be used to prototype and evaluate mobile communication systems:

(i) Link Level (LL) simulators.
(ii) System Level (SL) simulators.
(iii) Network Level (NL) simulators.

### 6.2.1 Link Level Simulators

Link level simulation focuses on the physical (PHY) layer characteristics with an emphasis on a single link between a user and a BS. The analysis can be for the DL or UL. With LL simulators, all PHY blocks are implemented in detail with little abstraction. A good example of an LL simulator is the LTE Link Level Simulator v1.3r620 (Vienna University of Technology 2010:1-12). This simulation package is made freely available under terms of a non-commercial academic licence. The simulator uses MATLAB and can be used to emulate transmission features between a BS and UE, specifically for the PHY layer. It was developed by the Vienna University of Technology. The LL simulator was introduced way back in 2009 when there was only one scheduling algorithm that was available at the time. This means that if the LTE Link Level Simulator v1.3r620 simulation package were to be used for the evaluation of the algorithms developed for this research project, major modifications would have been necessary.

### 6.2.2 System Level Simulators

SL simulators are used to analyse complex systems comprising of several BSs and UEs. They are used to facilitate a thorough assessment of spectral efficiency, data throughputs and network coverage incorporating interference affecting BSs and UEs. LTE-A Downlink System Level Simulator and LTE-A Uplink System Level Simulator are good examples of system level simulators which can be used for LTE-A and 5G systems (Rupp *et al*. 2016:6). These simulators are free for academic and non-commercial use and have the following features:

(i) Channel prediction and interpolation for time-variant channels can be undertaken.
(ii) Intercell interference can be quantified through simulations.
(iii) 3D modelling as specified in TR36.8973 is supported (3GPP 2015:1-43).
(iv) Different schedulers for multi-user MIMO systems can be implemented.
(v) Channel estimation for MIMO systems can be implemented.

### 6.2.3 Network Level Simulators

NL simulators facilitate the analysis of specific protocols and how the lower layers interact with the upper layers. BSs are treated as network entities having the capability of exchanging messages amongst themselves. NL simulators are also used to model and analyse backhaul issues in cellular networks. Figure 6.1 shows the position of NL simulators in relation to the other two types of simulation packages. NL ns-3 LTE module is a good example of a NL simulator (Piro *et al*. 2011:415-422). NL ns-3 LTE module is an open source simulation package that supports the evaluation of the following:

(i) End to end Quality of Experience (QoE).

(ii) Radio level performance.

It also enables algorithm prototyping of:

(i) Radio Resource Management (RRM).

(ii) The management of intercell interference.

(iii) Self-Organised Networks (SONs).

Strategies for interference management like coordinated multi-point (CoMP) and power control are not yet present in ns 3. CoMP is supported by the latest versions of Vienna SL Simulator. Both Vienna SL and ns-3 do support round robin (RR), channel quality indicator (CQI) and Proportional Fair (PF) schedulers. Vienna also provides max-min throughput scheduling. More sophisticated schedulers are provided by ns 3.

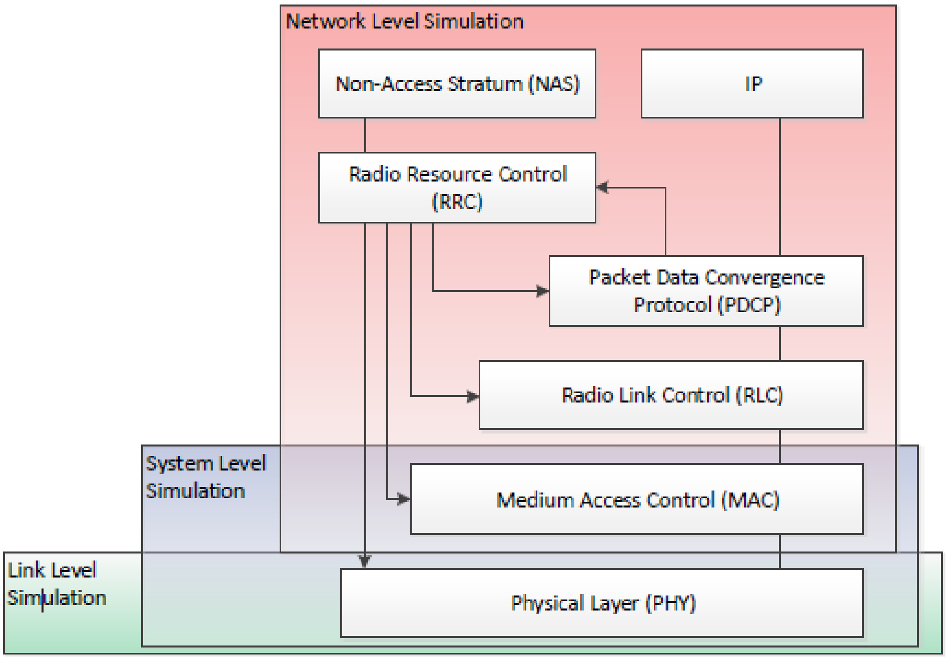


Figure 6.1: The mapping of the different simulator types onto LTE protocol stack layers (Finn, 2015, p46)

Designing a simulator which researchers can use to test the full functionality of their prototypes is a very complex task that cannot be realised in many research centres. This is the reason why most simulators fail to produce results desired by many researchers. It is not possible to design a “one size fits all” type of simulator. This is the reason why it was decided to develop an own simulator to specifically evaluate the functionality of the scheme in this research work. Most available simulators have not yet incorporated the convergence of cellular networks and wireless sensor technologies.

For this research work, LL simulators are inadequate as they are not capable of the analysis of network related issues that include scheduling and interference management. System level simulators are recommended for research projects where overall system reliability and the integration of specific technologies are to be evaluated. For this research project, a custom simulation package that makes use of system level was developed for use in the performance evaluation of the proposed design. The design in this research work is on the convergence of two networks, the cellular network, and the wireless sensor network. The complexity of such a network dictates that system level simulation be used for the evaluation of the developed strategy. Cellular networks and WSNs usually operate in hostile environments that include shadowing and multipath propagation amid heavy interference. It is difficult to accurately predict channel conditions with a simple analytical model. This is one of the reasons why it was decided to use system level simulation techniques in the evaluation process of the developed scheme as opposed to using traditional techniques. Creation of own system level simulator allowed the control of the level of abstraction. The developed simulation framework had to meet certain specifications.

## 6.3 Specifications of the Simulator

In 2008, the International Telecommunication Union (ITU), set up the International Telecommunications Advanced (IMT-Advanced) specifications which are requirements set to address the ever-changing needs of mobile services. The key features of the specification as outlined by Feng (2014:61) amongst others, are:

(i) High capability to internetwork with other radio access systems.

(ii) Ability to offer high quality and efficient mobile services.

According to Huawei Technologies (2017:2), the C-band (3 300-4 200MHz and 4 400-5 000MHz) is earmarked for the initial roll out of 5G by 2020 with the aim of providing a balanced coverage and cost-effective implementation. It is envisioned that a 100MHz channel bandwidth per 5G network utilising massive MIMO will provide ultra-high data throughputs with reasonable complexity. Ericsson (2015:2) pointed out that the existing radio-access technologies (RATs), like LTE, will be some of the 5G access networks providing a backward-compatible route for 5G systems in LTE spectrum. Other new RATs targeting new spectrum where backward compatibility with the already existing systems is not an issue will emerge. Taking this into consideration, the proposed solution was implemented using LTE specifications. LTE makes use of SC-FDMA for the uplink and OFDMA for the downlink. For LTE systems, Beard *et al*. (2016:478) recommend equation (6.1) to be used to calculate the amount of available RBs as:

$$r_a = \frac{0.9b}{c} \tag{6.1}$$

Where:

$r_a$ is the available resource blocks

*c* is 180 kHz

*b* is the total available bandwidth in kHz.

0.9 is a factor that incorporates 10% guard band.

180 kHz is the bandwidth of an RB that comprises 12 subcarriers of 15 kHz bandwidth each. For the time domain, radio frames of 10 ms are used with subframes of 1 ms each.

For a 5G network, it must be decided for every device needing to transmit to some other device, the frequency, and the time for the transmission to take place. This is where the BS comes. The resource allocation must be highly efficient and should be done in such a way that interference amongst the active devices is greatly minimised. Resource allocation gets complex as the number of active devices increases fighting over a limited bandwidth with most of the active devices having a high appetite for high data rates.

## 6.4 Selecting MATLAB for the Simulation Framework Development

For this research project, MATLAB was chosen in the development of a simulation model for the performance evaluation of the proposed algorithms. MathWorks developed MATLAB, a multi-paradigm programming language and numeric computing environment. Matrix operations, function and data visualization, algorithm implementation, user interface building, and interfacing with programs written in other languages are all possible with MATLAB (Gillman 2021). MATLAB was cchosen due to the following reasons:

(i) MATLAB comes with high compactness in that few lines can be used for very complex algorithms-MATLAB code is very concise.

(ii) MATLAB integrates a high computational capability with excellent graphical capabilities. It is a powerful tool not only for visualisation but also for graphical representation of scientific data. MATLAB has useful features that can be used for plotting functions, and it supports the exporting and importing of a variety of file formats for further and detailed analysis.

(iii) MATLAB allows a quick identification of conceptual errors.

(iv) MATLAB reduces the level of effort that is required to build a simulation model because of the availability of many model libraries containing established and already tested building blocks.

(v) MATLAB was chosen because of its high efficiency in testing and evaluation of algorithms without going into the intricacies of packet level implementation.

## 6.5 The Simulation Methodology

The simulation methodology involves the taking of a snapshot of an AOI. This is followed up by a computation of several statistical values. The flowchart of the procedure is shown in Figure 6.2.

In accordance with ITU-R (2009:1-72), when undertaking system level simulations, the following guidelines should be followed:

(i) Network layout is defined. This includes the placements of BSs, UEs and cluster heads for this research work.

(ii) Different channel conditions are assigned to UEs and CHs. This should include the line of sight (LOS) and non-line of sight (NLOS) propagation.

(iii) BS connection to a UE depends on the strongest link.

(iv) The simulation is run for a specific number of UE droppings and the process then repeated with UEs being placed at different locations. A big enough number of droppings should be allowed for convergence and for statistically valid results to be obtained.

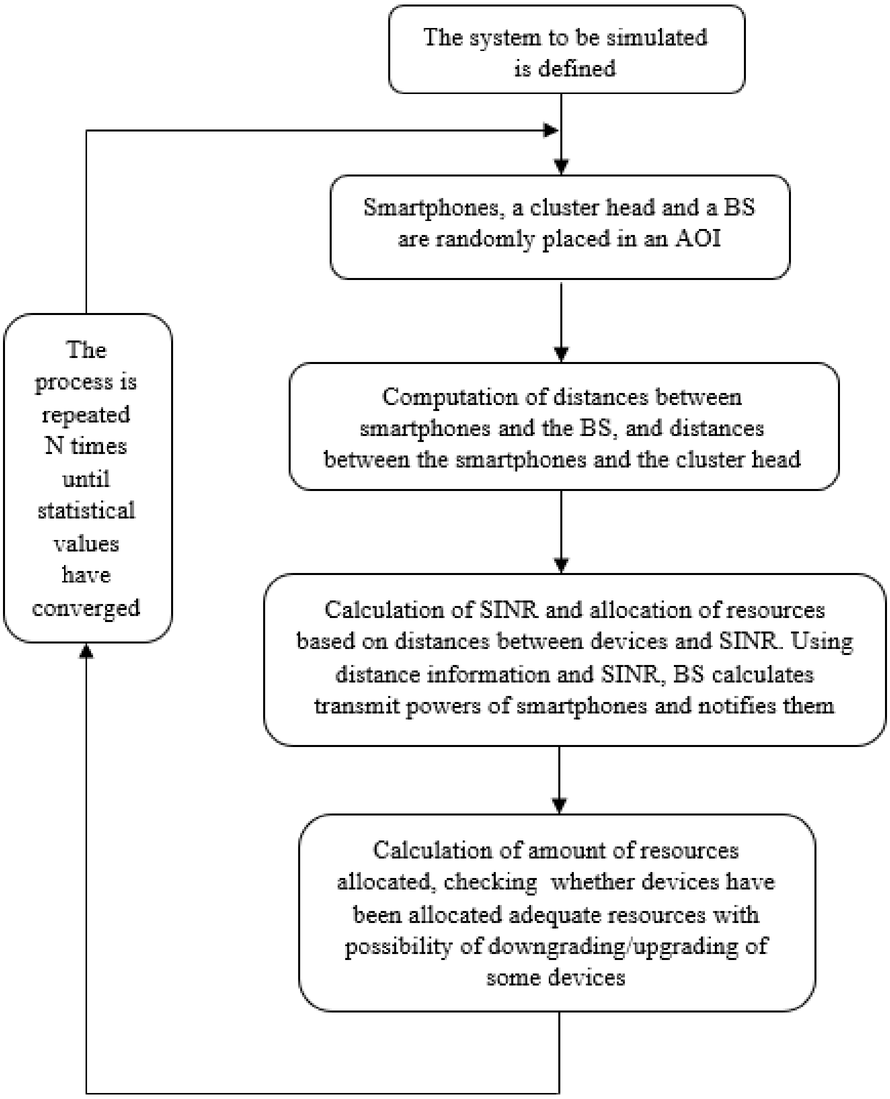


Figure 6.2: The simulation procedure

All the components of the simulation process are shown in Figure 6.3.

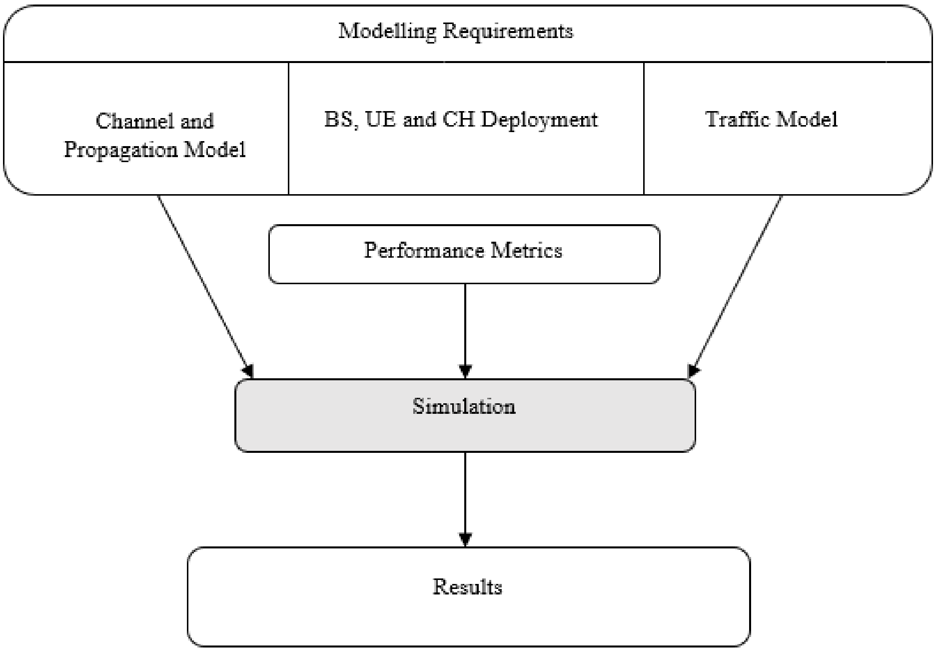

Figure 6.3: Simulation components

## 6.6 Simulation Parameters

To adequately evaluate the performance of the developed strategy for interference management, the correct parameters had to be selected for the simulation framework. Most of these parameters are taken from Bouras *et al.* (2014:1213–1237) who proposed a framework for use in the evaluation of interference mitigation schemes for heterogeneous cellular environments particularly for shopping malls.

### 6.6.1 Channel Model

It is always important to accurately model the effects of radio propagation as these effects degrade the system performance. Several factors affect wireless communication networks. The propagation environment, noise and interference are some of the factors. Shadowing from large obstacles, distance between communicating devices and multi-path fading all contribute to signal attenuation. This research project uses a channel model that factors in the effects of multipath fading, path loss and shadowing. For the D2D communication between sensors and UEs for this research work, dual mobility that affects normal D2D communication is not considered when selecting the channel model to use, since sensors are fixed and plugged onto fixed power points. The UEs are the only devices that are expected to be on the move.

For the evaluation of the proposed resource allocation algorithm, where it is necessary to adjust the height of cluster heads for maximum efficiency, the path loss model that is recommended by 3GPP (2014:39) was used. The path model is applicable for both suburban and urban areas. Table 6.1 shows the channel model assumptions for D2D scenarios.

Table 6.1: Channel model assumptions for simulating D2D scenarios (3GPP 2014:39)

| | Outdoor to outdoor | Outdoor to indoor | Indoor to indoor |
|---|---|---|---|
| Pathloss | ITU-1411-6 or Winner+ B1 | Dual strip or Winner + B4 or Winner + or Winner II A2 | Dual strip, or InH (TR 36.814 or Winner II A1) |
| Loss probability | ITU-R IMT Umi | ITU-R IMT Umi | ITU-R IMT Umi, or ITU-R IMT InH or Winner II A1 |
| Shadowing | 7 dB log-normal or 10 dB log-normal | 7 dB log-normal | LOS:3 dB Log-normal or NLOS: 4dB log-normal |
| Fast fading | ITU-R IMT Umi LOS and NLOS | ITU-R IMT Umi LOS 021 | ITU-R IMT InH LOS and NLOS |

According to ITU (2009:23), the most used channel models currently are drop based. This means that there is a scattering environment that is created randomly for each link. The traditional models do not cater for high density of links that is expected of 5G networks and do not cater for direct D2D connections between devices that are near each other.

### 6.6.2 Traffic Model

The traffic model used in this research work is adopted from Hossain *et al*. (2013:61) because this model gives a realistic traffic profile mimicking a practical cellular network. In practical cellular networks, traffic generation is inhomogeneous with the arrival rate varying both in space as well as in time. Smart phones in this research project send high quality level video streams to each other via the BS whilst CHs compete for resources to use for a D2D communication with nearby smartphones. For video streaming, according to IEEE (2007:36), frames of video data reach their destination at regular intervals, T, shown in Figure 6.4 (IEEE 2007:36).

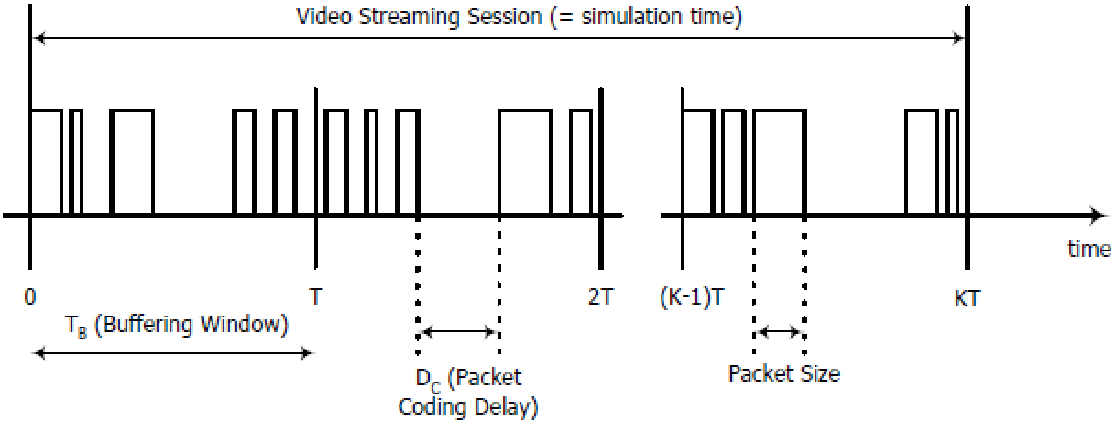


Figure 6.4: Near real-time video traffic model (IEEE 2006:36)

Table 6.2 presents other simulation parameters used in this research work.

Table 6.2: Simulation parameters

| Parameter | Value |
|---|---|
| System bandwidth | 100MHz |
| Carrier frequency | 4GHz |
| Maximum smartphone transmission power | 1.5W |
| Maximum BS transmission power | 24dBm |
| Maximum CH transmission power | 2.0W |
| Shadowing Standard Deviation | 10 dB |
| Noise Spectral Density | -174 dBm /Hz |
| Total number of available RBs | 50 |
| Data rate requirement for prioritised smartphones | 2Mbps |
| Data rate requirement for non-prioritised smartphones | 1.0Mbps |

Table 6.3 gives the simulation platform specifications.

Table 6.3: Simulation platform specifications

| MATLAB version | Computer Specifications | |
|---|---|---|
| MATLAB R2017a | Processor | Intel© Core© i3-6006U CPU @ 2 000MHz<br>2 core(s), 4 logical processors |
| | RAM | 4 GB |
| | Hard Disk | 1 TB |
| | OS | Microsoft Windows 10 Home Single Language |

## 6.7 Assumptions

For the sake of simplicity and generality, the simulations in this study are based on the following assumptions:

(i) The reuse factor is equal to 1 which means that the available spectrum is fully reused within the AOI.

(ii) Since the focus of this research work is resource allocation with the aim of minimising interference to allow for maximum data rates being achieved, the D2D discovery process is assumed to have been completed. The simulation process only concentrates on the communication between the smartphones and the BS, communication between the smartphones and the CH and the communication between the BS and the CH.

(iii) At the start of a simulation, it is assumed that the dejitter buffer of smartphones and the cluster heads are full of data bits. This data then 'leaks' from the buffer during a simulation.

(iv) One transmit antenna and one receive antenna for smartphones and cluster head and a MIMO antenna system for the BS. All smartphones communicating directly with the BS are allocated orthogonal sub-channels and a clusterhead can communicate with a smartphone by reusing any one of the orthogonal subchannels allocated to smartphones connected directly to a BS.

(v) It is also assumed that the positions of all devices within a specific area are known to the BS controlling those devices.

(vi) At one point in time, a smartphone can either be connected to a CH or BS and not to both at the same time. Likewise, a CH can be either be connected to a BS or a smartphone and not to both simultaneously.

## 6.8 Deployment of Network Elements

Five smartphone UEs are dropped randomly close to a CH some random distance from a fixed position 5G LTE BS. The random placements of smartphone UEs and the taking of measurements is repeated 100 times so that representative results may be obtained. Figure 6.5 shows some 5 UEs that are placed randomly covering an area of 140m by 120m. These 5 UEs, because of their proximity to the CH, can be allowed to communicate directly with the CH. The CH, if resources are available and QoS requirements are met, can directly communicate with the BS.

Figure 6.6 shows 5 smartphone UEs, that are randomly dropped 10 times around a BS and a cluster head covering an area of 1 500m by 1 400m. The positions of the CH and BS remain fixed. The process is repeated until statistically representative values are obtained.

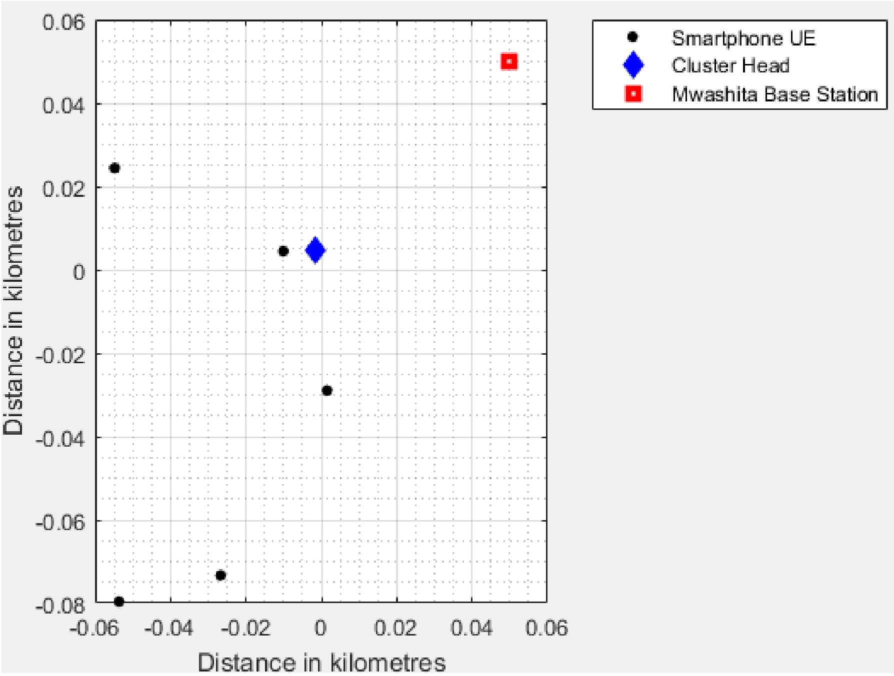


Figure 6.5 smartphone UEs, one cluster head and a base station

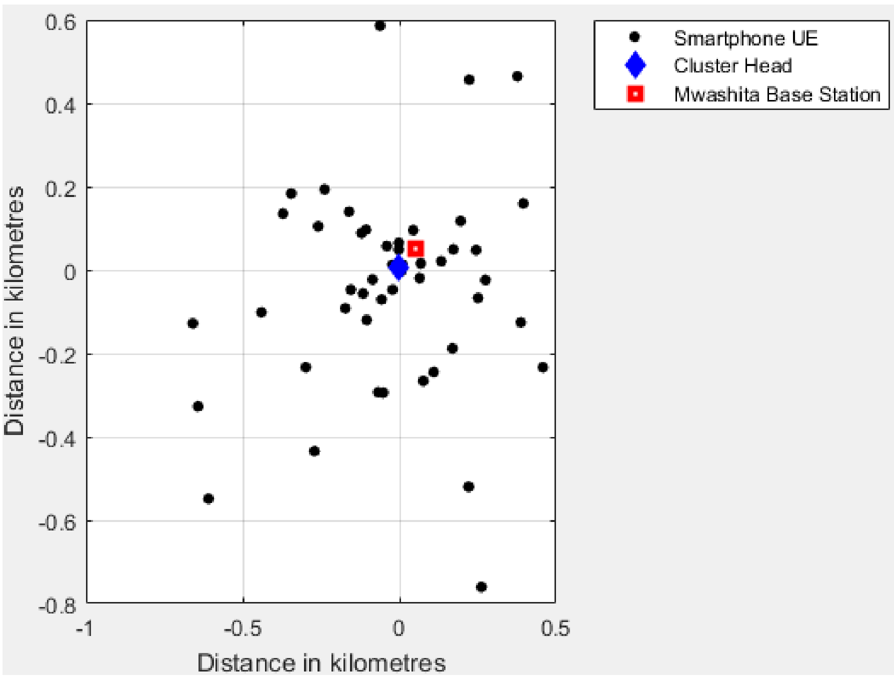


Figure 6:6 50 smartphone UEs, one cluster head and a base station

## 6.9 Implementation of the Power Control Mechanism

Once a D2D communication between a smartphone user equipment (SUE) and a CH has been allowed by the BS, the D2D transmitters need to transmit at specified maximum powers to guarantee an acceptable QoS for smartphones connected directly to a BS. For this research project, the power adjustment parameter proposed by Coupechoux and Kélif (2011:1-5) was used. Since CHs are not mobile and are plugged to reliable utility power, their transmit powers are obtained using the same power adjustment factor but the power remains fixed. This means that CHs that are at different distances from the BS would transmit at different powers to SUEs near them. The SUEs, because of their mobility, have their transmit powers constantly adjusted as their distances to the BS change as they move within the coverage area.

### 6.9.1 Variation of ProSe-Enabled Sensor Transmit Power

The variation with distance of transmit power that the Pro-enabled sensors must use to communicate with the BS is shown in Figure 6.7. This variation is shown for power control levels, α, of 0, 0.2, 0.4, 0.6, 0.8 and 1. In accordance with an SINR-optimising strategy proposed by Novlan *et al.* (2013:2669-2679), CUEs and DUEs in the cell interior have better RF conditions and are less susceptible to interference than users at the cell edge. Instead, they are more noise limited, which means that lowering their transmit power lowers the SINR they can achieve. This is especially true when using pathloss-based power control because high values of α reserve the most transmit power for users with high pathloss. As a result, the SINR-optimising strategy is to transmit at full power (α = 0) for cell edge devices.

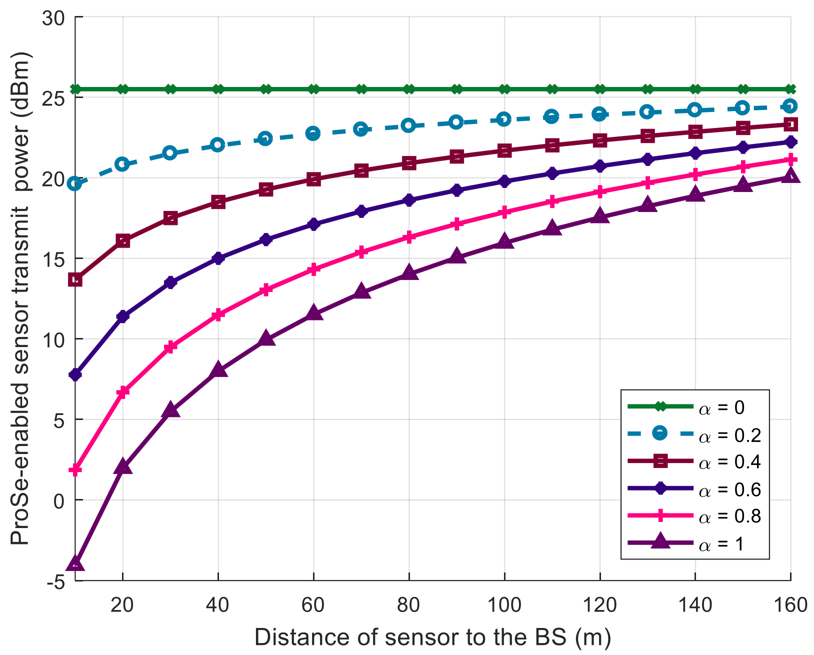


Figure 6.7: Variation of power with distance

It can be observed on Figure 6.7 that for α = 0, a sensor uses maximum power to the BS and as α increases, the transmit power required to establish communication with a

BS without causing interference to CUEs for the same distance decreases. This is good in maintaining a specified QoS of the network. This means that as α increases, interference to other cells utilising the same resources is reduced. It can also be seen in Figure 6.7 that ProSe-enabled sensors must transmit at higher power as the distance from the BS increases.

### 6.9.2 Reusable Distance

UL resources currently in use by a specific CUE can only be reused by a ProSe-enabled sensor if the distance condition specified by the developed algorithm is met. Figure 6.8 shows the distance from the BS UL RBs can be reused to ensure that the cellular network QoS is not compromised. It can be observed that for both NLOS and LOS propagation environments, the reusable distance decreases quickly as the power control level increases. It can also be seen from Figure 6.8 that the reusable distance decreases faster for a NLOS propagation environment compared to a LOS propagation environment. It can also be observed that sensors should not be allowed to share UL resources with CUEs that are further than 160m from the BS under NLOS environment and for the LOS propagation environment the distance is 150m.

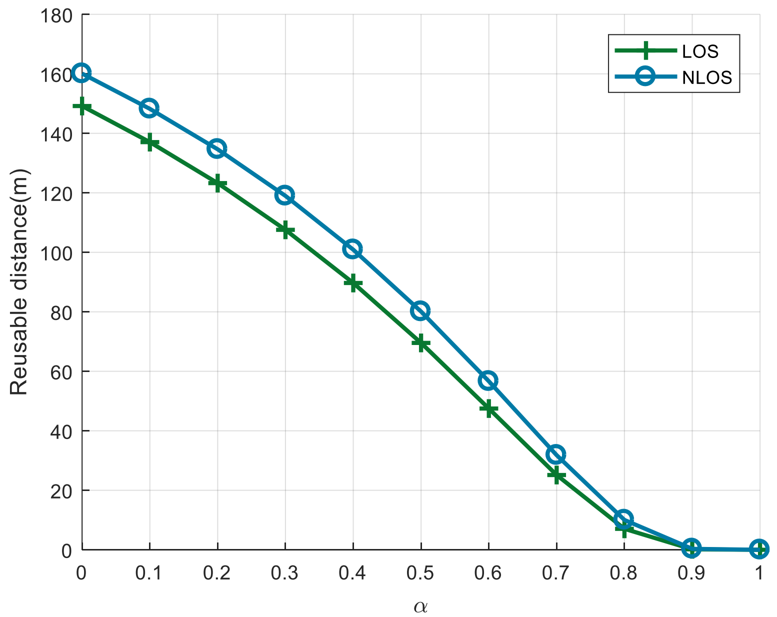


Figure 6.8: Reusable distance from BS vs power control levels

### 6.9.3 Sensors Maximum Allowed Transmit Power

Figures 6.9 and 6.10 show that that maximum allowed transmit power increases faster to attain their maximum levels for CUE distances that are nearer to the BS. It can be observed on Figure 6.9 that the reuse of subchannels for distances above 115m from the BS for a NLOS environment cannot not be permissible for CUEs that are very close to the BS. The algorithm limits the distance to minimise the effect of interference on SINR and subsequently maintaining the QoS of the cellular network within specified levels.

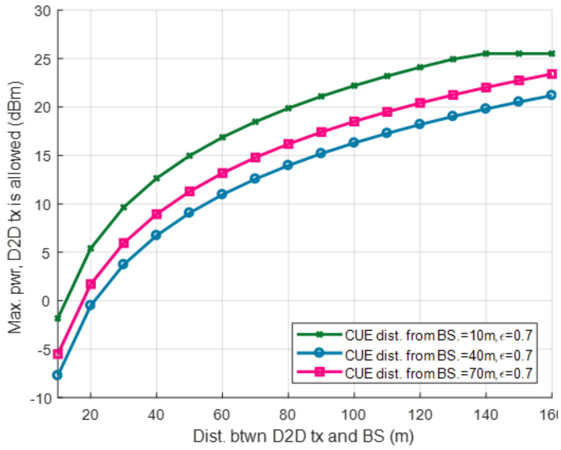


Figure 6.9: Maximum transmit power vs distance for LOS

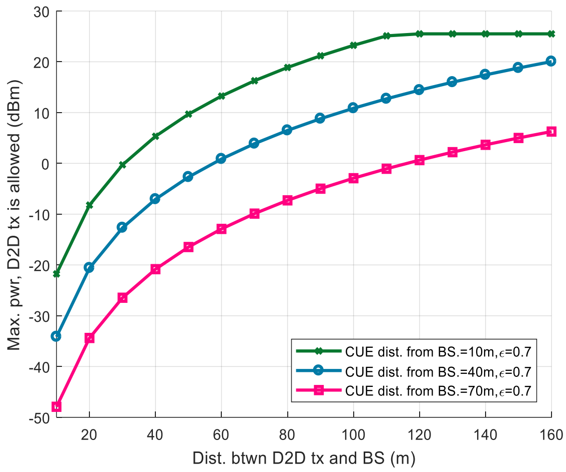


Figure 6.10: Maximum transmit power vs distance for NLOS

## 6.10 Conclusion

The development of a compact simulation framework for the complete and systematic evaluation of the proposed scheme for its performance analysis was presented in this chapter. The simulator's settings were selected from a range of parameters proposed by leading experts in the field of interference mitigation methods for use in evaluating interference mitigation schemes for heterogeneous cellular environments, particularly shopping malls. The simulation tests will be presented in the next chapter, along with a discussion of the test results.

# CHAPTER SEVEN: SIMULATION TESTS AND DISCUSSION OF RESULTS

## 7.1 Introduction

The simulation tests done on the proposed scheme to ensure that the design specifications were met are presented in this chapter. This chapter also explains why the tests were chosen in the first place. The findings from these tests are also reported. Both the wireless sensor network and the cellular network will benefit if the two networks converge. Smart phones as redundant gateways improve the efficiency with which sensed data is routed to a WSN's core networks. The cellular network benefits because network operators can provide additional services, attracting additional customer base. However, the additional sensing traffic degrades a cellular network's QoS. As a result, selecting relevant performance measures to assess how the proposed scheme mitigates the interference introduced to the cellular network is critical for evaluating the proposed scheme's performance. Cellular network providers will only accept ProSe-enabled sensors if they do not have a significant impact on the cellular networks' QoS. The developed method was evaluated using a variety of metrics.

## 7.2 Performance Tests

Table 7.1 gives the overview of the performance tests carried out and a summary of the results obtained.

Table 7.1 An overview of the results obtained

| Item | Performance Metrics | Description of performance test carried out | Summary of results obtained |
|---|---|---|---|
| 1 | User throughput | User throughput of a random CUE is monitored as the CUE moves about in an AOI before and after introduction of D2D and results collected. Throughputs of 80 CUEs are also measured before and after introduction of D2D. | For the random user, the proposed scheme greatly reduced the interference such that user throughput was not adversely affected. There was a marginal reduction in user throughput after the introduction of interference mitigation scheme. |
| 2 | CUE SINR | The SINR of a CUE is measured before and after the introduction of D2D communication. | The introduction of D2D did not seem to have affected the SINR of the CUE |
| 3 | Sensor SINR | The SINR for the ProSe-enabled sensor is measured for various distances from the BS for both the LOS and NLOS scenarios | The SINR of sensors decreases with distance, faster for LOS than it is for NLOS |
| 4 | Energy efficiency metric | EE was measured for both the proposed and baseline scheduling schemes | The proposed scheme did not affect the AEE of the network |

### 7.2.1 User Throughput

When it comes to issues of QoS, user throughput is a well-accepted performance metric in the research community (ITU-R 2009:1-72 and IEEE 2007:1-38). User throughput refers to the number of bits per second that are transferred from one location to another. A modified Shannon formula was used to give the data rate:

$$r_1 = mc\sigma \log_2(1 + SINR) \tag{7.1}$$

Where:

$r_1$ is the data rate.

m = the number of resource blocks allocated to a transmitting device.

$c$ = 180 kHz.

$\sigma$ = 0.4 according to 3GPP (2009:74) for a 16 QAM modulation scheme.

User throughput was used to investigate whether the interference management scheme designed for handing the interference that arises when ProSe-enabled sensors are integrated was effective.

(i) Impact of ProSe-enabled Sensor Traffic on CUE Throughput

A ProSe-enabled sensor is made to reuse UL resources of one CUE, CUE 1. The throughput of CUE is then measured as it moves about in an AOI. Figure 7.1 shows the variation of CUE 1's throughput as the user walks about randomly in an AOI.

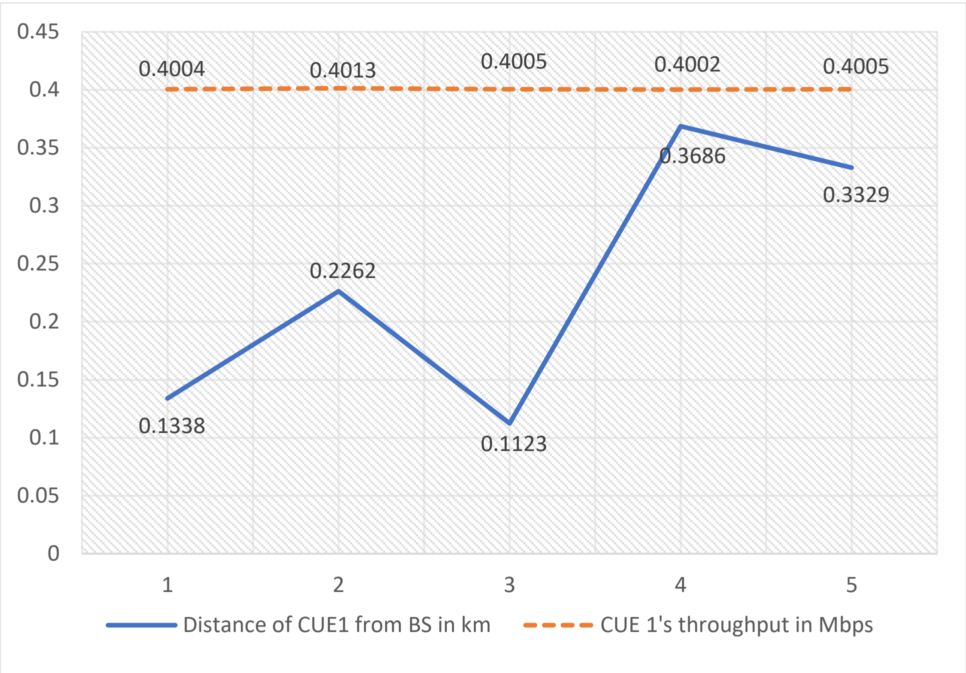


Figure 7.1: UE 1's throughput before introducing communication with ProSe-enabled sensors

The RB resources of the same user, CUE 1, are then allocated to a ProSe-enabled sensor for reuse and the process of measuring the user throughput of the user is repeated as the user walks randomly about an AOI. Figure 7.2 shows the results obtained for this process.

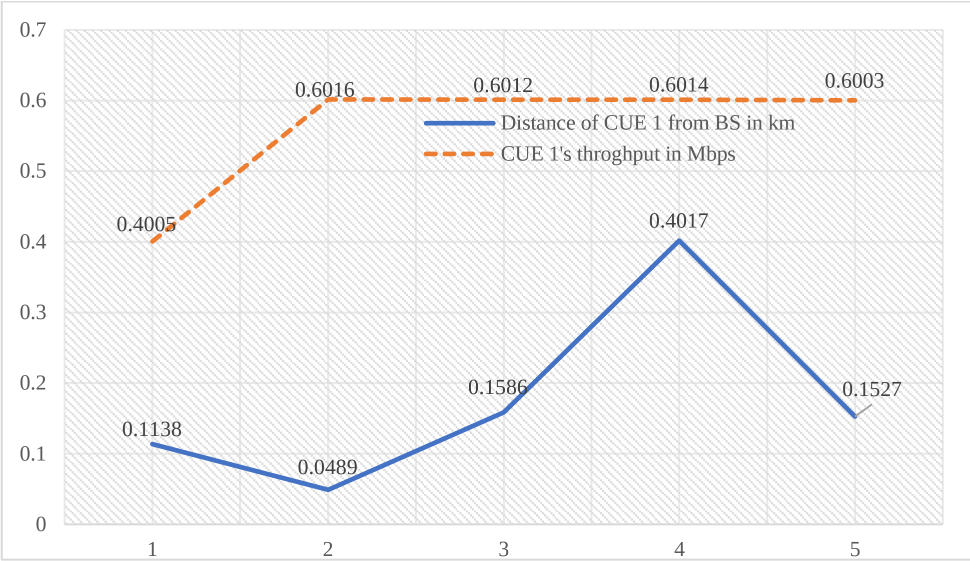


Figure 7.2: CUE 1's throughput after introducing D2D communication

The total throughput for users within 0-40m radius, 40-80m radius, 80-120m radius and 120-160m radius is measured before and after ProSe-enabled sensors are allowed to reuse UL as well as DL resources and the results obtained are presented in Figure 7.3.

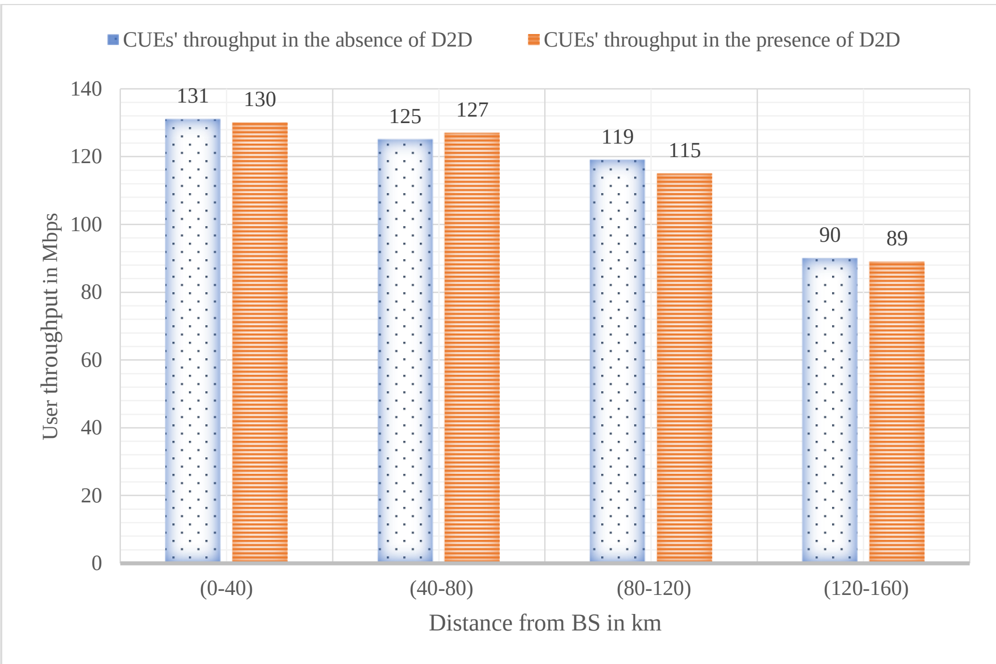


Figure 7.3: Total throughput of 80 UEs scattered around an AOI before and after introduction of D2D

(ii) Discussion on the Effect of the Developed Scheme on User Throughput

Key performance indicators (KPIs) like user throughput are usually incorporated into service level agreements to assist in the monitoring of system performance (Ammunouri *et al.* 2018:1147-1160). KPI metrics give an insight of how a telecommunication system under consideration may be perceived by stakeholders and in this regard may be taken as an abstraction of a complex system. According to Gamal *et al*. (2006:2568-2592), interference mitigation strategies enhance the individual devices' throughput in mobile networks. Integration of D2D communication into cellular networks introduces interference (Ramasamy 2017:130-150). The monitoring of user throughput becomes key in the validation of the developed interference mitigation scheme. It can be seen in Figures 7.1 and 7.2 that the re-assignment of some of the CUE's resources to a ProSe-enabled sensor did not adversely affect the CUE's throughput. There is, in fact, a slight increase in the throughput at 4.8m from the BS which can be attributable to the high SINR for small distances to the BS as shown in Figure 7.5. While Figures 7.1 and 7.2 are used to display the impact of allowing a single CUE randomly chosen to share its resources with a ProSe-enabled sensor, Figure 7.3 shows the impact of the introduction of ProSe-enabled sensors in an AOI with 80 randomly dropped CUEs. Table 7.2 summarises the reduction in the throughput.

Table 7.2: Throughput of 80 UEs scattered around an AOI before and after introduction of proposed scheme

| Distance from the BS in m | | 0-40 | 40-80 | 80-120 | 120-160 |
|---|---|---|---|---|---|
| | | 20 | 20 | 20 | 20 |
| Throughput in Mbps | Before D2D | 131 | 125 | 119 | 90 |
| | After D2D | 130 | 127 | 115 | 89 |
| Reduction of user throughput | | 0.76% | -1.6% | 3.36 | 1.11% |
| Reduction of user throughput for 0-80m | | -0.84% | | 4.47% | |
| Overall reduction of user throughput for 0-160m. | | 3.63% | | | |

An overall user throughput reduction of 3.63 % can be observed. This is a modest value in cellular networks. According to Ramasamy (2017:45), a reduction of up to 5% is acceptable to both users and network providers and is usually captured in service level agreements.

### 7.2.2 CUE SINR

SINR plays a pivotal role in multi-user systems and is a good metric in measuring channel quality of individual users in a cellular network (Farhana *et al.* 2015:1-11). The proposed scheme is designed in such a way that interference that arises when sensors directly communicate with nearby smartphones in a D2D fashion is effectively managed. It is quite appropriate therefore, to gauge the effectiveness of the scheme in this regard by closely monitoring the proposed scheme's effect on SINR of individual users.

To study the impact of sharing of DL and UL resources by ProSe-enabled sensors, the variation of SINR with distance within an AOI is noted and results obtained are compared to the SINR variation with distance when D2D communication between between ProSe-enabled sensors and smartphones is permitted. The results obtained in the study are captured in Figure 7.5.

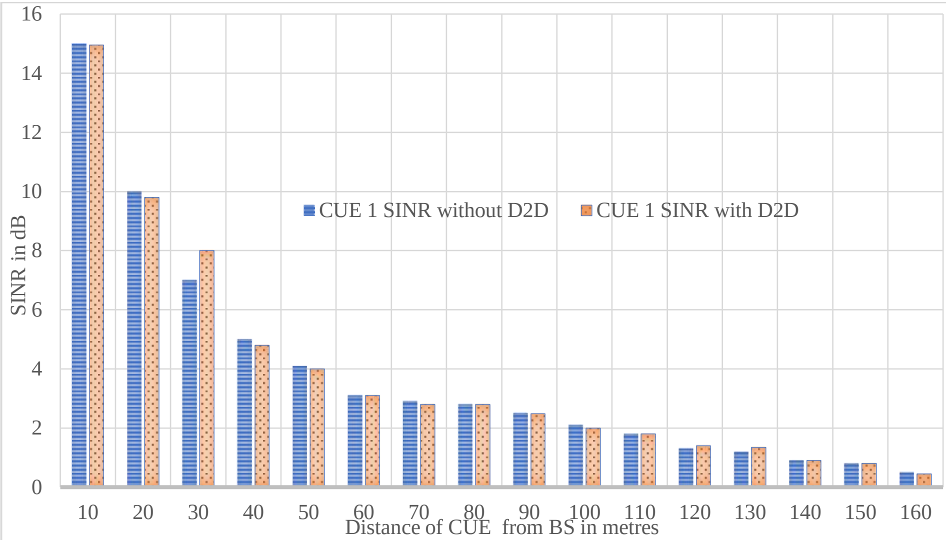


Figure 7.4: SINR of one CUE chosen randomly with and without resources being shared

The impact of the proposed scheme on the SINR of a CUE is very minimal as can be observed in Figure 7.4. The SINR decreases with distance on moving away from the BS. This reduction however affects both the optimal and the proposed scheme in a similar fashion. SINR is critical when it comes to issues of QoS of a network and Figure 7.4 shows that the introduction of D2D did not affect the SINR of the CUE. This means that the proposed scheme did not affect the QoS of a mobile network.

### 7.2.3 Sensor SINR

Figure 7.5 shows the variation of SINR of a ProSe-enabled sensor with distance from a BS for a power control of 0.7. The two curves are for LOS and NLOS communications.

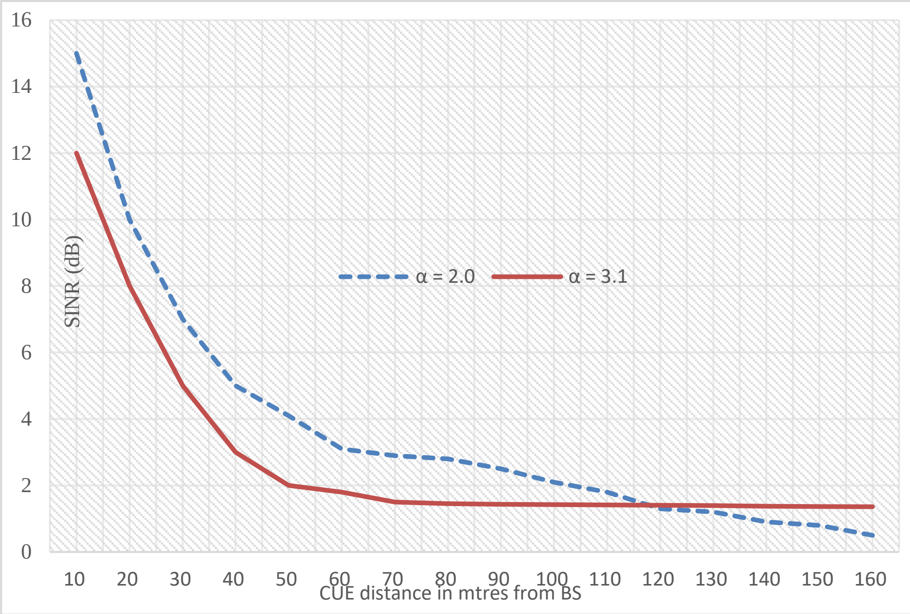


Figure 7.5: Variation of a sensor's SINR with distance from BS for (α = 2.0) LOS and (α = 3.1) NLOS

The variation of SINR of a ProSe-enabled sensor with distance from a BS is shown in Figure 7.5. It can be observed that for a power control of 0.7, the SINR is high when the ProSe-enabled sensor is very close to a BS, and it then decreases exponentially as distance increases. It can also be observed that for distances of up to 120m, the LOS propagation ceases to enjoy a superior SINR compared to NLOS propagation.  This is a strange phenomenon which can be explained by the fact that, according to Rappaport *et al.* (2017:6213-6230), many reflections and scatterings from ceilings and walls that are in abundance at highly built-up areas like shopping malls, and the waveguiding effects due to hallways, passages, and alleys, all contribute to an increased received power.

### 7.2.4 Energy Efficiency

According to Breeder *et al.* (2016:247-272), there are several definitions for energy efficiency (EE) metric. Buzzi *et al.* (2016:697-709) and Shi *et al.* (2016:7488-7500) concur that the EE metric is defined as a ratio of system throughput to energy consumption using a unit of bits per joule. The proposed scheme considers channel gains in the allocation of RB resources to CUEs to ensure equal distribution of transmission power to all RB resources. The CUEs are allocated resources first ahead of any ProSe-enabled sensor requesting to be connected to nearby smartphones to guarantee the QoS of the cellular links. ProSe-enabled sensors can then be allocated resources depending on availability of RBs. Figure 7.6 displays the energy efficiency for both the proposed scheme and a baseline resource allocation strategy. For the baseline resource allocation, no D2D commjunication is allowed during this itime and the allocation of RBS is as per 3GPP standards.

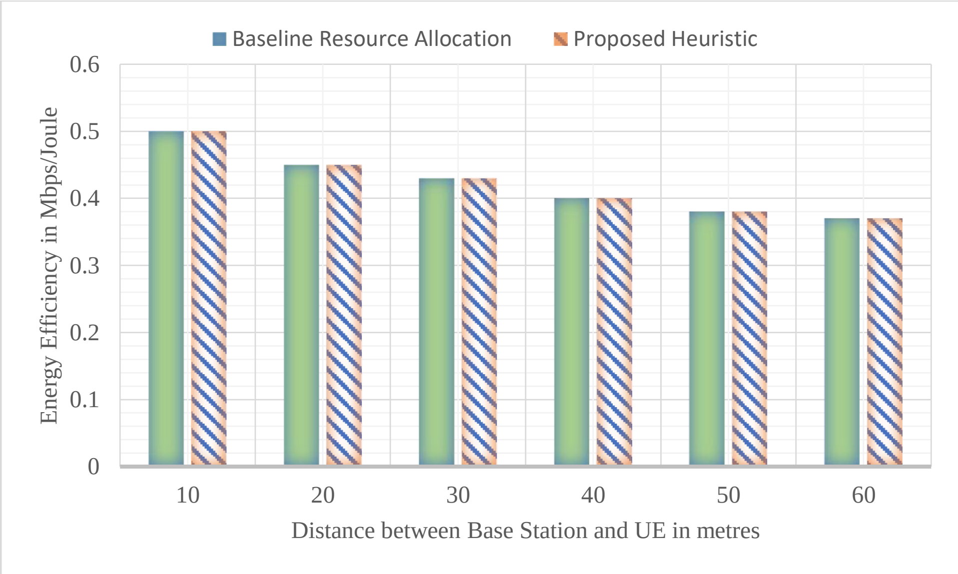


Figure 7.6: EE for the proposed and baseline resource allocation schemes

Battery lifetime is an aspect that is at the heart of an end user of cellular networks (Techradar, 2021). When it comes to design, camera, and even computing power, smartphones have come a long way in the previous few years. However, there have been few improvements in battery technology, which is crucial today because cellphones are loaded with large displays, additional sensors, and quicker processors, all of which deplete battery life. Any application or strategy that tends to reduce the battery lifetime is not welcome to the end user. The proposed scheme requires sensors to engage with smartphones only when there is positive detection of explosives in the vicinity. Figure 7.7 shows that energy efficiency is not affected by the introduction of the proposed scheme. This means that use of the proposed technology does not result in any noticeable battery deterioration

### 7.2.5 Comparison with an FFR Interference Mitigation Scheme

The proposed scheme was compared to a similar interference management scheme proposed by Kim *et al*. (2018:1-8) meant to deal with interference introduced by sensors in D2D-enabled cellular networks. A similar model and similar simulations assumptions were used for an accurate comparison and the results depicted in Figure 7.7 were obtained.

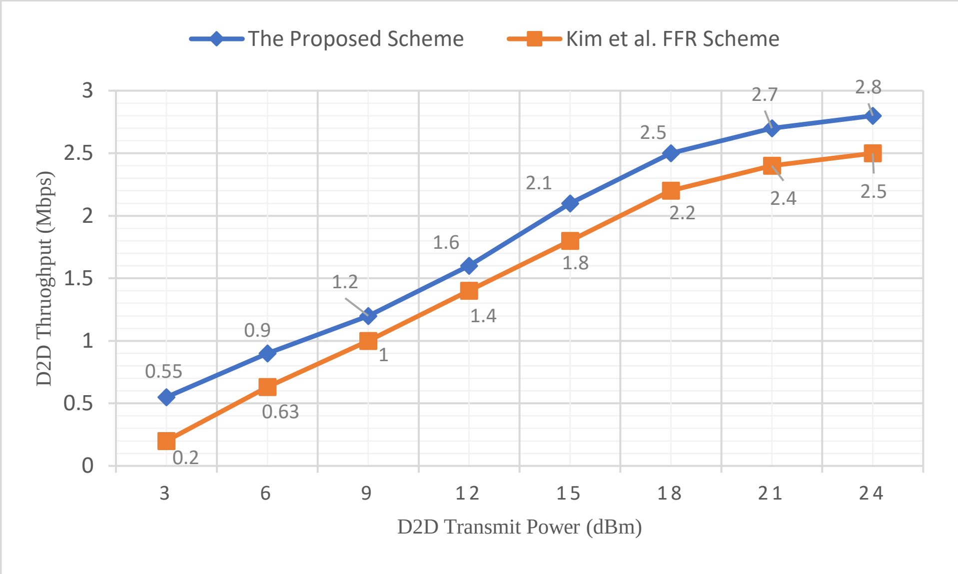


Figure 7.7: D2D link throughput versus D2D transmit power (cellular Tx power = 40 dBm).

It can be observed from Figure 7.7 that the proposed scheme outperforms that was proposed by Kim *et al*. (2018:1-8). This could be because the researchers did not incorporate a rigid power control strategy of the devices engaged in D2D communication. This is likely to affect the QoS of the underlying cellular network. The FFR proposed scheme does not limit D2D in the uplink using distance from the BS. The FFR proposed scheme also does not make use of the downlink.

## 7.3 Validation of the Results

Validating the results obtained from the tests that were performed on the developed scheme was firstly achieved by the validation of the developed MATLAB simulator. A set of empirical tests were carried out to validate its normal functioning. The tests in which the simulator was supposed to generate expected outputs in comparison to the ones obtained analytically appear in Table 7.2.

Table 7.2 Validation of the Simulator

| Empirical Test | Description |
|---|---|
| 1 | Check if an error message is displayed each time input values are inserted outside the confidence interval. |
| 2 | Verify that all input files are read correctly. |
| 3 | Verify that all output files do exist and are in the correct output directories. |
| 4 | Verify that potential smartphone-sensor pairing has been done correctly as expected. |
| 5 | Verify that the maximum distances between any two devices participating in a D2D communication has not been exceeded. |
| 6 | Check whether smartphones and sensors tagged as belonging to inner and outer regions really belong to those regions by verifying their physical distances. |

For the validation of the main tests that were performed using the simulator and to ensure statistical relevance, mean values of parameters used in the tests like user throughput, were calculated using equation 7.1.

$$\mu = \frac{1}{N}\sum_{n=1}^{N_s} \mu_n \tag{7.1}$$

Where $N_s$ = number of similarities

$\mu_n$ = mean value obtained in *n* simulations.

The standard deviation was calculated using 7.2.

$$\sigma = \sqrt{\frac{1}{N}\sum_{n=1}^{N} {\sigma_n}^2} \tag{7.2}$$

Where $\sigma_n$ = standard deviation for *n* simulations.

Percentage deviation was calculated using equation 8.3.

$$\Delta\% = \frac{|f_n - f_f|}{f_f}100 \tag{7.3}$$

Where $f_n$ = fractional output cumulative mean at interval *n*.

$f_f$ = total output cumulative mean.

It was found out that it was not necessary to undertake long duration simulations since the results that were obtained for 30 minutes of simulation were comparable to results obtained for simulation durations of 60, 90, 120, and 150 minutes. As can be observed in Figure 7.8, convergence is below 3%.

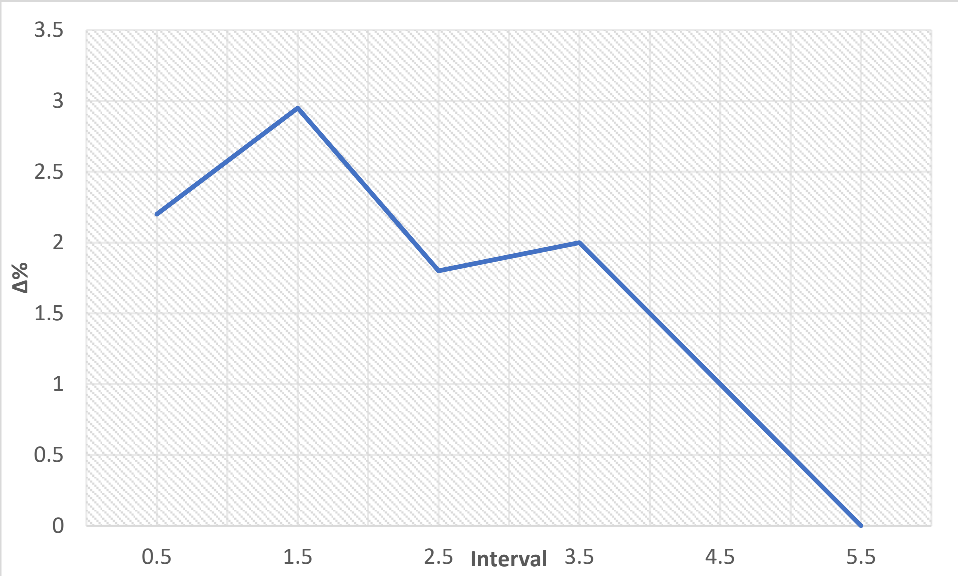


Figure 7.8 Convergence of the average smartphones' throughputs

Total throughput of smartphones scattered around an AOI before and after the introduction of the developed interference management scheme showed that the mean standard deviation and the smartphones' throughput approached a constant value as shown in Figure 7.9.

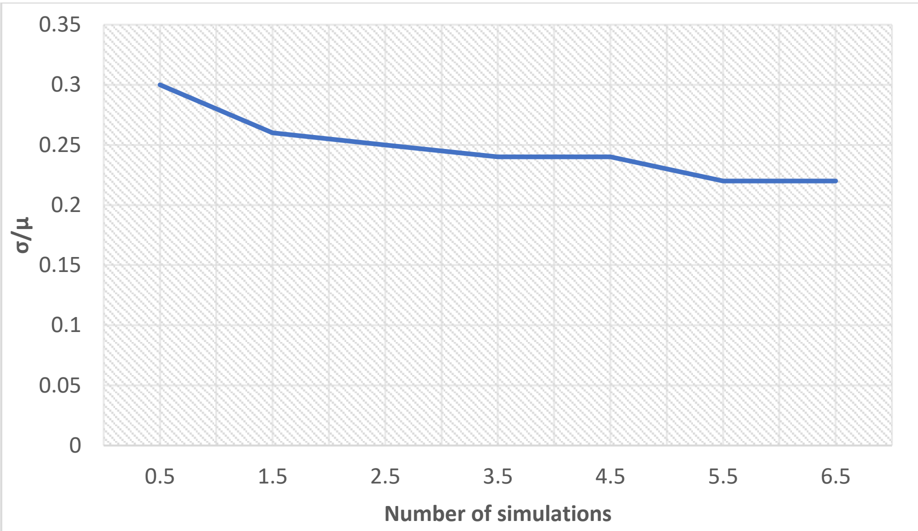


Figure 7.9 Mean standard deviation of the Ues throughput

## 7.4 Conclusion

This chapter has presented the simulation tests that were used in the evaluation of the proposed strategy. The performance metrics have been outlined. The results obtained shows that the proposed scheme can be deployed in cellular networks without compromising the QoS of the underlay cellular network. To display the advantages of the proposed scheme over other employed schemes in the literature based on similar system models, the proposed scheme was compared with a scheme proposed by other researchers who also worked on an interference mitigation scheme meant to deal with the interference that results when ProSe-enabled sensors are added to a D2D-enabled cellular network.

# CHAPTER EIGHT: CONCLUSION AND FURTHER WORK

## 8.1 Introduction

This last chapter is divided into four sections. The conclusions of the work reported in this thesis are presented in the first section. The thesis' main contributions are highlighted in the second section. The implications and applications of the research effort are then presented in the third section. A few potential research directions are highlighted in the last part to continue the research effort relevant to the challenges addressed in this thesis towards interference management in WSN/MCN converged networks.

## 8.2 Conclusions

The first chapter presented the introduction of the thesis. The second chapter presented the background of D2D communication, with a focus on its integration in future cellular networks, particularly in the domain of sensor networks. The design challenges of integrating D2D in cellular networks for sensor networking were also discussed in Chapter 2. Chapter 3 presented a discussion of the current state-of-the-art in interference management techniques for D2D-enabled cellular networks. Power control, mode selection, beamforming techniques, and other novel interference management approaches that have gotten a lot of attention from the research community were discussed. Machine learning's role in D2D-enabled network interference reduction was also discussed in this chapter. The formulation of the problem is presented in Chapter 4 as well as the system model that was used in the study. A description of the development of a collaborative area monitoring framework that focuses on the management of interference introduced to a cellular network by ProSe-enabled sensors and D2D communication was also presented. Chapter 5 describes the design of the interference control method. Chapter 6 presented details of the development of a state-of-the-art simulator as part of this research to enable studies in converged mobile cellular networks (MCNs) and wireless sensor networks (WSNs) for the implementation and investigation of novel techniques/ algorithms developed to reduce interference that occurs when sensors communicate with smartphones in a D2D manner. Chapter 7 presented the simulation tests done on the proposed scheme to ensure that the design specifications were met This chapter also explains why the tests were chosen in the first place. The findings from these tests are also reported in this chapter.

## 8.3 Contributions

### 8.3.1 Contribution 1

The main contribution addresses how sensors in cellular networks can share radio resources with no or minimal impact on present cellular services. As a result, a spectrally efficient technique was devised and presented A mobile environment with several sensors was studied, and detailed simulations were performed to determine how the addition of sensors would affect network throughput and SINR.

### 8.3.2 Contribution 2

Power control of DUEs is a significant and challenging task. A unique algorithm was proposed in this research study. The approach considered the channel capacity, network radius, and DUE transmission power optimisation. It was concluded that the inclusion of DUEs has no detrimental effect on the QoS of an underlay cellular network, according to the simulation results of the proposed power control strategy.

### 8.3.3 Contribution 3

A state-of-the-art simulator was developed as part of this research to enable studies in converged mobile cellular networks (MCNs) and wireless sensor networks (WSNs) for the implementation and investigation of novel techniques/ algorithms developed to reduce interference that occurs when sensors communicate with smartphones in a D2D manner. The developed model encompasses the connections between a BS, UEs, and sensors, allowing for realistic analysis of network-related issues such as interference mitigation and network planning optimization in urban settings such as shopping malls. The system level simulator follows the 3GPP standard for 5G network features and characteristics. Path-loss models, BS/UE standards, MIMO/ smart antenna designs, appropriate channel models such as the WINNER II model, and defined channel bandwidths are all features of the 5G network standard. The system-level simulator was developed by first abstracting the link-level features (i.e., the physical layer) to a sufficient level of detail and accuracy, and then mapping the link-level to the system-level.

## 8.4 Applications of the Research Work

Regarding data traffic by individual devices, a smartphone is predicted to generate 11 GB of traffic per month by 2022, up from 2GB in 2017 (Shi 2019). This rightfully positions 5G to become the cornerstone of the IoT. 5G is expected to be a revolutionary change in the whole network architectures that will trigger a lot of revenue generating services. It is anticipated that slightly over 50 billion devices will connect directly to mobile networks all over the world (Evans 2011:1-11). Most of these devices will make use of sensors for the measurement of pressure, temperature, stress or speed. 5G is likely to incorporate sensors that facilitate the remote monitoring of buildings, bridges and roads for minute structural changes for security and safety. For the unlocking of IoT, 5G must address issues like latency security and bandwidth. This revolutionary nature of 5G is likely to usher in technologies like D2D. Researchers that specialise in D2D communication are likely to benefit immensely with this literature that has been put together. The strategies developed for ProSe-enabled sensors will benefit those working on IoT.

Shopping mall owners are highly likely to embrace the technology as it enhances security at their shops which then becomes a pull factor for customers leading to increased revenue. According to Davis (2018), incidences of terrorist attacks at shopping malls has been in the increase of late, so any technology that warns smartphone users of any impending danger when undertaking their business at these places is highly welcome. Results from this research work have shown that sensors that are positioned at strategic points in a place with many users like at a shopping mall, can participate in D2D communication without adversely affecting the QoS of the underlay cellular network.

The strategies for interference mitigation can be integrated into cellular networks not only for sensor networking but for nearby devices to offload information to increase their spectral efficiency.

## 8.5 Implications of the Research

The aim of this research work was to develop new radio resource allocation and power control algorithms for machine type communication, where the same spectrum is shared by human to human and D2D communications. The focus in the algorithm's development was interference management and energy consumption minimisation so that the scheme is acceptable to both cellular network operators and smartphone users. This led to the development of the following:

(i) A scheme for interference mitigation for use in D2D sensor networks deployable at highly crowded public places such as shopping malls.
(ii) An analysis of mitigation techniques for the interference that arises from the integration of D2D and explosives detecting systems into the next generation mobile networks.
(iii) A framework for a hybrid sensor networking system that can be used to warn smartphone users, security agencies, emergency services and other stakeholders of an imminent terrorist attack at shopping malls and other crowded places.
(iv) A complete system level D2D communications simulation package for the evaluation of the developed scheme.

The results that were produced can be useful to quite a few entities. Cellular network operators are likely to embrace the technology as a way of broadening their offerings to the public in a bid to increase their revenue base. It is also sentimentally true that people need to feel safe and secure when visiting highly crowded places like shopping malls. Thus, naturally, the common person is likely to be excited about the proposed design. It is easy for the end user to accept the design because the design does not lead to accelerated battery deterioration as confirmed by the results. It is easy for the end user to accept the design because the design does not lead to accelerated battery deterioration as confirmed by the results. Cellular end users do not easily accept technologies that deplete their devices' batteries too quickly. Many apps deplete users' batteries even when they aren't using them. Certain apps provide communication services to keep people always linked. This means that the apps are always running in the background, collecting data, fetching users' whereabouts, sending notifications, and so on. Not to mention the fact that users tend to spend a lot of time on them, whether it's checking their news feeds or contacting friends and family. The results posted by the research are likely to be used to fast track the convergence of wireless sensor networks and cellular networks.

## 8.6 Recommendations for Further Work

The aim of the research was to develop an interference management method for usage in D2D-enabled cellular networks with ProSe-enabled sensors. Extensive simulations were used to evaluate the proposed scheme. mmWave communication was only studied for downlink transmission. It would be interesting to look at the prototype's performance with the uplink using mm Wave communication as well.

To cope with spectrum limitations, sensor traffic is expected to be sent using radio channels assigned to cellular subscribers. However, a crucial question arises: why should cellular users share their assigned subchannels with sensors which results in the degradation of the cellular QoS? It would be interesting to develop tactics and incentives to encourage resource sharing between cellular users and MTDs like sensors as a two-sided market, and then apply them to the proposed model. To overcome the incentive issue, new approaches for calculating the costs/benefits ratio in each sharing situation can be developed. MTDs, for example, may offer monetary compensation to H2H users even though they share the same spectrum. The cost of using the underlying D2D technology should be thoroughly investigated so that MTDs involved in D2D communication do not pay more than they would if they used a BS. Furthermore, it is critical to incorporate a level of confidence into incentive structures. Indeed, because both cellular users and MTD devices exchange information (distance, channel information, etc.), incorporating a mutual reputation reward in the incentive mechanism that reflects each node's reliability and performance will make resource sharing transparent and thus improve spectrum sharing.

Another angle is to apply the proposed adaptive and efficient radio resource sharing framework for MTC-based cellular networks to security system design concerns. M2M services are vulnerable to unique security threats due to the unique features of M2M communications that benefit from D2D technology. Direct communication between devices is more risky than traditional infrastructure-based communication. M2M devices are semi- or entirely self-managed, and they have a limited computing capability, which might make MTC adoption difficult. While monitoring has long been touted as a viable approach for safeguarding the network and detecting breaches by a centralised body, it is not the most practical solution for dealing with the large number of MTC. As a result, focusing on making the design of security and privacy solutions for M2M communications easier by designing novel security procedures that compensate for the power consumption and processing capacity of M2M devices with restricted capacity is a difficult task.

## 8.7 Conclusion

This chapter has provided a summary of the work that was carried out, the main contributions as well as implications and applications of the research work. Directions for future work have also been presented.

References

3rd Generation Partnership Project Organizational Partners. 2011. *Evolved Universal Terrestrial Radio Access (E-UTRA) and Evolved Universal Terrestrial Radio Access Network (E-UTRAN);* Overall description; Stage 2 (3GPP TS 36.300 version 10.2.0 Release 10), Valbonne: 3GPP Organizational Partners' Publications Offices, 1-208.

3rd Generation Partnership Project Organizational Partners. 2013. *Study on Provision of Low-Cost Machine-Type Communications (MTC) User Equipment Based on LTE* (Release 12)," Valbonne: 3GPP Organizational Partners' Publications Offices, 1-55.

3rd Generation Partnership Project Organizational Partners. 2013. *Feasibility study for Proximity Services (ProSe),* 3GPP TR22.803 V12.2.0, Valbonne: 3GPP Organizational Partners' Publications Offices, 1-45.

3rd Generation Partnership Project Organizational Partners. 2013. *Technical Technical Specification Group Radio Access Network; Study on 3D channel model for LTE, 3*GPP TS 36.873 V1.3.0, Valbonne, 3GPP Organizational Partners' Publications Offices, 1-37.

3rd Generation Partnership Project Organizational Partners. 2014. *Study on LTE Device to Device Proximity Services,* 3GPP TR 22.803 V12.2.0, Valbonne: 3GPP Organizational Partners' Publications Offices, 1-50.

3rd Generation Partnership Project Organizational Partners. 2015. *Technical Specification Group Radio Access: Network; Evolved Universal Terrestrial Radio Access (E-UTRA) and Evolved Universal Terrestrial Radio Access Network (E-UTRAN),* 3GPP TS 36.300 V12.6.0, Valbonne: 3GPP Organizational Partners' Publications Offices, 1-267.

3rd Generation Partnership Project Organizational Partners. 2015. *Technical Specification Group Radio Access Network; Evolved Universal Terrestrial Radio Access (E-UTRA); Packet Data Convergence Protocol (PDCP) specification, 3*GPP TS 36.323 V12.4.0, Valbonne: 3GPP Organizational Partners' Publications Offices, 1-35.

3rd Generation Partnership Project Organizational Partners. 2015. *Technical Specification Group Radio Access Network; Evolved Universal Terrestrial Radio Access (E-UTRA); Radio Link Control (RLC) protocol specification,* 3GPP TS 36.322 V12.2.0, Valbonne: 3GPP Organizational Partners' Publications Offices, 1-43.

3rd Generation Partnership Project Organizational Partners. 2015. *Technical Specification Group Radio Access Network; Evolved Universal Terrestrial Radio Access (E-UTRA); Medium Access Control (MAC) protocol specification* 3GPP TS 36.321 V12.6.0, Valbonne: 3GPP Organizational Partners' Publications Offices, 1-79.

3rd Generation Partnership Project Organizational Partners. 2015. *Technical Specification Group Radio Access Network; Evolved Universal Terrestrial Radio Access (E-UTRA); Physical channels and modulation*, 3GPP TS 36.211 V12.6.0, Valbonne: 3GPP Organizational Partners' Publications Offices, 1-138.

3rd Generation Partnership Project Organizational Partners. 2015. *Proximity-based Services (ProSe (ProSe)*, 3GPP TS23.303 v13.4.0, Valbonne: 3GPP Organizational Partners' Publications Offices, 1-147.

3rd Generation Partnership Project Organizational Partners. 2017. *Proximity-based services (ProSe)*, 3GPP TS 23.303 V15.0.0, Valbonne: 3GPP Organizational Partners' Publications Offices, 1-130.

3rd Generation Partnership Project Organizational Partners. 2017. *Proximity-based services (ProSe)*, 3GPP TS 23.303 V15.0.0, Valbonne: 3GPP Organizational Partners' Publications Offices, 1-63.

3rd Generation Partnership Project Organizational Partners. 2020. The 5G Evolution :3GPP Releases 16-17. Valbonne : 3GPP Organizational Partners' Publications Offices, 1-54.

5G / NR LTE study notes: open loop power control and closed loop power control Available at: https://www.programmersought.com/article/30372214138/ Accessed: 24th Oct. 2020.

Adnan, M. H. and Zuriati A., Z. 2020. "Device-To-Device Communication in 5G Environment: Issues, Solutions, and Challenges," *Symmetry* 12, no. 11: 1762-1784. Available at: https://doi.org/10.3390/sym12111762 Accessed: 20 Oct. 2021.

Ahmad, A., S. 2017. Resource allocation, interference management, and mode selection in device-to-device communication: A survey. *Trans Emerging Tel Tech.* 2017; 28: e3148. Available at: https://doi.org/10.1002/ett.3148 Accessed: 22nd Oct. 2020.

Alnoman, A and Anpalagan, A. 2017. “On D2D communications for public safety applications,” in *Proceedings of the IEEE Canada International Humanitarian Technology Conference (IHTC),* 20-21 July 2017, Toronto, IEEE, 124-127, doi: 10.1109/IHTC.2017.8058172.

Al-Sakran, A., Qutqut, M.H., Almasalha, F., Hassanein, H.S., Hijjawi, M. An Overview of the Internet of Things Closed Source Operating Systems. In Proceedings of the 2018 14th International Wireless Communications Mobile Computing Conference (IWCMC), Limassol, Cyprus, 25–29 June 2018; pp. 291–297.

Alsharif, Mohammed H., Anabi H. Kelechi, Mahmoud A. Albreem, Shehzad A. Chaudhry, M. S. Zia, and Sunghwan Kim. 2020. "Sixth Generation (6G) Wireless Networks: Vision, Research Activities, Challenges and Potential Solutions" *Symmetry* 12, no. 4: 676. https://doi.org/10.3390/sym12040676

Alvarez, M. A., Soatti, G., Nicoli, M. and Spagnolini, U. 2016. “Device-todevice resource scheduling by distributed interference coordination,” in *2016 IEEE International Conference on Communications Workshops (ICC),* 23-27 May 2016, Kuala Lumpur, IEEE, pp. 505–510.

Amirteimoori, A., and Tabar, M. M. 2010. Resource allocation and target setting in data envelopment analysis. *Expert Systems with Applications*, *37*(4):3036-3039.

Ammouri, A., Andrews, J. G. and Baccelli, F. 2018. SINR and throughput of dense cellular networks with stretched exponential path loss. *IEEE Transactions on Wireless Communications*, 17(2):1147-1160.

Andrews, J. G. 2017. Interference cancellation for cellular systems: a contemporary overview. *IEEE Wireless Communications*, *12*(2):19-29.

Ansari, R. I., Hassan, S. Ali, A., Chrysostomou, C. and Lestas, M. 2017. “On the outage analysis of a d2d network with uniform node distribution in a circular region,” *Physical Communication*, pp. 277-283.

Ansari, R.I., Chrysostomou, C., Hassan, S.A., Guizani, M., Mumtaz, S., Rodriguez, J., & Rodrigues, J.J. 2018. 5G D2D Networks: Techniques, Challenges, and Future Prospects. *IEEE Systems Journal*, (12):3970-3984.

Asadi, A. and Wang, Q. 2014. A survey on Device-to-Device communication in cellular networks. *IEEE Communications and Tutorials*, 16(4):1801-1819. Available at: https://telecoms.com/495666/almost-one-zettabyte-of-mobile-data-traffic-in-2022-cisco/ Accessed on 24th Oct. 2020.

Ayach, O. E., Peters, S. W. and Heath, R. W. 2013. “The practical challenges of interference alignment,” *IEEE Wireless Commun*., 20(1):35–42.

Bagheri, H., Sartori, P., Desai, V., Classon, B., Al-Shalash, M. and Soong, A. “Device-to-device proximity discovery for LTE systems,” in *IEEE International Conference on Communication Workshop*, 591–595, 8-12 Jun. 2015, London.

Ban T.W, Lee W. 2019. A Deep Learning Based Transmission Algorithm for Mobile Device-to-Device Networks. *Electronics*. 8(11):1-12.

Beard, C. and Stalling, W. 2016. *Wireless Communication Networks and Systems*. 1st ed. Essex: Pearson.

Biswash, S.K., Ziviani, A., Jain, R. *et al.* 2017. Editorial: Device-to-Device Communication in 5G Networks. *Mobile Netw Appl* 22**:**995–997.

Bouras, C., Diles, G., Kokkinos, V. 2014. A Simulation Framework for Evaluating Interference Mitigation Techniques in Heterogeneous Cellular Environments. *Wireless Pers. Commun* **77,** 1213–1237 (2014). https://doi.org/10.1007/s11277-013-1562-5.

Brijesh K. 2020. Challenges of WSNs in IoT, Wireless Sensor Networks - Design, Deployment and Applications, Siva S. Yellampalli, IntechOpen, DOI: 10.5772/intechopen.95352. Available from: https://www.intechopen.com/chapters/74540 Accessed: 22 Oct. 2021.

Buzzi, S., Klein, C. L. I, T. E., Poor, H. V. Yang, C. and Zappone, A. A. 2016. A survey of energy-efficient techniques for 5G networks and challenges ahead. *IEEE Journal on Selected Areas in Communications*, 34(4):697–709.

Cai, X., Zheng, J. and Zhang, Y. 2015. “A Graph colouring-based resource allocation algorithm for D2D communication in cellular networks,” in *Proceedings of the IEEE International Conference on Communications (ICC)*, London, 8-12 Jun. 2015, 5429-5434.

Câmara, D. and Nikaein, N. 2015. *Wireless Public Safety Networks Volume 1: Overview and Challenges*. Elsevier Science, Amsterdam.

Candès, E. J. and Recht, B. 2009. Exact matrix completion via convex optimization," *Foundations of Computational mathematics*, 9, (6): 717.

Chaaban, A. and Sezgin, A. 2015. “Device relaying in Cellular Device-to-Device networks: A fairness perspective,” in *Proceedings of the 10th International Conference on Cognitive Radio Oriented Wireless Networks (CROWNCOM)*, Doha, 21-23 Apr. 2015, Doha, Springer, 654-695.

Chang, R. Y., Tao, Z., Zhang, J. and Kuo, C. C. J. 2019. A Graph Approach to Dynamic Fractional Frequency Reuse (FFR) in Multi-Cell OFDMA Networks. In *ICC*, Vol. 9:3993-3998.

Charar, M. A., Guennoun, Z. and Aniba, G. 2015. "Achieving energy efficiency for Device-to-Device communications using power control: A low complexity algorithm," in *Proceedings of the 10 th International Conference on Intelligent Systems: Theories and Applications (SITA*), Rabat, 20-21 Oct. 2015, 1-6.

Chaudhari S. and Prashant K. 2017. Joint mode selection and power control scheme for interference alleviation in device-to-device communications. *International Journal of Electronics, Electrical and Computational System.* 6(3):136-141.

Chen, J., Qian, Z., Wang, T. and Li, X. 2017. Modelling and simulation of IMT-2020 (5G) systems and satellite communication systems based on OPNET network simulation technology," in *Proceedings of the 3rd IEEE International Conference on Computer and Communications (ICCC)*, 13-16 Dec. 2017, Chengdu, IEEE, 920-924.

Cicalo, S., Tralli, V., and Perez-Neira, A. I. 2011. Centralized vs distributed resource allocation in multi-cell OFDMA systems, in *Vehicular Technology Conference (VTC Spring)*, 15-18 May **2011,** Budapest Marriott, IEEE, pp. 1-6.

Cintron, F., Griffith, D., Liu, C., Rouil, R., Sun, Y., Wang, J., Liu, P., Shen, C., Ben, A. and Gamboa, S. 2021. Study of 5G New Radio (NR) Support for Direct Mode Communications, NIST Interagency/Internal Report (NISTIR), National Institute of Standards and Technology, Gaithersburg, MD, Available at: https://doi.org/10.6028/NIST.IR.8372,
communications; functional prospects for LTE-advanced networks," in Proceedings *of the International Conference on Communications Workshops,* 14-18 Jun 2010, Dresden, IEEE, 1-6.

Conceição, F., Gomes, M., Silva, V., Dinis, R., Silva, A., Castanheira, D. 2020. 'A Survey of Candidate Waveforms for beyond 5G Systems', *Electronics*, 10(1): 1-26. Available: http://dx.doi.org/10.3390/electronics10010021. Accessed: 20 Oct. 2021.

Coupechoux, M. and Kélif, J. 2011. *How to Set the Fractional Power Control Compensation Factor in LTE?* IEEE Sarnoff Symposium, May 2011, Princeton, 1-5.

Das, S., Viswanathan, H., and Rittenhouse, G. 2013. Dynamic load balancing through coordinated scheduling in packet data systems, in *INFOCOM 2003. Twenty-Second Annual Joint Conference of the IEEE Computer and Communications. IEEE Societies,* 30 Mar. to Apr. 3, 2003, San Francisco, IEEE, Vol. 1, pp. 786-796).

Davis R.C. 2014. Preventing of terror at shopping malls. In: Bruinsma G., Weisburd D. (eds) Encyclopaedia of Criminology and Criminal Justice. New York: Springer.

Demóstenes Z. Rosa, R. L., Nunes R., D. and Affonso E, T., International Journal of Digital Information and Wireless Communications (IJDIWC) 6(4): 241-259 The Society of Digital Information and Wireless Communications, 2016 *(PDF) Assessment of Quality-of-Experience in Telecommunication Services*. Available at: https://www.researchgate.net/publication/309493443_Assessment_of_Quality-of-Experience_in_Telecommunication_Services Accessed: 13 Sep. 2019.

Doppler, K., Rinne, M. P., Janis, P., Ribeiro, C. and Hugl, K. 2009. "Device-to-device

Doppler, K., Rinne, M., Wijting, C., Ribeiro, C. B. and Hugl, K. 2009. Device-to-Device Communication as an Underlay to LTE-Advanced Networks. *IEEE Communications Magazine*, 47(12):42-49.

Doppler, K., Wijting, C., and Valkealahti, K. 2009. Interference aware scheduling for soft frequency reuse, in *Vehicular Technology Conference, VTC Spring 2009. IEEE 69th*, 26-29 April 2009, Barcelona, IEEE, pp. 1-5.

Duong, Q. and Shin, O., 2013. "Distance-based interference coordination for device-to-device communications in cellular networks," in *Proceedings of the Fifth International Conference on Ubiquitous and Future Networks (ICUFN)*, 2-5 July, Da Nang, 776-779.

ElSawy, H. and Hossain, E. 2017. Analytical modelling of mode selection and power control for underlay D2D communication in cellular networks. *IEEE Transactions on Communications*, 2:1-7.

ElSawy, H., Hossain, E. and Haenggi, M. 2013. Stochastic geometry for modelling, analysis, and design of multi-tier and cognitive cellular wireless networks: A Survey. *IEEE communications surveys & tutorials,* 15(3):996-1019.

Energy-efficient transmission in heterogeneous wireless networks: A delay-aware approach. *IEEE Transactions on Vehicular Technology*, 65(9):7488–7500.

Ericsson. 2014. 5G radio access. Stockholm: Ewaldsson.

Evans, D. 2011. The Internet of Things: How the Next Evolution of the Internet Is Changing Everything Available at: http://www.cisco.com/web/about/ac79/docs/innov/IoT_IBSG_0411FINAL.pdf Accessed: 20 Oct. 2019.

Fan, Z., Gu, X., Nie, S., Chen, M. 2017. D2D power control based on supervised and unsupervised learning. In *The 3rd IEEE International Conference on Computer and Communications (ICCC),* Chengdu, 13-16 Dec.2017, 558–563.

Farhana A., Ramprasad S., Roshanak H., Kumbesan S. and Solaiman A. 2015. SINR, RSRP, RSSI and RSRQ measurements in Long Term Evolution networks. *International Journal of Wireless & Mobile Networks (IJWMN)*, 7(4):1-11.

Feng, J. 2014. *Device-to-Device Communications in LTE-Advanced Network.* PhD. University of Brittany.

Finn, D. 2015. *Enhanced Multi-Antenna Capabilities through Small Cell Collaboration.* PhD. University of Dublin.

Fodor, G., Parkvall, S., Sorrentino, S., Wallentin, P., Lu, Q., & Brahmi, N. 2014. Device-to-Device Communications for National Security and Public Safety. *IEEE Access, 2*, 1510-1520.

Fodor, G., Penda, D. D., Belleschi, M., Johansson, M., and Abrardo, A. 2013. A comparative study of power control approaches for device-to-device communications. In *Proceedings of the 2013 IEEE International Conference on Communications (ICC)* Budapest: IEEE, 6008-6013.

Gamal, A. E, Mammen, J., Prabhakar, B. and D. Shah, 2006. Optimal throughput-delay scaling in wireless networks part I: The fluid model, *IEEE Transactions on Information Theory*, (52):2568-2592.

Gandotra, P., Jha, R. K., Jain, S. 2018. Green NOMA with multiple interference cancellation (MIC) using sector-based resource allocation. *IEEE Trans. Netw. Serv. Manag*, 15:1006–1017.

Gandotra, P., Jha, R., K. and Jain, S. 2017. A survey on device-to-device (D2D) communication. *J. Netw. Comput. Appl. 78, 9–29. DOI:* https://doi.org/10.1016/j.jnca.2016.11.002

Ghazanfari, S. A. A. Rajatheva, N. and Latva-aho, M. 2014. “Effect of residual of self-interference in performance of full-duplex D2D communication,” in *5G for Ubiquitous Connectivity (5GU), 2014 1st International Conference on*, 8-8 Nov. 2014, Semarang, IEEE, pp. 46–51.

Giatsoglou, A., Antonopoulos, A., Kartsakli, E., Vardakas, J. and Verikoukis, C. 2016. “Transmission policies for interference management in full-duplex d2d communication,” in *Global Communications Conference (GLOBECOM), 2016 IEEE*. 4-8 Dec. 2016, Washington DC, pp. 1–6.

Gillman, L. 2021. Is Matlab a high-level language? *Comu-Success, Available at: https://www.compsuccess.com/is-matlab-a-high-level-language/* Accessed on: 20.10.2021.

Guo, G., Sun, S. and Gao, Q. 2014. Graph-Based Resource Allocation for D2D Communications Underlying Cellular Networks in Multiuser Scenario. *International Journal of Antennas and Propagation*, 2014:1-27.

Hakola, S., Chen, T., Lehtomaki, J. and Koskela, T., 2010. “Device-to-device communication in cellular networks: Performance analysis of optimum and practical communication mode selection,” in *Proceedings of the IEEE Wireless Communication and Networking Conference*, 18-21 Apr. 2010, Sydney, IEEE, 1-6.

Hamoud, O. N., Kenaza, T., and Challal, Y. 2017. Security in Device-to-Device communications (D2D): a survey. *IET Networks*, 7(1)14-22.

Hamza, A. S., Khalifa, S. S., Hamza, H. S., and Elsayed, K. 2013. A survey on inter-cell interference coordination techniques in OFDMA-based cellular networks. *IEEE Communications Surveys & Tutorials*, *15*(4):1642-1670.

Han, S., Chen, P. and Yang, C. 2014. “Full duplex assisted interference suppression for underlay device-to-device communications,” in *2014*

Hashima, S., ElHalawany, B.M., Hatano, K., Wu, K., and Mohamed, E.M. 2021. Leveraging Machine-Learning for D2D Communications in 5G/Beyond 5G Networks. *Electronics*, *10*(2):1-16.

He, R. and Ding, Z. 2019. Applications of Machine Learning in Wireless Communications; IET, London.

Hongnian, X. and Hakola, S. 2010. The investigation of power control schemes for a device-to-device communication integrated into OFDMA cellular system. in

Proceedings *of the 21st Annual IEEE International Symposium on Personal, Indoor and Mobile Radio Communications* Istanbul: IEEE, 1775-1780.

Hossain, M. F. 2013. *Traffic-driven energy efficient operational mechanisms in cellular access networks.* PhD. The University of Sydney.

Hou, G. and Chen, L. 2020. D2D communication mode selection and resource allocation in 5G wireless networks, *Computer Communications*, Vo.155(2020): 244-251.

Hou, W., Li, S., Sun, Y., Zhou, J., Yun, X. and Lu, N., 2019. Interference-Aware Subcarrier Allocation for Massive Machine-Type Communication in 5G-Enabled Internet of Things. *Sensors*, 19(20):4530-4543.

Höyhtyä, M., Apilo, O. and Lasanen, M., 2018. Review of Latest Advances in 3GPP Standardization: D2D Communication in 5G Systems and Its Energy Consumption Models. *Future Internet*, 10(1):1-18. Available at: http://dx.doi.org/10.3390/fi10010003. Accessed: 10 Aug. 2018.

Hu, L. and Yuan, C. 2015. "Beamforming and Interference Cancellation in D2D Random Network", *International Journal of Antennas and Propagation*, 2015(1-12):607563-607574. Available at: https://doi.org/10.1155/2015/607563 Accessed: 30 Sept. 2021.

Hu, R. and Qian, Y. 2013. *Heterogeneous cellular networks*, West Sussex: John Wiley & Sons.

Huang, J., Zhao, Y. and Sohraby, K. 2014. Resource allocation for intercell device-to-device communication underlaying cellular network: A game-theoretic approach. In *Proceedings of the 2014 23rd International Conference on Computer Communication and Networks (ICCCN)*, Shanghai: IEEE, 1-8.

Huawei Technologies. 2017. 5G Spectrum Public Policy Position. Shenzhen. Huawei Technologies.

*IEEE Globecom Workshops (GC Wkshps).* IEEE, 8-12 Dec. 2014, Austin, IEEE, pp. 851–856.

Institute of Electrical and Electronics Engineers. 2007. *multi-hop relay system evaluation methodology (channel model and performance metric)*. IEEE C802.16j-06/013r3. New York: IEEE.

International Telecommunication Union. 2009. *Guidelines for evaluation of radio interface technologies for IMT-Advanced*, Rep. ITU-R M.2135-1, Geneva, ITU, 1-72.

Iswarya, N. and Jayashree, L. S. 2021. A Survey on Successive Interference Cancellation Schemes in Non-Orthogonal Multiple Access for Future Radio Access, 2021(2):1057-1059.

Jafar, S. A. 2014. Topological interference management through index coding," *IEEE Transactions on Information Theory*, 60(1):529-568.

Jameel, F., Hamid, Z, Jabeen, F., Zeadally S. and M. A. Javed. 2018. "A Survey of Device-to-Device Communications: Research Issues and Challenges," in *IEEE Communications Surveys & Tutorials*, 20(3):2133-2168.

Janis, P., Yu, C. H., Doppler, K., Rebeiro, C. Wijting, C., Hugl, K., Tirkkonen, O. and Koivunen, O. 2009. Device-to-Device communication underlaying cellular communication. *International Journal of Communications, Networks and System Sciences*, 2(3):169-179.

Jiming, C., Peng, W., and Jie, Z. 2013. Adaptive soft frequency reuse scheme for in-building dense femtocell networks. *China Communications*, *10*(1): 44-55.

Kang, S. H. and Kim, J. G., 2017. Power Control Performance Evaluation for Efficiency in D2D Cellular Network. *International Journal of Applied Engineering Research*, 12(20):9924-9930.

Kar, U. N., Sanyal, D. K. 2018. An overview of device-to-device communication in cellular networks, ICT Express, 4(4):203-208.

Kar, U., N., and Sanyal, D. K. 2018. An overview of device-to-device communication in cellular networks, *ICT Express*, 4(4):203-208, Available at: https://doi.org/10.1016/j.icte.2017.08.002. Accessed on 22 Oct. 2020.

Khan, F. 2019. *LTE for 5G mobile broadband: air interface technologies and performance*. Cambridge University Press, London.

Kim, J. Karim, N. A. and Cho, S. 2017. An interference mitigation scheme of device-to-device communications for sensor networks underlaying LTE-A. *Sensors2017*, 17(1):1-18.

Kim, J., Park, J., Noh, J., Cho, S. 2020. "Autonomous Power Allocation Based on Distributed Deep Learning for Device-to-Device Communication Underlaying Cellular Network," in *IEEE Access*, vol. 8:107853-107864

Kizilirmak, R.C. 2016. Non-Orthogonal Multiple Access (NOMA) for 5G Networks.

Koutsopoulos, I. and Tassiulas, L., 2002. "Adaptive resource allocation in SDMA-based wireless broadband networks with OFDM signalling," in *Proceedings Twenty-First Annual Joint Conference of the IEEE Computer and*

*Communications Societies*, New York, NY, USA, 23-27 Jun. 2002, IEEE, 1376-1385.

Kumbhar, F.H., Roy, A. and Saxena, N. 2017. Convergence of WSN and cognitive cellular network using maximum frequency reuse. *IET Commun., 11*, 664-672.

Lai, W. K., Chin-Shiuh., Fu-Sheng C., Chia-Yu H., and Meng-Han S. 2020. “Handover Management for D2D Communication in 5G Networks” *Applied Sciences* 10, no. 12: 4409.

Lee, J. Andrews, J., and Hong, D. “Spectrum-sharing transmission capacity with interference cancellation*,” IEEE Transactions on Communications,* 61(1)76–86.

Lee, N., Lin, X., Andrews, J. G., and Heath, R. W. 2015. Power control for D2D underlaid cellular networks: Modelling, algorithms, and analysis. *IEEE Journal on Selected Areas in Communications*. 33(1):1-13.

Lei, L., Zhong, Z. Lin, C., and X. Shen, X. 2012. “Operator controlled device-to-device communications in lte-advanced networks.” *IEEE Wireless Communications*, vol. 19, 96–104.

Leyton-Brown, K. and Shoham, Y. 2008. *Essentials of Game Theory (2nd* ed.). Oregon State: Morgan & Claypool.

Li, J. Lei, G. Manogaran, G. Mastorakis, G. and Mavromoustakis, C. X. 2019. ‘‘D2D communication mode selection and resource optimization algorithm with optimal throughput in 5G network,’’ IEEE Access, vol. 7:25263–25273.

Li, Y., Shi, Y., Sheng, M., Wang, C. X., Li, J., Wang, X. and Zhang, Y. 2016.

Li, Y., Su, S. and Chen, S. 2015. Social-aware resource allocation for device-to-device communications underlaying cellular networks. *IEEE Wireless Communications Letters*, 4(3):293-296.

Li, Z., Chen, J., Zhen, L., Cui, S., Shin, K. G. and Liu, J. 2019. "Coordinated Multi-Point Transmissions Based on Interference Alignment and Neutralization," in *IEEE Transactions on Wireless Communications*, 18(7):3347-3365.

Li, Z., Guo, C. "A Multi-Agent Deep Reinforcement Learning Based Spectrum Allocation Framework for D2D Communications," *2019 IEEE Global Communications Conference (GLOBECOM)*, from 9 -13 December 2019, Hawaii, pp. 1-6, doi: 10.1109/GLOBECOM38437.2019.9013763.

Liang, L. Li, G. Y., and Xu, W. “Resource Allocation for D2D-Enabled Vehicular Communications,” *IEEE Transactions on Communications*, 65:3186–3197.

Lin Z., Song H, Pan, D. 2019. A Joint Power and Channel Scheduling Scheme for Underlay D2D Communications in the Cellular Network. *Sensors (Basel)*, 19(21):4799-4811.

Lin, Y., D., and Hsu, Y. C. 2000. Multi-hop Cellular: A new architecture for wireless communications. In *Proceedings of IEEE INFOCOM,* Tel Aviv, 26-30 Mar. 2000 IEEE, 1273-1282.

Liu, J., Kato, N., Ma, J. and Kadowaki, N. 2015. "Device-to-Device Communication in LTE-Advanced Networks: A Survey," *IEEE Commun. Surv. Tutorials*, 17(4):1923–1940.

Liu, J., Kawamoto, Y., Nishiyama, H., Kato, N., & Kadowaki, N. 2014. Device-to-device communications achieve efficient load balancing in LTE-advanced networks. *IEEE Wireless Communications, 21*, 57-65.

Liu, J., Wang, D., Pang, J., Wang, J., and Shen, G. 2016. Inter-cell interference coordination based on soft frequency reuse for relay enhanced cellular network in *Personal Indoor and Mobile Radio Communications (PIMRC), 2016 IEEE 21st International Symposium on,* 4-7 Sep. 2016, Valencia, IEEE, pp. 2304-2308.

Lopez-Perez, D., Guvenc, I., Roche, G., Kountouris, M., Quek, T. Q. S., and Zhang, J. 2011. "Enhanced intercell interference coordination challenges in heterogeneous networks," *IEEE Wireless Commun.*, 18(3):22–30.

López-Pérez, D., Valcarce, A., De La Roche, G., and Zhang, J. 2009. OFDMA femtocells: A roadmap on interference avoidance. *IEEE Communications Magazine*, *47*(9):41-48.

Lucas-Estañ, M. C. and Gozalvez, J. 2017. Distributed radio resource allocation for device-to-device communications underlaying cellular networks, *Journal of Network and Computer Applications,* 99(2017):120-130.

Ma, C., Wu, W., Cui, Y., & Wang, X. (2015). On the performance of successive interference cancellation in D2D-enabled cellular networks. *2015 IEEE Conference on Computer Communications (INFOCOM)*, 26 Apr. - 1 May - Hong Kong, pp. 37-45.

Malik, P.K., Wadhwa, D.S. and Khinda, J.S. 2020. A Survey of Device to Device and Cooperative Communication for the Future Cellular Networks. *Int J Wireless Inf Networks* **27,** 411–432.

Mandeep, K. and Amandeep, K. 2015. Cognitive Radio Spectrum Sharing Techniques: A Review, *International Journal of Computer Science and Information Technologies*, 6(3):3089-3091.

Maraj, U., Ahmed, S., Faizan, Q., Faisal, A., Quang, N. N., Rosilah, H. 2021. Interference management in 5G and beyond network: requirements, challenges, and future directions. *IEEE Access (IF3.367)*, DOI: 10.1109/access.2021.3073543 2021: 68932-68965).

Marsch, P and Fettweis, G. 2011. "Uplink CoMP under a constrained backhaul and imperfect channel knowledge," *IEEE Trans. Wireless Commun.*, 10(6): 1730–1742.

Masroor, R., Abrar, M. and Gui, X. 2017. Device-to-device communication: Interference management perspective, *Technical Journal University of Engineering and Technology (UET) Taxila*, 22(2):1-13.

Matyjaszek, H. 2021. 'The Energy Impact of Mobile Phones,' *Energy Live News, 3 Jun. 2021*. Available at: https://www.energylivenews.com/2021/06/03/the-energy-impact-of-mobile-phones/ Accessd: 10 Nov. 2021.

Mcdermott. J., 2016. Professor designs explosives detector to rival a dog's nose. Available at: https://phys.org/news/2016-02-professor-explosives-detector-rival-dog.html Accessed: 12 Sep. 2018.

Meng, Z., Wu, Z. and Gray, J., 2017. A Collaboration-Oriented M2M Messaging Mechanism for the Collaborative Automation between Machines in Future Industrial Networks. Sensors, 17(11), p.2694. Available at: http://dx.doi.org/10.3390/s17112694 Accessed: 12 Oct. 2021.

Militano, L., Araniti, G., Condoluci, M., Farris, I. and Iera, A. 2015. Device-to-device communications for 5G Internet of Things. *EAI Endorsed Transactions on Internet of Things*. 1(4):1-16.

Mittal K. Pedhadiya, Rakesh K., J., Hetal G. B. 2019. Device to device communication: A survey, *Journal of Network and Computer Applications*, 129,71-89,

Mumtaz, S., Huq, K. M. S. and Rodriguez, J. 2014. "Coordinated paradigm for d2d communications," in *Computer Communications Workshops\ (INFOCOM WKSHPS), 2014 IEEE Conference on*. 27 April - 2 May 2014, Toronto, IEEE, pp. 718–723.

Mwashita, W. 2019. Wernhill Park, Central Windhoek, Namibia. (Weston Mwashita's private collection).

Mwashita, W. and Odhiambo, M. O. 2018. "Interference management techniques for device-to-device communications," in *Predictive Intelligence Using Big Data and the Internet of Things*. P.K. Gupta, Ed. Hershey: IGI Global, 219-245.

Navaratnarajah, S., Saeed, A., Dianati, M., & Imran, M. A. 2013. Energy efficiency in heterogeneous wireless access networks. *IEEE Wireless Communications*, *20*(5):37-43.

Nitti, M., Stelea, G. A., Popescu, V., & Fadda, M. 2019. When Social Networks Meet D2D Communications: A Survey. *Sensors (Basel, Switzerland)*, *19*(2), 396.

Nouran, M. and Nordin, R. 2016. A survey on interference management for Device-to-Device (D2D) communication and its challenges in 5G networks. *Journal of Network and Computer Applications*, 71:130-150.

Novlan, T., Dhillon, H. and Andrews, J. 2013. "Analytical modeling of uplink cellular networks," *Wireless Communications, IEEE Transactions on*, vol. (12)6:2669‑2679.

Nurmela, V. and Kyosti, P. 2014. "A spatially consistent radio channel model enabling dual mobility," *2014 IEEE 80th Vehicular Technology Conference (VTC2014-Fall)*, 14–17 September 2014, Vancouver. pp 1-5.

Orsino, A., Araniti, G., Militano, L., Alonso-Zarate, J., Molinaro, A., and Iera, A. 2016. Energy Efficient IoT Data Collection in Smart Cities Exploiting D2D Communications. *Sensors (Basel, Switzerland)*, *16*(6), 836. Available at: https://doi.org/10.3390/s16060836 (1-19). Accesssed on 23 Oct. 2021.

Panaitopol, D., Mouton, C., Lecroart, B., Lair, Y. and Delahaye, P. 2015. Recent Advances in 3GPP Rel-12 Standardization related to D2D and Public Safety Communications. *ArXiv, abs/1505.07140*, 1-8.

Park S. and Choi, S. 2015. "Semi-Distributed Resource Selection for D2D Communication in LTE-A Network," *2015 IEEE Global Communications Conference (GLOBECOM)*, 6-10 December 2015, San Diego, pp. 1-6, IEEE. doi: 10.1109/GLOCOM.2015.7417617.

Park, J., 2019. Advances in Future Internet and the Industrial Internet of Things. *Symmetry*, 11(2), p.244. Available at: http://dx.doi.org/10.3390/sym11020244. Accessed: 12 Oct. 2021.

Patel, P. 2010. An Ultrasensitive Explosives Detector: Nanowire arrays are a thousand times more sensitive than dog noses at sniffing out explosives. Available at: https://www.technologyreview.com/s/420882/an-ultrasensitive-explosives-detector/ Accessed: 10 Sep. 2018.

Pedersen, K. I. Wang, Y. Strzyz, S. and F. Frederiksen, 2013. "Enhanced inter-cell interference coordination in co-channel multi-layer LTE-advanced networks," IEEE Wireless Commun., vol. 20, no. 3:120–127.

Penda, D. D. 2018, "Device-to-Device Communication in Future Cellular Networks: Resource allocation and mode selection," Doctoral Thesis, KTH Royal Institute of Technology, Stockholm.

Peng, T., Lu, Q., Wang, W., Wang, H. and Xu, S. 2009. "Interference avoidance mechanisms in the hybrid cellular and device-to-device system," in *the Proceedings of the IEEE 20th International Symposium on Personal, Indoor and Mobile Radio Communication*, Tokyo, 13-16 Sep. 2009, IEEE, 2385-2389.

Peterson, L. L. and Davie, B. S. 1996. Computer Networks: A systems approach. *Morgan Kaufmann*, pp. 94-95. ISBN: 1-55860-368-9.

Piro, G., Baldo, N. and Miozzo, M. 2011. "An LTE module for the ns-3 network simulator," in *International ICST Conference on Simulation Tools and Techniques (SIMUTools),* 21-25 March 2011, Barcelona, 415-422.

Porambage, P., Heikkinen, A., Harjula, E., Gurtov, A., Ylianttila, M. 2016. Quantitative Power Consumption Analysis of a Multi-tier Wireless Multimedia Sensor Network. *In Proceedings of the 22nd European Wireless Conference,* Oulu, 18–20 May 2016; pp. 1–6.

Porjazoski, M. and Popovski, B. 2010. Analysis of intercell interference coordination by fractional frequency reuse in LTE, in *SoftCOM 2010, 18th International Conference on Software, Telecommunications and Computer Networks*, 23-25 Sept. 2010, Dubrovnik, IEEE, pp 160-164.

Prasad, A., Moya, F. S., Ericson, M. Fantini, R. and Bulakci, O. 2016. "Enabling RAN Moderation and Dynamic Traffic Steering in 5G," in *Proceedings of the 84th Vehicular Technology Conference*, VTC-Fall, 18-21 Sep. 2016, VTC-Fall, IEEE, 1-6.

Pratas, N. K. and Popovski, P. 2014. "Underlay of low-rate machine-type D2D links on downlink cellular links," *2014 IEEE International Conference on Communications Workshops (ICC),* 10-14 June 2014, Sydney, 423-428.

Rahi, K. D. and Hasan, Y., M. 2020. Utilizing Device to Device Communication in Cellular Networks with the distance-based model selection method Published in *The International Conference on Engineering and Advanced Technology (ICEAT 2020)* 11-12 Feb. 2020, Assiut.

Ramasamy, K. and Medhi, D. 2017. Network Routing: Algorithms, Protocols, and Architectures. San Francisco: Morgan Kaufmann.

Rappaport, T. S., Xing, Y., MacCartney, G. R., Molisch, A. F., Mellios E. and Zhang, J. 2017. Overview of millimeter wave communications for fifth generation (5G) wireless networks—With a focus on propagation models. *IEEE Transactions on Antennas and Propagation*, 65(12):6213-6230.

RF Wireless World, *Difference between open loop power control vs closed loop power control.* Available at : https://www.rfwireless-world.com/Terminology/Open-Loop-Power-Control-vs-Closed-Loop-Power-Control.html Accessed: 16 Aug. 2018.

Rodziewicz, M. 2015. "Location-based mode selection and resource allocation in cellular networks with D2D underlay," in *Proceedings of European Wireless 2015; 21st European Wireless Conference*, Budapest, 20-22 May 2015, 1-6.

Rupp, M., Schwarz, S. and Taranetz, M. 2016. *The Vienna LTE-Advanced Simulators: Up and Downlink, Link and System Level Simulation (Signals and Communication Technology).* 1st ed. New York: Springer.

Safdar, G. A., Ur-Rehman, M., Muhammad, M., Imran, M. A., and Tafazolli, R. 2016. Interference Mitigation in D2D Communication Underlaying LTE-A Network. *IEEE Access*, 4:7967-7987.

Salam, D., Mohamad A., Hassan A. A. 2019. A Framework of Topological Interference Management and Clustering for D2D Networks. *IEEE Transactions on Communications*, Institute of Electrical and Electronics Engineers, 67 (11):7856-7871.

Santana, T.V., Combes, R., & Kobayashi, M. 2018. Device-to-Device Aided Multicasting. *2018 IEEE International Symposium on Information Theory (ISIT)*, 771-775.

Saranya, J. and Selvakumar, J. 2013. "Implementation of children tracking system on android mobile terminals," in *Proceedings of the International Conference on Communications and Signal Processing (ICCSP)*, 3-5 April 2013, Melmaruvathur, IEEE, 961-965.

Sawahashi, M., Higuchi, K., Andoh, H. and Adachi, F. 2016. Experiments on pilot symbol-assisted coherent multistage interference canceller for DS-CDMA mobile radio. *IEEE Journal on Selected Areas in Communications*, *20*(2):433-449.

Schlienz, J. and Roessler, A. 2015. Device to device communication in LTE. *Rohde & Schwarz,* 1-36.

Schlienz, J. and Roessler, A., 2015. *Device to device communication in LTE.* Munich: Rohde & Schwarz, 1-36.

Segura, D., Khatib, E.J., Munilla, J. and Barco, R. 2021. 5G Numerologies Assessment for URLLC in Industrial Communications. *Sensors*. 21 (7): 1-11. Available from: http://dx.doi.org/10.3390/s21072489. Accessed: 12 Oct. 2021.

Sesia, S., Toufik, I., and Baker, M. 2011. *LTE-The UMTS Long Term Evolution: From theory to practice*, London: John Wiley & Sons Ltd.

Shah, S. T., Gu, J., Hasan, S. F. and Chung, M. Y. 2015. SC-FDMA-based resource allocation and power control scheme for D2D communication using LTE-A uplink resource. *EURASIP Journal on Wireless Communications and Networking*, 2015(1):137-152.

Shamrao, C. and Kumar, P. 2017. “Interference mitigation by switching the underlaying transmitter in D2D communications,” in *Proceedings of the 2017 Innovations in Power and Advanced Computing Technologies (i-PACT2017),* 21-22 Apr. 2017, Vellore, 1-6.

Shi, W. 2019. Almost one zettabyte of mobile data traffic in 2022.

Shuang, W. and Ronghui, H. 2017. Network coding-based interference management scheme in D2D communications. *ZTE Communications*, 15(2):48-54.

Singh, A. P., Luhach, A. K., Gao, X.-Z., Kumar, S., and Roy, D. S. 2020. ‘Evolution of wireless sensor network design from technology centric to user centric: An architectural perspective’, *International Journal of Distributed Sensor Networks*. (1-24),

Son, K., Lee, S., Yi, Y. and Chong, S. 2011. “REFIM: a practical interference management in heterogeneous wireless access networks," *IEEE Journal on Selected Areas in Communications*, 29(6): 1260-1272.

Song, L., Niyato, D., Han, Z. and Hossain, E. 2015. *Wireless Device-to-Device Communications and Networks.* New York: Cambridge University Press.

Stefansdottir, B. and Grunow, M. 2018. Selecting new product designs and processing technologies under uncertainty: Two-stage stochastic model and application to a food supply chain, *International Journal of Production Economics*, 201:89-101.

Sun, S., Gao, Q., Peng, Y. Wang, Y., and Song, L. 2013. "Interference management through CoMP in 3GPP LTE-advanced networks," *IEEE Wireless Commun.* 20(1): 59–66.

Swain, Anita; Ray, Árun Kumar. 2020. A Survey on WSN and MCN Convergence Networks. *Journal of Telecommunications and Information Technology;* 1(2020): 39-49. DOI:10.26636/jtit.2020.137619

Tao, Y., Sun, J. and Shao, S. 2013. "Radio resource allocation based ongreedy algorithm and successive interference cancellation in deviceto-device (D2D) communication," in *Information and Communications Technologies (IETICT 2013), IET International Conference on.* 27th -29th Apr. 2013, Beijing, IET, pp. 452–458.

Techradar, 2021. 10 tips to better your smartphone battery life. Available at: https://www.techradar.com/news/10-tips-to-better-your-smartphone-battery-life Accessed: 10 Nov. 2021.

Tehrani, M. N., Uysal, M. and Yanikomeroglu, H. 2014. Device-to-Device communications in 5G networks: Challenges, solutions, and future directions. *IEEE Communications Magazine*, 52(5):86-92.

The 5G Infrastructure Public Private Partnership (5G PPP). The next generation of communication networks and services. Available at: http://superfluidity.eu/wp-content/uploads/5GPPP-brochure-draft02.pdf Accessed: 15 Oct. 2017.

The National Counter Terrorism Security Office. 2017. Crowded places guidance. London: NACTSO Crown.

Tranter, W. H., Shanmugan, K. S., Rappaport, T. S. and Kosbar, K. L. 2003. *Principles of Communication Systems Simulation with Wireless Applications.* Prentice Hal: New Jersey.

Trifunovic, S. Hossmann-Picu, A. and Hossmann, T. 2013. Fair and efficient energy usage in opportunistic D2D group communication via Time-Adaptive-Topology-Aware Role Switching. *IEEE Transactions on Mobile Computing*, 6(6):606-620.

Usman, M., Jan, M., He, X.S., Nanda, P. 2016. Data Sharing in Secure Multimedia Wireless Sensor Networks. In *Proceedings of the IEEE Trustcom/Big Data SE/ISPA,* Tianjin, 23–26 Aug. 2016; pp. 590–597.

Vanimireddy, A and Kumari, D. A. 2012. Detection of explosives using Wireless Sensor Networks. *Engineering International Journal of Trends and Technology*," 3(3):277-280.

Vannithamby, R. and Talwar, S. 2017. *Towards 5G: Applications, Requirements and Candidate Technologies*. Wiley, New Jersey.

Veeravalli, V. V. and El Gamal, A. 2018. Interference Management in Wireless Networks: Fundamental Bounds and the Role of Cooperation. Cambridge University Press.

Vienna University of Technology. 2010. LTE Link Level Simulator Documentation, v1.3r620. Vienna, Vienna University of Technology.

Viering, I., Klein, A., Ivrlac, M., Castaneda, M., and Nossek, J. A. 2006. On uplink intercell interference in a cellular system. In *Communications, 2006. ICC'06. IEEE International Conference on* Vol. 5:2095-2100. IEEE.

Vo, N., Duong, T.Q., Tuan, H.D., and Kortun, A. 2018. Optimal Video Streaming in Dense 5G Networks with D2D Communications. *IEEE Access*, *6*, 209-223.

Wang, J., Zhu, D., Zhao, C., James C. F. and Ming L. 2013. Resource Sharing of Underlaying Device-to-Device and Uplink Cellular Communications 17(6):1148-1151.

Wang, L., Liu, L., Cao, X., Tian, X., and Cheng, Y. 2015. Sociality-aware resource allocation for device-to-device communications in cellular networks, *IET Communications*, 9(3):342-349.

Wang, M and Yan, Z. 2015. "Security in D2D Communications: A Review," 2015 IEEE Trustcom/ Big Data SE/ISPA, Helsinki, 2015, 1199-1204, doi: 10.1109/Trustcom.2015.505.

Waqas, M., Niu, Yong, L., Yong, A., Manzoor, J., Depeng, A., Manzoor, C., Sheng, T. and Han, Z. 2020. A comprehensive survey on mobility-aware device-to-device communications: Principles, practice and challenges. *IEEE Communications Surveys & Tutorials*, 22 (3), 18631886. (doi:10.1109/COMST.2019.2923708). Accessed: 10 Oct. 2021.

Weinstein, H., Frazier, D. & Bongar, B. 2009. Why are they Attacking us? Decoding the Messages of al-Qaeda Terrorists Targeting the United States and Europe. *International Journal of Social Psychology*, tome 22(3):65-85.

Wen, S. Zhu, X. Lin, Z. Zhang, X. and Yang, D. 2012. “Optimization of interference coordination schemes in device-to-device (D2D) communication,” in *Communications and Networking in China (CHINACOM), 2012 7th International ICST Conference on*, 8-10 Aug. 2012, Kunming, IEEE, pp. 542–547.

Wen, S., Zhu, X., Lin, Z., Zhang, X. and Young, D. 2012. “Optimization of interference coordination schemes in device-to-device communication,” *7th Conference on Communications and Networking in China (CHINACOM),* Kun Ming, 8-10 Aug. 2012, Kun Ming, IEEE, 542-547.

Wijk, F., Janssen, G. M., and Prasad, R. 2015. Groupwise successive interference cancellation in a DS/CDMA system. In *Personal, Indoor and Mobile Radio Communications. Wireless: Merging onto the Information Superhighway., Sixth IEEE International Symposium on* Vol. 2:742-746. IEEE.

Wu, F., Zhang, H., Di, B., Wu, J. and Song, L. 2019. “Device-to-Device Communications Underlaying Cellular Networks: To Use Unlicensed Spectrum or Not?” in *IEEE Transactions on Communications*, vol. 67, no. 9:6598-6611.

Wu, X., Tavildar, S., Shakkottai, S., Richardson, T., Li, J., Laroia, R. and Jovicic, A. 2010. “FlashLinQ: a synchronous distributed scheduler for peer-to-peer ad hoc networks,” in *Proceedings on IEEE International Conference on Communication Control and Computing Technologies (ICCCCT),* Tamil Nadu, 07-09 Oct. 2010, 521-524.

Xing. H. and Hakola, S. 2010. "The investigation of power control schemes for a device-to-device communication integrated into OFDMA cellular system," *21st Annual IEEE International Symposium on Personal, Indoor and Mobile Radio Communications*, 2010:1775-1780, doi: 10.1109/PIMRC.2010.5671643.

Xu, C., Song, L. and Zhu, H. 2013. Resource management for device-to-device underlay communication. Available at: https://arxiv.org/pdf/1311.1018.pdf Accessed: 21 Sep. 2019.

Yang, C., Xu, X., Han, J., Rehman, W. and Tao, X 2014. “Ga based optimal resource allocation and user matching in device-to-device underlaying network,” in

*Wireless Communications and Networking Conference Workshops (WCNCW)*, 2014, 6-9 May 2014, Istanbul, IEEE, pp. 242–247.

Yang, T., Zhang, R., Cheng, X., Yang, L. 2017. Graph colouring based resource sharing (GCRS) scheme for D2D communications underlaying full-duplex cellular networks. *IEEE Trans. Veh. Technol*., (66):7506–7517.

Yi, X. and Gesbert, D. 2015. Topological interference management with transmitter cooperation," *IEEE Transactions on Information Theory*, 1(11): 6107-6130.

Yin, R., Yu, G. Zhang, H., Zhang, Z. and Li, G. Y. 2015. "Decentralized interference coordination for D2D communication underlying cellular networks," in *2015 IEEE International Conference on Communications (ICC)*, 8 - 12 Jun. 2015, London, IEEE, pp. 2626–2631.

Yu, W., Xu, H., Nguyen, J., Blasch, E., Hematian, A. and Gao, W. 2018. "Survey of Public Safety Communications: User-Side and Network-Side Solutions and Future Directions," in *IEEE Access*, vol. 6, 70397-70425.

Yufeng W., Athanasios V. V., Qun J., Hongbo Z. 2020. Device-to-Device based Proximity Service Architecture, Issues, and Applications, CRC Press, Florida.

Zaky, A.B.; Huang, J.Z., Wu, K.; ElHalawany, B.M. Generative neural network-based spectrum sharing using linear sum assignment problems. China Communications **2020**, 17:14–29.

Zhang, D. Q. and Tian, X. J. 2018. Overview on Interference Management Technology for Ultra-Dense Network. *Open Access Library Journal*, 5: e4675. https://doi.org/10.4236/oalib.1104675

Zhao, J. Liu, Y. Chai, K. K. Chen, Y., Elkashlan, M., and Alonso-Zarate, J. 2016. "NOMA-Based D2D Communications: Towards 5G," *2016 IEEE Global Communications Conference (GLOBECOM)*, 2016, pp. 1-6, doi: 10.1109/GLOCOM.2016.7842024.

Zhou, Z., Ota, K., Dong, M. and Xu, C. 2017. "Energy-Efficient Matching for Resource Allocation in D2D Enabled Cellular Networks," in *IEEE Transactions on Vehicular Technology*, 66(6): 5256-5268, doi: 10.1109/TVT.2016.2615718.

Zia, K., Javed, N., Sial, M.N., Ahmed, S., Iram, H. and Pirzada, A.A. A Survey of conventional and artificial intelligence / learning based resource allocation and interference mitigation schemes in D2D enabled networks. Available at: https://arxiv.org/abs/1809.08748 Accessed: 24 Oct. 2021.

Appendix 1

## A. Initialisation, declaration of entities and placement of devices in an AOI

```
BANDWIDTH = 100; % Total available Bandwidth
RB = (BANDWIDTH*0.9)/0.18;% Calculation gives the total number of available Resource Blocks(RBs)
PCHW = 2.5; % Cluster Head power in Watts
PCHdB = 10*log10(PCHW); % Cluster Head power in dB
P_smartphone_Watt = 1.5; % Smartphone power in Watts
P_smartphone_dB = 10*log10(P_smartphone_Watt); % Smartphone power in dB
 Smartphone_users = 5; % The number of users is steadily increased to evaluate perfomance as the number          increases
THE_TARGETED_RATES = [0.4 0.6 0.8 1.0 1.2 1.8 2.0]; % This table gives the_targeted rates
THE_TARGETED_RATES_l = length(THE_TARGETED_RATES);
Prioritised_Group = [1]; % Smartphones in the prioritised group
Prioritised_Group_size = length(Prioritised_Group);
Smartphone_user_table = [];
D2d_with_CH = [];
Table_of_prioritised_smartphones = [];
Table_of_connected_smaartphones = [];
Main_tabulation = zeros(Smartphone_users,10);
Assigned_rates = zeros(9,4);
alg_smartphone_droppings_sum = zeros(9,4);
Optional_prioritised_req_met= 0;
Optional_non_prioritised_req_met= 0;
Prioritised_req_not_met = 0;
non_Prioritised_req_not_met = 0;
Smartphone_axes = [];
line = 1;
next = 1;
flag = 0;
CH_distance = 0;
Smartphone_distance_max= 0;
for Step_Cluster_Head = 0.05:1:0.05 % CH-BS distance in paces of 1 beginning at 0.05
for Step_Smartphone = 1:1:10 % Smartphone-Cluster Head in paces of 1m starting at 1m
for smartphone_droppings = 1:1:1 % Gives the number of random smartphone droppings
% Gives smartphones and Cluster Head new locations
[ CH_distance, CH_angle, Smartphone_distance, Smartphone_angle,
                Smartphone_distance_CH, Smartphone_distance_max] =
                Place_devices( Smartphone_users,
                Step_Smartphone, Step_Cluster_Head )
Smartphone_distance_ch = Smartphone_distance_CH'
Smartphone_distance = [1.5682 1.4325 1.3457 1.1363 1.4509]
Smartphone_angle = [256.2544 100.4536 214.9497 235.4325 224.9382]
Smartphone_distance_CH = [0.067 0.0145 0.0243 0.0344 0.0566]
% Setting up of the crucial tables
[ Smartphone_user_table, D2d_with_CH, Table_of_prioritised_smartphones,
                Table_of_connected_smartphones ] = Cluster_tables( PCHdB,
                P_smartphone_dB,
```

```
                    Smartphone_users, CH_distance, CH_angle, Smartphone_distance, Smartphone_angle,
                    Smartphone_distance_CH, THE_TARGETED_RATES, THE_TARGETED_RATES_l, Prioritised_Group,
                    Prioritised_Group_size );
%%% The_targeted_rates: For non-prioritised smartphones = 0,8 and prioritised smartphones is 2 %%%
minimum = find(abs(THE_TARGETED_RATES-0.8) < 0.001);
desired = find(abs(THE_TARGETED_RATES-2) < 0.001);
not_possible = 0;
    for f = 1:1:Smartphone_users
            if (Table_of_prioritised_smartphones(f,2) == 1) && (Table_of_connected_smartphones (f,1+desired)  == 1)&& (D2d_with_CH(f,1+desired) ~= 1) %prioritised smartphones user, connected, d2d  connection
            Main_tabulation(f,1) = Smartphone_user_table(f,4+desired);
            elseif (Table_of_prioritised_smartphones(f,2) == 1) &&
                        (Table_of_connected_smartphones(f,1+desired) == 1)&&
                        (D2d_with_CH(f,1+desired) == 1) %  prioritised, connected, clusterhead
            Main_tabulation(f,2) = Smartphone_user_table(f,4+(2*THE_TARGETED_RATES_l)+desired);
            Main_tabulation(f,2+desired) = 1;
            elseif (Table_of_prioritised_smartphones(f,2) ~= 1) &&
                        (Table_of_connected_smartphones(f,1+minimum) == 1)&&
                        (D2d_with_CH(f,1+minimum) ~= 1) % Non-prioritised smartphones, connected, d2d connection
            Main_tabulation(f,1) = Smartphone_user_table(f,4+minimum);
            elseif (Table_of_prioritised_smartphones(f,2) ~= 1) &&
                        (Table_of_connected_smartphones(f,1+minimum) == 1)&&
                        (D2d_with_CH(f,1+minimum) == 1) % Non-prioritised smartphones, connected, cluster head
                        Main_tabulation(f,2) = Smartphone_user_table(f,4+(2*THE_TARGETED_RATES_l)+minimum);
            Main_tabulation(f,2+minimum) = 1;
            end
    end
Main_tabulation_secure_1 = Main_tabulation
```

**B. Checking whether all smartphones are connected**

```
    for f = 1:1:Smartphone_users
        fit = Main_tabulation(f,1) + Main_tabulation(f,2);
            if fit == 0
            not_possible = not_possible +1;
            end
    end
[ Main_tabulation_sum_init, Main_tabulation_calc_init ] = Main_tabulation_calc(
                Main_tabulation, Smartphone_users, THE_TARGETED_RATES, THE_TARGETED_RATES_l, RB, PCHdB,     CH_distance);
% If the setup is not right, upgrade non-prioritised smartphones
```

```
if (Main_tabulation_calc_init(4,1) > 0) && (not_possible == 0)
Main_tabulation_secure = Main_tabulation;
[ Main_tabulation ] = Cluster_upgrade( Smartphone_user_table,
                Table_of_prioritised_smartphones,
                Table_of_connected_smartphones, D2d_with_CH,
                Main_tabulation, Smartphone_users, THE_TARGETED_RATES,
    THE_TARGETED_RATES_l, RB,                PCHdB, CH_distance);
     [ Main_tabulation_check2, D2d_with_CH_check2, check_count_2 ] =
    checking_efficiency(     Smartphone_user_table, D2d_with_CH, Main_tabulation,
                    Smartphone_users, THE_TARGETED_RATES,
    THE_TARGETED_RATES_l, RB, PCHdB, CH_distance );
    if check_count_2 > 0
                Main_tabulation = Main_tabulation_check2;
                D2d_with_CH = D2d_with_CH_check2;
    end
[ ~, Main_tabulation_calc_plot ] = Main_tabulation_calc( Main_tabulation,
Smartphone_users, THE_TARGETED_RATES, THE_TARGETED_RATES_l, RB,
PCHdB, CH_distance); % only provides insight into used RBs
%else % If the setup is not right, downgrade all smartphones until it is right
Main_tabulation_secure = Main_tabulation;
[ Main_tabulation ] = Cluster_downgrade( Smartphone_user_table,
                    Table_of_prioritised_smartphones,
                    Table_of_connected_smartphones, D2d_with_CH,
                    Main_tabulation, Smartphone_users, THE_TARGETED_RATES,
                    THE_TARGETED_RATES_l, RB, PCHdB, CH_distance );
 [ ~, Main_tabulation_calc_plot ] = Main_tabulation_calc( Main_tabulation,
                    Smartphone_users, THE_TARGETED_RATES,
THE_TARGETED_RATES_l, RB, PCHdB,                CH_distance);
end
% Plot and show results
[ ~, final_rate, final_resources ] = Cluster_draw(Smartphone_user_table,
                    Main_tabulation_calc_plot, Main_tabulation, Smartphone_users,
Prioritised_Group,
                    Smartphone_angle, Smartphone_distance, CH_angle, CH_distance )
Assigned_rates(9,4)= 0;
```

**C. Determination of Resource Allocation**

```
[ opt_rates, opt_resources ] = Cluster_optimal_scalelable_6_function_v6(
                Smartphone_user_table, Smartphone_users, PCHdB, CH_distance,
                THE_TARGETED_RATES);
alg_rates(smartphone_droppings,:) = final_rate;
rates_ideal(smartphone_droppings,:) = opt_rates;
alg_resources(smartphone_droppings,:) = final_resources;
resources_ideal(smartphone_droppings,:) = opt_resources;
tot_alg_rates(line,:) = final_rate;
tot_rates_ideal(line,:) = opt_rates;
tot_alg_resources(line,:) = final_resources;
tot_resources_ideal(line,:) = opt_resources;  line = line + 1;
 Main_tabulation = zeros(Smartphone_users,10);
    end
```

```
End
```

**D. Placement of Mobiles, a Cluster Head and a Base Station**

```
%The following function facilitates the random placement of smartphoness
function [ CH_distance_new, CH_angle, Smartphone_distance_n, Smartphone_angle_n,
Smartphone_distance, Smartphone_distance_max_new] = Place_devices(
Smartphone_users, count_smartphone, count_cluster_head)
%This function is responsible for the updating of the locations of the smartphones and
the cluster head
Smartphone_distance_max_initial = 0.1;
CH_distance_initial = 0.1;
CH_angle = 106;
Smartphone_distance_max_new = (Smartphone_distance_max_initial - 0.1) + (0.1 *
count_smartphone);
CH_distance_new = (CH_distance_initial - 0.1) + (0.1 * count_cluster_head);
Smartphone_distance = round( 1000*(0 + (Smartphone_distance_max_new - 0)*rand
                  (Smartphone_users,1)))/1000;
Smartphone_angle = round((0 + (360-0)*rand(Smartphone_users,1)));
% Setting up of distances of smartphones from the Base Station to the Cluster Head
            for f = 1:1:Smartphone_users
                    [ Smartphone_distance_n(f), Smartphone_angle_n(f)] =
                    Loc_random_smartphone(
                    Smartphone_distance(f), Smartphone_angle(f), CH_
                    distance_new, CH_angle);
            end
   End\
function [ beta_x, alpha_x] = Loc_random_smartphone( d_smartphone,
Smartphone_angle, d_clusterhead, CH_angle )
% Mobile smartphones that are scattered around the centre in polar plot to area around
cluster head
```

**E. The calculation of distances to a Base Station**

```
[x_clusterhead,y_clusterhead] = pol2cart(deg2rad(CH_angle),d_clusterhead);
[x_smartphone,y_smartphone] = pol2cart(deg2rad(Smartphone_angle),d_smartphone);
x_n = x_smartphone + x_clusterhead;
y_n = y_smartphone + y_clusterhead;
```

**F. Plotting the AOI**

```
plot(x_smartphone, y_smartphone, 'blao', 'MarkerSize', 2, 'LineWidth', 3), hold on
plot(x_clusterhead, y_clusterhead,'bD', 'MarkerSize', 5, 'LineWidth', 4 ), hold on
BaseStationX = 0.05;
BaseStationY = 0.05;
plot(BaseStationX, BaseStationY, 'rs', 'MarkerSize', 6, 'LineWidth', 4), hold on, grid on,
grid minor;
hleg = legend('Smartphone UE', 'Cluster Head', 'Mwashita Base Station')
set(hleg, 'Location', 'NorthEastOutside')
xlabel('Distance in kilometres')
ylabel('Distance in kilometres')
[theta,beta_x] = cart2pol(x_n,y_n);
alpha_x = rad2deg(theta);
```

```
if alpha_x < 0
alpha_x = alpha_x + 360;
end
end
```

### G. Taking a Snapshot

```
function [ Smartphone_user_table, D2d_with_CH, Table_of_prioritised_smartphones,
                        Table_of_connected_smartphones ] = Cluster_tables( PCHdB,
                        P_smartphone_dB,
                        Smartphone_users, CH_distance, CH_angle, Smartphone_distance,
                        Smartphone_angle,
                        Smartphone_distance_CH,THE_TARGETED_RATES,
                        THE_TARGETED_RATES_l, Prioritised_Group,
                        Prioritised_Group_size )
                % This function creates the Smartphone_user_table, dir-ch_table,
                 Table_of_prioritised_smartphones and Table_of_connected_smartphones.
% based on these tables the proposed Heuristic algorithm makes a resolution on
utilisation of resources.
% The setting up of resources table
for d = 1:1:Smartphone_users
                        Smartphone_user_table(d,1) = d; % User ID
                        Smartphone_user_table(d,2) = Smartphone_distance(d); % distance
                        of smartphone user to BS
                        Smartphone_user_table(d,3) = Smartphone_angle(d); % angle
                        Smartphone_user_table(d,4) = Smartphone_distance_CH(d); %
                        distance to cluster head for comparison
                        % Smartphone_user_table(d,4) =
                        Dist_smartphone_clusterhead(Smartphone_distance(d),
                        Smartphone_angle(d), CH_distance, CH_angle); % distance to
                        cluster head for cluster_main_v5
                        D2d_with_CH(d,1) = d; % setting up direct-clusterhead table.
                        Table_of_prioritised_smartphones(d,1) = d; % The setting up of a
                        prioritised table
                        Table_of_connected_smartphones(d,1) = d; % The setting up of a
                        table of connected smartphones
                for f = 1:1:THE_TARGETED_RATES_l
                % resources table
                        Smartphone_user_table(d,4+f) =
                        Smartphone_direct(THE_TARGETED_RATES(f),
                        P_smartphone_dB, Smartphone_distance(d));
    [Smartphone_user_table(d,4+THE_TARGETED_RATES_l+f),Smartphone_user_tab
    le(d,4+ (2*THE_TARGETED_RATES_l)+f)] =
    Smartphone_to_clusterhead(THE_TARGETED_RATES(f), PCHdB,
    P_smartphone_dB, CH_distance, Smartphone_user_table(d,4));
    % Smartphone to Base Station versus smartphone to Cluster Head table
    if ((Smartphone_user_table(d,4+f) >= Smartphone_user_table(d,
    4+THE_TARGETED_RATES_l+f)) && (Smartphone_user_table(d,4+f) > 0)...
                                &&
    (Smartphone_user_table(d,4+THE_TARGETED_RATES_l+f) > 0)) ||
    ((Smartphone_user_table(d,4+f) == 0) && (Smartphone_user_table(d,
```

```
                    4+THE_TARGETED_RATES_l+f)~= 0))
                    D2d_with_CH(d,1+f) = 1; 166
                    else
                    D2d_with_CH(d,1+f) = 0;
                    end
                    if (Smartphone_user_table(d,4+f) == 0) &&
                    (Smartphone_user_table(d,
                    4+THE_TARGETED_RATES_l+f) == 0)
                    Table_of_connected_smartphones(d,1+f) = 0;
                    else
                    Table_of_connected_smartphones(d,1+f) = 1;
                    end
                End
```

## H. Table of prioritised Smartphones

```
                if any(d==Prioritised_Group)
                Table_of_prioritised_smartphones(d,2) = 1; % setting a
                prioritised flag
                else
                Table_of_prioritised_smartphones(d,2) = 0; % setting a prioritised
                flag
                end
            end
    end
%The following function is used to determine the amount of resources to Cluster head
function [ RBs_total, RBs_smartphone ] = Smartphone_to_clusterhead(
                Smartphone_the_target_rate, PCHdB, P_smartphone_dB, drs, due )
% The function calculates the required resources for a given the_target rate when
communicating with the cluster      head.
%Ldsmartphone = 128.1+(37.6*log10(due)); %loss due to distance Smartphone to
                Clusterhead (dB). Antenna at height BS
% Ldsmartphone = 131.3+(38.4*log10(due)); %loss due to distance UE-RS (dB).
Antenna at 10m height
Ldsmartphone = 148+(40*log10(due)); %loss due to distance UE-RS (dB). antenna at
vehicle height
RBsmartphone_max = floor (10^((P_smartphone_dB-(-10+Ldsmartphone+(-
146.45)))/10)); % determine the maximum resource blocks of smartphone-cluster head
%Ldch = 10000000+(100000*log10(drs)); % impossible to use relay station
Ldch = 128.1+(37.6*log10(drs)); %loss due to distance RS-BS (dB)
RBch_max = floor (10^((PCHdB-(-10+Ldch+(-146.45)))/10)); % determine max RBs
RS_BS
% calculates the BRs needed to The_targeted_ratesansmit via the RS
Rate_min = 0;
time = 0;

            for BRs_Smartphone_users = 1:1:50 %Increasing the number of RBs for the
                smartphone
                if Rate_min == 0
                % determination of the smartphone rate
                RBmin = BRs_Smartphone_users-1;
```

```
SINSmartphone_rate = 10^((P_smartphone_dB-(10*log10(BRs_Smartphone_users))-Ldsmartphone-(-146.45))/10);
Smartphone_rate = (BRs_Smartphone_users*0.18)*0.4*log2(1+SINSmartphone_rate);
% determine SINRi + rate rate RBsmartphone-1

SINSmartphone_rate_1 = 10^((P_smartphone_dB-(10*log10(RBmin))-Ldsmartphone-(-146.45))/10);
Smartphone_rate_M1 = (RBmin*0.18)*0.4*log2(1+SINSmartphone_rate_1);
if (Smartphone_rate >=Smartphone_the_target_rate) && (RBmin ~= 0)
diff = Smartphone_rate-Smartphone_rate_M1;
short = Smartphone_the_target_rate-Smartphone_rate_M1;
time =ceil((short/diff)*1000)/1000;
SmartphoneRate =((1-time)*Smartphone_rate_M1)+(time*Smartphone_rate);
Rate_min = 1;
elseif (Smartphone_rate >=Smartphone_the_target_rate) && (RBmin == 0)
time = ceil((Smartphone_the_target_rate/Smartphone_rate)*1000)/1000;
SmartphoneRate = time*Smartphone_rate;
Rate_min = 1;
end
```

**I. Determining if BS can accommodate a Cluster Head**

```
RB_ClusterHead =0;
if Smartphone_rate >=Smartphone_the_target_rate;
RB_smartphone = RBmin+time;
x =0;
ClusterHeadRate =0;
time_M1 =0;
time_P1 = 0;
time_P11 =0;
for RBch = 1:1:50 % Number of Resource Blocks
if x==0
```

**J. Determination of the rate of the Cluster Head**

```
SINRch = 10^((PCHdB-(10*log10(RBch))-Ldch-(-146.45))/10)
Rch = (RBch*0.18)*0.4*log2(1+SINRch);
if (Rch >= SmartphoneRate) && (x==0)
x =1;
RB_clusterheadmin1 = RBch-1;
SINR_1 = 10^((PCHdB-(10*log10(RB_clusterheadmin1))-Ldch-(-146.45))/10);
Rch_1 = (RB_clusterheadmin1*0.18)*0.4*log2(1+SINR_1);
if RB_clusterheadmin1 ~= 0
diff = Rch-Rch_1;
short = (SmartphoneRate)-Rch_1;
time_M1 =ceil((short/diff)*1000)/1000;
ClusterHeadRate =((1-time_M1)*Rch_1)+(time_M1*Rch);
elseif RB_clusterheadmin1 == 0
time_M1 = ceil((SmartphoneRate/Rch)*1000)/1000;
ClusterHeadRate = time_M1*Rch;
```

```
end
RB_clusterhead = RB_clusterheadmin1 + time_M1;
RBs_subtotal = RB_smartphone+RB_clusterhead % Total number of resource blocks
%
end
end
end
end
end
end
if (Rate_min == 0) || (x == 0) || (RB_clusterhead > RBch_max) || (RB_smartphone > RBsmartphone_max)
RBs_total = 0;
RBs_smartphone = 0;
else
RBs_total = RBs_subtotal;
RBs_smartphone = RB_smartphone;

end
end
%determine amount of resources direct to base station
function [ RB_direct ] = Smartphone_direct( Smartphone_the_target_rate, P_smartphone_dB, due_dir )
% This function calculates the RBs needed for transmission to the BS
Ldsmartphone_dir = 128.1+(37.6*log10(due_dir)); %loss due to distance smartphonebase station in -+dB
RBsmartphone_max = floor (10^((P_smartphone_dB-(-10+Ldsmartphone_dir+(-146.45)))/10)); % determine max RBs
Rate_min_RBs = 0;
time_dir = 0;
for BRs_Smartphone_users = 1:1:50 %Increase the number of RBs
if Rate_min_RBs == 0
RBmin_dir = BRs_Smartphone_users-1;
% determine SINRi + rate for RBsmartphone
SINSmartphone_rate_dir = 10^((P_smartphone_dB-(10*log10(BRs_Smartphone_users))-Ldsmartphone_dir-(-146.45))/10);
Smartphone_rate_dir = (BRs_Smartphone_users*0.18)*0.4*log2(1+SINSmartphone_rate_dir)
% detemine SINRi + rate ahead of RBsmartphone-1
SINSmartphone_rate_1_dir = 10^((P_smartphone_dB-(10*log10(RBmin_dir))-Ldsmartphone_dir-(-146.45))/10);
Smartphone_rate_M1_dir = (RBmin_dir*0.18)*0.4*log2(1+SINSmartphone_rate_1_dir);
if (Smartphone_rate_dir >=Smartphone_the_target_rate) && (RBmin_dir ~= 0)
diff_dir = Smartphone_rate_dir-Smartphone_rate_M1_dir;
short_dir = Smartphone_the_target_rate-Smartphone_rate_M1_dir;
time_dir =ceil((short_dir/diff_dir)*1000)/1000;
SmartphoneRate_dir =((1-time_dir)*Smartphone_rate_M1_dir)+
```

```
(time_dir*Smartphone_rate_dir);
Rate_min_RBs = 1;
elseif (Smartphone_rate_dir >=Smartphone_the_target_rate) && (RBmin_dir == 0)
time_dir = ceil((Smartphone_the_target_rate/Smartphone_rate_dir)*1000)/1000;
SmartphoneRate_dir = time_dir*Smartphone_rate_dir;
Rate_min_RBs = 1;
end
end
end
% if the amount of required resources tallies with the available resources, give the value
otherwise return a zero
if (Rate_min_RBs == 1) && ((RBmin_dir+time_dir) <= RBsmartphone_max)
RB_direct = RBmin_dir+time_dir;
else
RB_direct = 0;
end
end
%Downgrading  SUEs
function [ Main_tabulation ] = Cluster_downgrade( Smartphone_user_table,
                              Table_of_prioritised_smartphones, Table_of_connected_smartphones,
D2d_with_CH,
        Main_tabulation, Smartphone_users, THE_TARGETED_RATES,
THE_TARGETED_RATES_l, RB, PCHdB,              CH_distance )
% If a smartphone does not meet the requirement find its highest rate
for f = 1:1:Smartphone_users
if (Main_tabulation(f,1) == 0) && (Main_tabulation(f,2) == 0)
[~, col_cee] = find(abs(Table_of_connected_smartphones(f,2:8)-1) < 0.001);
tmp_c = length(col_cee);
if tmp_c > 0
if D2d_with_CH(f,1+tmp_c) == 0
Main_tabulation(f,1) = Smartphone_user_table(f,4+tmp_c);
elseif D2d_with_CH(f,1+tmp_c) == 1
Main_tabulation(f,2) =
Smartphone_user_table(f,4+(2*THE_TARGETED_RATES_l)+tmp_c)
Main_tabulation(f,2+tmp_c) = 1;
end
end
end
end
Main_tabulation_secure_2a = Main_tabulation
[ Main_tabulation_down_1, D2d_with_CH_down_1, down_count_1 ] =
checking_efficiency...
( Smartphone_user_table, D2d_with_CH, Main_tabulation, Smartphone_users,
                              THE_TARGETED_RATES, THE_TARGETED_RATES_l, RB,
PCHdB, CH_distance );
if down_count_1 > 0
Main_tabulation = Main_tabulation_down_1;
D2d_with_CH = D2d_with_CH_down_1;
end
Main_tabulation_secure_2b = Main_tabulation
```

```
if (sum(Main_tabulation(:,1)) + sum(Main_tabulation(:,2))) > 0
for down = 1:1:10 % go through resolution theThe_targeted_ratesix (10 steps)
% determine downgrade values
for f = 1:1:Smartphone_users
if (Table_of_prioritised_smartphones(f,2) ~= 1) && ((Main_tabulation(f,1)+ Main_tabulation(f,2)) > 0) % non-prioritised smartphones and connected
[~, col_dee]                    = find(abs(Main_tabulation(f,3:9)-1) < 0.001);
     if col_dee == resolution_The_targeted_rate(down,1)% when using CH
     if D2d_with_CH(f,1+col_dee-1) == 1
     Main_tabulation(f,10) = Smartphone_user_table(f,4+THE_TARGETED_RATES_l+col_dee)- Smartphone_user_table(f,4+THE_TARGETED_RATES_l+col_dee-resolution_The_targeted_rate(down, 2));
     elseif D2d_with_CH(f,col_dee) ~= 1
     Main_tabulation(f,10) = Smartphone_user_table(f,4+THE_TARGETED_RATES_l+col_dee)- Smartphone_user_table(f,4+col_dee-resolution_The_targeted_rate(down,2));
 end
elseif (sum(Main_tabulation(f,3:2+THE_TARGETED_RATES_l)) == 0) && (Main_tabulation (f,1) ~= 0)
if find(abs(Smartphone_user_table(f,5:11)-Main_tabulation(f,1)) < 0.001) == resolution_The_targeted_rate(down,1)
[f_user, f_col] = find(abs(Smartphone_user_table(f,5:4+THE_TARGETED_RATES_l)-Main_tabulation(f,1)) < 0.001);
Main_tabulation(f,10) = Main_tabulation(f,1)-Smartphone_user_table(f,4+f_col-resolution_The_targeted_rate(down,2));
end
end
elseif (Table_of_prioritised_smartphones(f,2) == 1)% prioritised smartphones, communicating with Cluster Head
[~, col_ee] = find(abs(Main_tabulation(f,3:9)-1) < 0.001);
if col_ee == resolution_The_targeted_rate(down,4);
if D2d_with_CH(f,1+col_ee-1) == 1
Main_tabulation(f,11) = Smartphone_user_table(f,4+THE_TARGETED_RATES_l+col_ee)- Smartphone_user_table(f,4+THE_TARGETED_RATES_l+col_ee-resolution_The_targeted_rate(down, 5));
elseif D2d_with_CH(f,col_ee) ~= 1
Main_tabulation(f,11) = Smartphone_user_table(f,4+THE_TARGETED_RATES_l+col_ee)- Smartphone_user_table(f,4+col_ee-resolution_The_targeted_rate(down,5));
end

elseif (sum(Main_tabulation(f,3:2+THE_TARGETED_RATES_l)) == 0) && (Main_tabulation (f,1) ~= 0)
```

```
if find(abs(Smartphone_user_table(f,5:11)-Main_tabulation(f,1)) < 0.001) == resolution_The_targeted_rate(down,4)
[~, col_gee] = find(abs(Smartphone_user_table(f,5:4+THE_TARGETED_RATES_l)-Main_tabulation(f,1)) < 0.001)
Main_tabulation(f,11) = Main_tabulation(f,1)-Smartphone_user_table(f,4+col_gee-resolution_The_targeted_rate(down,5))
end
end
end
end
Main_tabulation_secure_2c = Main_tabulation
[ ~, Main_tabulation_calc_down ] = Main_tabulation_calc( Main_tabulation, Smartphone_users, THE_TARGETED_RATES, THE_TARGETED_RATES_l, RB, PCHdB, CH_distance)
if resolution_The_targeted_rate(down,2) == 1
while (max(Main_tabulation(:,10)) ~= 0) && (Main_tabulation_calc_down(4,1) <= 0) % loop for non-priotised smartphones
% determine downgrade values and downgrade
[~,ndi_smartphone] = max(Main_tabulation(:,10));
if Main_tabulation(ndi_smartphone,1) == 0 % smartphone connected via a cluster head
[ndi_user, ucol_ee] = find(abs(Main_tabulation(ndi_smartphone,3:9)-1) < 0.001);
if D2d_with_CH(ndi_smartphone,1+ucol_ee-resolution_The_targeted_rate(down,2)) == 1 Main_tabulation(ndi_smartphone,2) = Smartphone_user_table(ndi_smartphone,4+↙
    (2*THE_TARGETED_RATES_l)+ucol_ee-resolution_The_targeted_rate(down,2));
Main_tabulation(ndi_smartphone,2+ucol_ee) = 0;
Main_tabulation(ndi_smartphone,2+ucol_ee-resolution_The_targeted_rate(down,2)) = 1;
Main_tabulation(ndi_smartphone,3+THE_TARGETED_RATES_l) = 0;
elseif D2d_with_CH(ndi_smartphone,1+ucol_ee-resolution_The_targeted_rate(down,2)) ~= 1
Main_tabulation(ndi_smartphone,1) = Smartphone_user_table(ndi_smartphone,4+ucol_ee-resolution_The_targeted_rate(down,2));
Main_tabulation(ndi_smartphone,2) = 0;
Main_tabulation(ndi_smartphone,2+ucol_ee) = 0;
Main_tabulation(ndi_smartphone,3+THE_TARGETED_RATES_l) = 0;
D2d_with_CH(ndi_smartphone,1+ucol_ee-1) = 0;
end
elseif Main_tabulation(ndi_smartphone,1) ~= 0 % connected directly to BS
[~, ucol_ee] = find(abs(Smartphone_user_table(ndi_smartphone,5:11)-Main_tabulation(ndi_smartphone,1)) < 0.001)
ndi_smartphone

Main_tabulation(ndi_smartphone,1) = Smartphone_user_table(ndi_smartphone,4+ucol_ee-resolution_The_targeted_rate(down,2));
Main_tabulation(ndi_smartphone,3+THE_TARGETED_RATES_l) = 0
D2d_with_CH(ndi_smartphone,1+ucol_ee-1) = 0
end

```

```
Main_tabulation_secure_3a = Main_tabulation
[ Main_tabulation_down_2, D2d_with_CH_down_2, down_count_2 ] = checking_efficiency...
( Smartphone_user_table, D2d_with_CH, Main_tabulation, Smartphone_users, THE_TARGETED_RATES, THE_TARGETED_RATES_l, RB, PCHdB, CH_distance );
if down_count_2 > 0
Main_tabulation = Main_tabulation_down_2;
D2d_with_CH = D2d_with_CH_down_2;
end
Main_tabulation_secure_3b = Main_tabulation
% check if the downgrade is enough for the available resources
Main_tabulation_down = Main_tabulation(:,1:2+THE_TARGETED_RATES_l);
[ ~, Main_tabulation_calc_down ] = Main_tabulation_calc( Main_tabulation_down, Smartphone_users, THE_TARGETED_RATES, THE_TARGETED_RATES_l, RB, PCHdB, CH_distance)
end
elseif resolution_The_targeted_rate(down,2) ~= 1
while (max(Main_tabulation(:,11)) ~= 0) && (Main_tabulation_calc_down(4,1) <= 0) % loop for prioritised smartphones
[~,h_prioritised] = max(Main_tabulation(:,11))
[~, pee_col] = find(abs(Main_tabulation(h_prioritised,3:9)-1) < 0.001)
if Main_tabulation(h_prioritised,1) == 0
if D2d_with_CH(h_prioritised,1+pee_col-resolution_The_targeted_rate(down,5)) == 1
Main_tabulation(h_prioritised,2) = Smartphone_user_table(h_prioritised,4+(2*THE_TARGETED_RATES_l)+pee_col-resolution_The_targeted_rate(down,5));
Main_tabulation(h_prioritised,2+pee_col) = 0;
Main_tabulation(h_prioritised,2+pee_col-resolution_The_targeted_rate(down,5)) = 1;
Main_tabulation(h_prioritised,4+THE_TARGETED_RATES_l) = 0;
elseif D2d_with_CH(h_prioritised,1+pee_col-resolution_The_targeted_rate(down,5)) ~= 1
Main_tabulation(h_prioritised,1) = Smartphone_user_table(h_prioritised, 4+pee_col-1);
Main_tabulation(h_prioritised,2) = 0;
Main_tabulation(h_prioritised,2+pee_col) = 0;
Main_tabulation(h_prioritised,4+THE_TARGETED_RATES_l) = 0;
end
elseif Main_tabulation(h_prioritised,1) ~= 0
Main_tabulation(h_prioritised,1) = Smartphone_user_table(h_prioritised,4+col_gee-resolution_The_targeted_rate(down,5));
Main_tabulation(h_prioritised,4+THE_TARGETED_RATES_l) = 0;
end
Main_tabulation_secure_4a = Main_tabulation
[ Main_tabulation_down_3, D2d_with_CH_down_3, down_count_3 ] = checking_efficiency( Smartphone_user_table, D2d_with_CH, Main_tabulation, Smartphone_users, THE_TARGETED_RATES, THE_TARGETED_RATES_l, RB, PCHdB, CH_distance );
if down_count_3 > 0
Main_tabulation = Main_tabulation_down_3;
D2d_with_CH = D2d_with_CH_down_3;
end
Main_tabulation_secure_4b = Main_tabulation
```

```
% check if the downgrade fits the resources available
Main_tabulation_down = Main_tabulation(:,1:2+THE_TARGETED_RATES_l);
[ ~, Main_tabulation_calc_down ] = Main_tabulation_calc( Main_tabulation_down,
Smartphone_users, THE_TARGETED_RATES, THE_TARGETED_RATES_l, RB,
PCHdB, CH_distance);
end
end
if Main_tabulation_calc_down(4,1) > 0
Main_tabulation = Main_tabulation(:,1:2+THE_TARGETED_RATES_l);
break
end
end
[ Main_tabulation ] = Cluster_upgrade( Smartphone_user_table,
            Table_of_prioritised_smartphones, Table_of_connected_smartphones,
D2d_with_CH,
 Main_tabulation, Smartphone_users, THE_TARGETED_RATES,
THE_TARGETED_RATES_l, RB, PCHdB,
 CH_distance);
end
end
```

### K. Upgrading of non-prioritised smartphones

```
function [ Main_tabulation ] = Cluster_upgrade( Smartphone_user_table,
 Table_of_prioritised_smartphones, Table_of_connected_smartphones, D2d_with_CH,
 Main_tabulation, Smartphone_users, THE_TARGETED_RATES,
THE_TARGETED_RATES_l, RB, PCHdB,                    CH_distance )
% this function upgrades non-priotised smartphones
for step = 1:1:7
for f = 1:1:Smartphone_users % determine the upgrade values
if Main_tabulation(f,1) ~= 0
waarde = Main_tabulation(f,1);
[~, col_a] = find(abs(Smartphone_user_table(f,5:4+THE_TARGETED_RATES_l)-
waarde) <
0.001)
if isempty(col_a)
Main_tabulation(f,3+THE_TARGETED_RATES_l) = 0;
Main_tabulation(f,4+THE_TARGETED_RATES_l) = 0;
else

value_loc = col_a
if (Table_of_prioritised_smartphones(f,2) ~= 1) && (Table_of_connected_smartphones
(f,value_loc+1) == 1) && (D2d_with_CH(f,value_loc+1) ~= 1) && (value_loc <=
6)%nonprioritised, connected, direct
if (Table_of_connected_smartphones(f,value_loc+2) == 1) && (D2d_with_CH(f,
value_loc+2) ~= 1) % 1 up rate, connected, direct

Main_tabulation(f,3+THE_TARGETED_RATES_l) =
Smartphone_user_table(f,value_loc+5)-
Smartphone_user_table(f,value_loc+4);
Main_tabulation(f,4+THE_TARGETED_RATES_l) = 0;
```

```
elseif (Table_of_connected_smartphones(f,value_loc+2) == 1) && (D2d_with_CH(f,value_loc+2) == 1) % 1 up rate, connected, direct becomes ch
Main_tabulation(f,3+THE_TARGETED_RATES_l) = Smartphone_user_table(f,THE_TARGETED_RATES_l+value_loc+5)-Smartphone_user_table(f,value_loc+4);
Main_tabulation(f,4+THE_TARGETED_RATES_l) = 1;
else
Main_tabulation(f,3+THE_TARGETED_RATES_l) = 0;
Main_tabulation(f,4+THE_TARGETED_RATES_l) = 0;
end
end
end
elseif Main_tabulation(f,2) ~= 0
value_loc = find(abs(Main_tabulation(f,3:2+THE_TARGETED_RATES_l)-1) < 0.001);
if (Table_of_prioritised_smartphones(f,2) ~= 1) && (Table_of_connected_smartphones(f,value_loc+1) == 1)&& (D2d_with_CH(f,value_loc+1) == 1) && (value_loc <= 6)%nonprioritised, connected, ch
if (Table_of_connected_smartphones(f,value_loc+2) == 1)&& (D2d_with_CH(f,value_loc+2) == 1) % 1 up rate, connected
Main_tabulation(f,3+THE_TARGETED_RATES_l) = Smartphone_user_table(f,THE_TARGETED_RATES_l+value_loc+5)-Smartphone_user_table(f,THE_TARGETED_RATES_l+value_loc+4);
Main_tabulation(f,4+THE_TARGETED_RATES_l) = 0;
else
Main_tabulation(f,3+THE_TARGETED_RATES_l) = 0;
Main_tabulation(f,4+THE_TARGETED_RATES_l) = 0;
end
end
end
if (length(Main_tabulation(f,:)) > 9)
if (Main_tabulation(f,10) < 0.0001)
Main_tabulation(f,10) = round(0);
end
end
end
Main_tabulation(Smartphone_users,13)= 0;
% search smartphone which is in a position to be upgraded using a minimum of exThe_targeted_rates resources.
for f = 1:1:Smartphone_users
Main_tabulation_secure_up = Main_tabulation
if isempty(Main_tabulation(:,3+THE_TARGETED_RATES_l))
break
else
if (Main_tabulation(f,10) < 0.0001) && (Main_tabulation(f,10) > -0.0001)
Main_tabulation(f,10) = 0;
end
tmp_a = unique(Main_tabulation(:,3+THE_TARGETED_RATES_l))
if (tmp_a(1) == 0) && (length(tmp_a) > 1)
min_RBs = tmp_a(2)
elseif (tmp_a(1) == 0) && (length(tmp_a) == 1)
break
else
```

```
min_RBs = tmp_a(1)
end
end
[a_smartuser, col_aee] = find(abs(Main_tabulation(:,3+THE_TARGETED_RATES_l)-min_RBs) < 0.00001);
a_smartuser_lenght = length(a_smartuser);
if a_smartuser_lenght > 1
a_smartuser = a_smartuser(1)
col_aee = col_aee(1)
end
tmp_b = Main_tabulation(a_smartuser,1)+Main_tabulation(a_smartuser,2);
if Main_tabulation(a_smartuser,1) ~= 0

[b_smartuser,col_bee] = find(abs(Smartphone_user_table(a_smartuser,5:4+THE_TARGETED_RATES_l)-tmp_b) < 0.00001)
base = 4
else
[b_smartuser,col_bee] = find(abs(Smartphone_user_table(a_smartuser,5+(2*THE_TARGETED_RATES_l):4+(3*THE_TARGETED_RATES_l))-tmp_b) < 0.00001)
base = 4+(2*THE_TARGETED_RATES_l)
end
b_smartuser_length = length(b_smartuser);
if b_smartuser_length > 1
b_line = b_smartuser(1);
col_bee = col_bee(1);
end
if (base > 4) && (Table_of_connected_smartphones(a_smartuser,1+col_bee+1) ~= 0) % next is cluster head and connected
Main_tabulation(a_smartuser,1) = 0;
Main_tabulation(a_smartuser,2) = Smartphone_user_table(a_smartuser,4+↙
(2*THE_TARGETED_RATES_l)+col_bee+1);
Main_tabulation(a_smartuser,2+col_bee) = 0;
Main_tabulation(a_smartuser,3+col_bee) = 1;
Main_tabulation(a_smartuser,3+THE_TARGETED_RATES_l) = 0;
elseif (base > 4) && (Table_of_connected_smartphones(a_smartuser,1+col_bee+1) == 0)
% cluster and next is not connected

Main_tabulation(a_smartuser,1) = 0;
Main_tabulation(a_smartuser,2) = 0;
Main_tabulation(a_smartuser,2+col_bee) = 0;
Main_tabulation(a_smartuser,3+col_bee) = 0;
Main_tabulation(a_smartuser,3+THE_TARGETED_RATES_l) = 0;
elseif (base == 4) && (D2d_with_CH(a_smartuser,1+col_bee+1) == 0) && (Table_of_connected_smartphones(a_smartuser,1+col_bee+1) ~= 0
Main_tabulation(a_smartuser,1) = Smartphone_user_table(a_smartuser,4+col_bee+1);
Main_tabulation(a_smartuser,2) = 0;
Main_tabulation(a_smartuser,3+THE_TARGETED_RATES_l) = 0;
elseif (base == 4) && (D2d_with_CH(a_smartuser,1+col_bee+1) ~= 0) &&
```

```
(Table_of_connected_smartphones(a_smartuser,1+col_bee+1) ~= 0) %  next cluster head and connected
Main_tabulation(a_smartuser,1) = 0;
Main_tabulation(a_smartuser,2) = Smartphone_user_table(a_smartuser,4+(2*THE_TARGETED_RATES_l)+col_bee+1);
Main_tabulation(a_smartuser,3+col_bee) = 1;
Main_tabulation(a_smartuser,3+THE_TARGETED_RATES_l) = 0;
elseif (base == 4) && (Table_of_connected_smartphones(a_smartuser,1+col_bee+1) == 0)
%  not connected
Main_tabulation(a_smartuser,1) = 0;
Main_tabulation(a_smartuser,2) = 0;
Main_tabulation(a_smartuser,3+THE_TARGETED_RATES_l) = 0;
end
[ Main_tabulation_up_1, D2d_with_CH_up, up_count_1 ] = checking_efficiency( Smartphone_user_table, D2d_with_CH, Main_tabulation, Smartphone_users, THE_TARGETED_RATES, THE_TARGETED_RATES_l, RB, PCHdB, CH_distance )
if up_count_1 > 0
Main_tabulation = Main_tabulation_up_1;
D2d_with_CH = D2d_with_CH_up;
end
% does the upgrade fit the total amount of resources?
Main_tabulation_up_1 = Main_tabulation(:,1:2+THE_TARGETED_RATES_l)
[ ~, Main_tabulation_calc_up_1 ] = Main_tabulation_calc( Main_tabulation_up_1, Smartphone_users, THE_TARGETED_RATES, THE_TARGETED_RATES_l, RB, PCHdB, CH_distance)
if (Main_tabulation_calc_up_1(4,1) <= 0) &&(Main_tabulation(a_smartuser,2) == 0)
[ Main_tabulation_up_2, D2d_with_CH_up, up_count_2 ] = checking_efficiency( Smartphone_user_table, D2d_with_CH, Main_tabulation, Smartphone_users, THE_TARGETED_RATES, THE_TARGETED_RATES_l, RB, PCHdB, CH_distance )
if up_count_2 > 0
Main_tabulation = Main_tabulation_up_2;
D2d_with_CH = D2d_with_CH_up;
end
[ ~, Main_tabulation_calc_up_2 ] = Main_tabulation_calc( Main_tabulation, Smartphone_users, THE_TARGETED_RATES, THE_TARGETED_RATES_l, RB, PCHdB, CH_distance)
if (Main_tabulation_calc_up_2(4,1) <= 0) && (Main_tabulation(a_smartuser,2) == 0)
Main_tabulation = Main_tabulation_secure_up
break
end
elseif (Main_tabulation_calc_up_1(4,1) <= 0) && (Main_tabulation(a_smartuser,2) ~= 0)
Main_tabulation = Main_tabulation_secure_up;
Main_tabulation(a_smartuser,10) = 0;
end
end
Main_tabulation_up_3 = Main_tabulation
[ ~, Main_tabulation_calc_up_2 ] = Main_tabulation_calc( Main_tabulation_up_3,
```

```
Smartphone_users, THE_TARGETED_RATES, THE_TARGETED_RATES_l, RB, PCHdB, CH_distance)
if Main_tabulation_calc_up_2(4,1) <= 0;
Main_tabulation = Main_tabulation_up_3
break
end
Main_tabulation1 = Main_tabulation
end
end
%Undertaking the efficiency check
function [ Main_tabulation, D2d_with_CH, check_count ] = checking_efficiency( Smartphone_user_table, D2d_with_CH, Main_tabulation, Smartphone_users, THE_TARGETED_RATES, THE_TARGETED_RATES_l, RB, PCHdB, CH_distance )
% checks if resources can be scheduled more efficiently
count_ch = 0;
count_dir = 0;
check_count = 0;
[ ~, Main_tabulation_calc_check ] = Main_tabulation_calc( Main_tabulation, Smartphone_users, THE_TARGETED_RATES, THE_TARGETED_RATES_l, RB, PCHdB, CH_distance);
Main_tabulation_ch(:,1) = Main_tabulation(:,2);
for f = 1:1:Smartphone_users
if Main_tabulation_ch(f,1) > 0
[~, col_cee] = find(abs(Smartphone_user_table(f,19:25)-Main_tabulation_ch(f,1)) < 0.001);
if Smartphone_user_table(f,4+col_cee) > 0
count_ch = count_ch + 1;
Main_tabulation_ch(f,2) = abs(Smartphone_user_table(f, 4+THE_TARGETED_RATES_l+col_cee) - Smartphone_user_table(f,4+col_cee));
end
end
end
if sum(Main_tabulation_ch(:,1)) > 0
for f = 1:1:count_ch
Main_tabulation_tmp = Main_tabulation
D2d_with_CH_tmp = D2d_with_CH;
[ ~, Main_tabulation_calc_check ] = Main_tabulation_calc( Main_tabulation, Smartphone_users, THE_TARGETED_RATES, THE_TARGETED_RATES_l, RB, PCHdB, CH_distance);
tmp_a = unique(Main_tabulation_ch(:,2))
if tmp_a(1) > 0
tmp_b = tmp_a(1)
elseif (tmp_a(1) == 0) && (length(tmp_a) > 1)
tmp_b = tmp_a(2)
else
Main_tabulation = Main_tabulation_tmp;
D2d_with_CH = D2d_with_CH_tmp;
break
end
[a_smartuser, col_aee] = find(abs(Main_tabulation_ch-tmp_b) < 0.001);
```

```
a_smartuser_lenght = length(a_smartuser);
if a_smartuser_lenght > 1
a_smartuser = a_smartuser(1);
col_aee = col_aee(1);
end
Main_tabulation_ch(a_smartuser,2) = 0;
value_loc = find(abs(Main_tabulation(a_smartuser,3:9)-1) < 0.001);
new_forue = Smartphone_user_table(a_smartuser,4+value_loc)
if new_forue > 0
Main_tabulation(a_smartuser,1) = new_forue;
Main_tabulation(a_smartuser,2) = 0;
Main_tabulation(a_smartuser,2+value_loc) = 0
D2d_with_CH(a_smartuser,1+value_loc) = 0;
end
[ ~, Main_tabulation_calc_eff ] = Main_tabulation_calc( Main_tabulation, Smartphone_users, THE_TARGETED_RATES, THE_TARGETED_RATES_l, RB, PCHdB, CH_distance);
if Main_tabulation_calc_eff(4,1) < Main_tabulation_calc_check(4,1)
Main_tabulation = Main_tabulation_tmp;
D2d_with_CH = D2d_with_CH_tmp;
break
end
check_count = check_count +1;
end
end
end
```

**L.**

```
function [ rates_ideal, resources_ideal ] = Cluster_optimal_scalelable_6_function_v07( Smartphone_user_table, Smartphone_users, PCHdB, CH_distance, THE_TARGETED_RATES)
% setting up of the baseline table
bin_table= abs(dec2bin(0:(2^Smartphone_users-1)) - '1');
[lines_a,Smartphone_users] = size(bin_table);
for i = 1:1:lines_a
for k = 1:1:Smartphone_users
if bin_table(i,k) == 0
bin_table(i,k) = 8;
end
end
end
information_aa = {[0:4],[0:6]};
sub_combination_a = combine_all(information_aa{:});
[len_aa,~] = size(sub_combination_a);
information_bb = {[5:6],[3:6]};
sub_combination_b = combine_all(information_bb{:});
[bb_length,~] = size(sub_combination_b);
resolution_The_targeted_rate = sub_combination_a;
```

```
resolution_The_targeted_rate(len_aa+1:len_aa+bb_length,:) = sub_combination_b(1:bb_length,:);
[bb_length,~] = size(resolution_The_targeted_rate);
% searching for the baseline
y = 1;
for i = 1:1:lines_a
for j = 1:1:bb_length
for k = 1:1:Smartphone_users
if (k == 1)
the_the_target(y,k) = bin_table(i,k) + resolution_The_targeted_rate(j,1);

else
the_the_target(y,k) = bin_table(i,k) + resolution_The_targeted_rate(j,2);
end
end
y = y + 1;
end
end
the_target_secure_a = the_target;
[len_aa,~] = size(the_target);
the_the_target(y-1,(2*Smartphone_users)+4) = 0;
for j = 1:1:y-1
for k = 1:1:Smartphone_users
if (the_the_target(j,k) == 1)
if Smartphone_user_table(k,4+1) ~= 0
the_the_target(j,Smartphone_users+1+k) = 0.1;
else
the_the_target(j,Smartphone_users+1+k) = 0;
end
resources(j,k) = Smartphone_user_table(k,5);
elseif (the_the_target(j,k) == 2)
if Smartphone_user_table(k,4+2) ~= 0
the_the_target(j,Smartphone_users+1+k) = 0.2;
else
the_the_target(j,Smartphone_users+1+k) = 0;
end
resources(j,k) = Smartphone_user_table(k,6);
elseif (the_the_target(j,k) == 3)
if Smartphone_user_table(k,4+3) ~= 0
the_the_target(j,Smartphone_users+1+k) = 0.3;
else
the_the_target(j,Smartphone_users+1+k) = 0;
end
resources(j,k) = Smartphone_user_table(k,7);
elseif (the_the_target(j,k) == 4)
if Smartphone_user_table(k,4+4) ~= 0
the_the_target(j,Smartphone_users+1+k) = 0.4;
else
the_the_target(j,Smartphone_users+1+k) = 0;
```

```
end
resources(j,k) = Smartphone_user_table(k,8);
elseif (the_the_target(j,k) == 5)
if Smartphone_user_table(k,4+5) ~= 0
the_the_target(j,Smartphone_users+1+k) = 0.8;
else
the_the_target(j,Smartphone_users+1+k) = 0;
end
resources(j,k) = Smartphone_user_table(k,9);
elseif (the_the_target(j,k) == 6)
if Smartphone_user_table(k,4+6) ~= 0
the_the_target(j,Smartphone_users+1+k) = 1.2;
else
the_the_target(j,Smartphone_users+1+k) = 0;
end
resources(j,k) = Smartphone_user_table(k,10);
elseif (the_the_target(j,k) == 7)
if Smartphone_user_table(k,4+7) ~= 0
the_the_target(j,Smartphone_users+1+k) = 2;
else
the_the_target(j,Smartphone_users+1+k) = 0;
end
resources(j,k) = Smartphone_user_table(k,11);
elseif (the_the_target(j,k) == 8)
if Smartphone_user_table(k,4+8) ~= 0
the_the_target(j,Smartphone_users+1+k) = 0.1;
else
the_the_target(j,Smartphone_users+1+k) = 0;
end
resources(j,k) = Smartphone_user_table(k,19);
elseif (the_the_target(j,k) == 9)
if Smartphone_user_table(k,4+9) ~= 0
the_the_target(j,Smartphone_users+1+k) = 0.2;
else
the_the_target(j,Smartphone_users+1+k) = 0;
end
resources(j,k) = Smartphone_user_table(k,20);
elseif (the_the_target(j,k) == 10)
if Smartphone_user_table(k,4+10) ~= 0
the_the_target(j,Smartphone_users+1+k) = 0.3;
else
the_the_target(j,Smartphone_users+1+k) = 0;
end
resources(j,k) = Smartphone_user_table(k,21);
elseif (the_the_target(j,k) ==11)
if Smartphone_user_table(k,4+11) ~= 0
the_the_target(j,Smartphone_users+1+k) = 0.4;
else
the_the_target(j,Smartphone_users+1+k) = 0;
```

```
end
resources(j,k) = Smartphone_user_table(k,22);
elseif (the_the_target(j,k) == 12)
if Smartphone_user_table(k,4+12) ~= 0
the_the_target(j,Smartphone_users+1+k) = 0.8;
else
the_the_target(j,Smartphone_users+1+k) = 0;
end
resources(j,k) = Smartphone_user_table(k,23);
elseif (the_the_target(j,k) == 13)
if Smartphone_user_table(k,4+13) ~= 0
the_the_target(j,Smartphone_users+1+k) = 1.2;
 else
the_the_target(j,Smartphone_users+1+k) = 0;
end
resources(j,k) = Smartphone_user_table(k,24);
elseif (the_the_target(j,k) == 14)
if Smartphone_user_table(k,4+14) ~= 0
the_the_target(j,Smartphone_users+1+k) = 2;
 else
the_the_target(j,Smartphone_users+1+k) = 0;
end
resources(j,k) = Smartphone_user_table(k,25);
end
if the_the_target(j,k) >= 8
the_the_target(j,(2*Smartphone_users)+3) = the_the_target(j,(2*Smartphone_users)+3) + the_the_target(j,Smartphone_users+1+k); % determine THE_TARGETED_RATES for cluster head
end
end
the_the_target(j,(2*Smartphone_users)+4) = sum(the_the_target(j,Smartphone_users+2:(2*Smartphone_users)+1));

[ resources(j,Smartphone_users+2) ] = Smartphone_direct(the_the_target(j,(2*Smartphone_users)+3), PCHdB, CH_distance); % resources cluster head
if (the_the_target(j,(2*Smartphone_users)+3) > 0) && (resources(j,Smartphone_users+2) == 0)
resources(j,Smartphone_users+2) = 100 ;
end
resources(j,Smartphone_users+3) = sum(resources(j,1:Smartphone_users+2));

if (sum(resources(j,Smartphone_users+3)) > 50) || (any(resources(j,1:Smartphone_users) == 0))
resources(j,Smartphone_users+3) = 0;
end
if j > (len_aa/2)
if (resources(j,Smartphone_users+3) >= resources(j-(len_aa/2),Smartphone_users+3)) && (resources(j-(len_aa/2),Smartphone_users+3) > 0)
resources(j,Smartphone_users+3) = 0;
```

```
elseif (resources(j,Smartphone_users+3) < resources(j-(len_aa/2), Smartphone_users+3)) && (resources(j,Smartphone_users+3) > 0)
resources(j-(len_aa/2),Smartphone_users+3) = 0;
end
end
end
resources_secure_a = resources;
% remove all lines from tables which do not fit in RB
loc_a = 1;
for j = 1:1:len_aa
if (resources(j,Smartphone_users+3) == 0)
to_del_a(loc_a) = j;
loc_a = loc_a + 1;
end
end
the_the_target(to_del_a,:) = [];
resources(to_del_a,:) = [];
[bb_length,~] = size(the_target);
% find highest rate for prioritised smartphones and delete all lines with lower rates
for prioritised_highest = 7:-1:1
if (any(the_the_target(:,1) == prioritised_highest)) || (any(the_the_target(:,1) == prioritised_highest+7))
highest = prioritised_highest;
break
end
end
the_target_secure_b = the_target;
resources_secure_b = resources;
loc_b = 1;
for f = 1:1:bb_length
if (the_the_target(f,1) < highest) || ((the_the_target(f,1) > highest) && (the_the_target(f,1) < (highest+7)))
to_del_b(loc_b) = f;
loc_b = loc_b + 1;
end
end
the_the_target(to_del_b,:) = [];
resources(to_del_b,:) = [];
the_target_secure_c1 = the_target;
resources_secure_c1 = resources;
% find highest base rate for non-prioritised smartphones
max_for_a = max(the_the_target(:,(2*Smartphone_users)+4));
[line_max, ~] = ind2sub(size(the_target),find(the_the_target(:,(2*Smartphone_users)+4)==max_for_a));
[len_c,~] = size(line_max);
for f = 1:1:len_c
base_the_target_1(f,:) = the_the_target(line_max(f,1),:);
resources_base_1(f,:) = resources(line_max(f,1),:);
end
the_target_secure_c2 = base_the_target_1;
```

```
resources_secure_c2 = resources_base_1;
P_smartphone_DB_min = min(base_the_target_1(:,1));
P_smartphone_DB_max = max(base_the_target_1(:,1));
[len_c,~] = size(base_the_target_1);
the_target_secure_d1 = base_the_target_1;
resources_secure_d1 = resources_base_1;
% if more options available take cheapest in ch RBs
if len_c > 1
min_for_a = min(resources_base_1(:,Smartphone_users+2));
loc_b2 = 1;
for f = 1:1:len_c
if resources_base_1(f,Smartphone_users+2) > min_for_a
to_del_b2(loc_b2) = f;
loc_b2 = loc_b2 + 1;
end
end
if loc_b2 > 1
base_the_target_1(to_del_b2,:) = [];
resources_base_1(to_del_b2,:) = [];
end
the_target_secure_d = base_the_target_1;
resources_secure_d = resources_base_1;
[len_cc,~] = size(base_the_target_1);
if len_cc > 1
min_for_aa = min(resources_base_1(:,Smartphone_users+3));
[line_min_a,~] = ind2sub(size(resources_base_1),find(resources_base_1==min_for_aa));
[len_d,~] = size(line_min_a);
for f = 1:1:len_d
base_the_the_target(f,:) = base_the_target_1(line_min_a(f),:);
resources_base(f,:) = resources_base_1(line_min_a(f),:);
end
else
base_the_target = base_the_target_1;
resources_base = resources_base_1;
end
else
base_the_target = base_the_target_1;
resources_base = resources_base_1;
end
% check if a non-prioritised smartphone is at highest and if so, upgrade prioritised smartphone if possible.

if (base_the_the_target(1,Smartphone_users+2) < 2) && base_the_the_target(1,
Smartphone_users+3) < 2
flag_a = 0;
for f = 2:1:Smartphone_users
if base_the_the_target(1,f) > 7
np_base_forue = base_the_the_target(1,f)-7
else
np_base_forue = base_the_the_target(1,f)
```

```
end
if (Smartphone_user_table(f,5+np_base_forue) < 0.0001) && (Smartphone_user_table(f,12+np_base_forue) < 0.0001) % if a smartphone is at limit, first upgrade prioritised smartphones
flag_a = 1
break
end
end
if flag_a == 1
for f = 1:1:Smartphone_users
x(f) = base_the_the_target(1,f);
if x(f) < 8
b(f) = x(f) + 7;
a(f) = x(f);
else
b(f) = x(f);
a(f) = x(f) - 7;
end
one(f) = 7;
two(f) = 14;
end
information_aa = {[a(1):one(1) b(1):two(1)],[a(2) b(2)],[a(3) b(3)],[a(4) b(4)],[a(5) b(5)],[a(6) b(6)]};
sub_combination_2 = combine_all(information_aa{:});
[len_dd,~] = size(sub_combination_2);
rates_for_prioritised(:,1:Smartphone_users) = sub_combination_2(:,1:Smartphone_users);
for j = 1:1:len_dd
for k = 1:1:Smartphone_users
if (rates_for_prioritised(j,k) == 1)
if Smartphone_user_table(k,4+1) ~= 0

rates_for_prioritised(j,Smartphone_users+1+k) = 0.1;
else
rates_for_prioritised(j,Smartphone_users+1+k) = 0;
end
resources_for_prioritised(j,k) = Smartphone_user_table(k,5);
elseif (rates_for_prioritised(j,k) == 2)
if Smartphone_user_table(k,4+2) ~= 0
rates_for_prioritised(j,Smartphone_users+1+k) = 0.2;
else
rates_for_prioritised(j,Smartphone_users+1+k) = 0;
end
resources_for_prioritised(j,k) = Smartphone_user_table(k,6);
elseif (rates_for_prioritised(j,k) == 3)
if Smartphone_user_table(k,4+3) ~= 0
rates_for_prioritised(j,Smartphone_users+1+k) = 0.3;
else
rates_for_prioritised(j,Smartphone_users+1+k) = 0;
end
resources_for_prioritised(j,k) = Smartphone_user_table(k,7);
```

```
elseif (rates_for_prioritised(j,k) == 4)
if Smartphone_user_table(k,4+4) ~= 0
rates_for_prioritised(j,Smartphone_users+1+k) = 0.4;
else
rates_for_prioritised(j,Smartphone_users+1+k) = 0;
end
resources_for_prioritised(j,k) = Smartphone_user_table(k,8);
elseif (rates_for_prioritised(j,k) == 5)
if Smartphone_user_table(k,4+5) ~= 0
rates_for_prioritised(j,Smartphone_users+1+k) = 0.8;
else
rates_for_prioritised(j,Smartphone_users+1+k) = 0;
end
resources_for_prioritised(j,k) = Smartphone_user_table(k,9);
elseif (rates_for_prioritised(j,k) == 6)
if Smartphone_user_table(k,4+6) ~= 0
rates_for_prioritised(j,Smartphone_users+1+k) = 1.2;
else
rates_for_prioritised(j,Smartphone_users+1+k) = 0;
end
resources_for_prioritised(j,k) = Smartphone_user_table(k,10);
elseif (rates_for_prioritised(j,k) == 7)
if Smartphone_user_table(k,4+7) ~= 0
rates_for_prioritised(j,Smartphone_users+1+k) = 2; 971
else
rates_for_prioritised(j,Smartphone_users+1+k) = 0;
end
resources_for_prioritised(j,k) = Smartphone_user_table(k,11);
elseif (rates_for_prioritised(j,k) == 8)
if Smartphone_user_table(k,4+8) ~= 0
rates_for_prioritised(j,Smartphone_users+1+k) = 0.1;
else
rates_for_prioritised(j,Smartphone_users+1+k) = 0;
end
resources_for_prioritised(j,k) = Smartphone_user_table(k,19);
elseif (rates_for_prioritised(j,k) == 9)
if Smartphone_user_table(k,4+9) ~= 0
rates_for_prioritised(j,Smartphone_users+1+k) = 0.2;
else
rates_for_prioritised(j,Smartphone_users+1+k) = 0;
end
resources_for_prioritised(j,k) = Smartphone_user_table(k,20);
elseif (rates_for_prioritised(j,k) == 10)
if Smartphone_user_table(k,4+10) ~= 0
rates_for_prioritised(j,Smartphone_users+1+k) = 0.3;
else
rates_for_prioritised(j,Smartphone_users+1+k) = 0;
end
resources_for_prioritised(j,k) = Smartphone_user_table(k,21);
```

```
elseif (rates_for_prioritised(j,k) ==11)
if Smartphone_user_table(k,4+11) ~= 0
rates_for_prioritised(j,Smartphone_users+1+k) = 0.4;
else
rates_for_prioritised(j,Smartphone_users+1+k) = 0;
end
resources_for_prioritised(j,k) = Smartphone_user_table(k,22);
elseif (rates_for_prioritised(j,k) == 12)
if Smartphone_user_table(k,4+12) ~= 0
rates_for_prioritised(j,Smartphone_users+1+k) = 0.8;
else
rates_for_prioritised(j,Smartphone_users+1+k) = 0;
end
resources_for_prioritised(j,k) = Smartphone_user_table(k,23);
elseif (rates_for_prioritised(j,k) == 13)
if Smartphone_user_table(k,4+13) ~= 0
rates_for_prioritised(j,Smartphone_users+1+k) = 1.2;
else
rates_for_prioritised(j,Smartphone_users+1+k) = 0;
end

resources_for_prioritised(j,k) = Smartphone_user_table(k,24);
elseif (rates_for_prioritised(j,k) == 14)
if Smartphone_user_table(k,4+14) ~= 0
rates_for_prioritised(j,Smartphone_users+1+k) = 2;
else
rates_for_prioritised(j,Smartphone_users+1+k) = 0;
end
resources_for_prioritised(j,k) = Smartphone_user_table(k,25);
end
if rates_for_prioritised(j,k) >= 8
rates_for_prioritised(j,(2*Smartphone_users)+3) = rates_for_prioritised(j,(2*Smartphone_users)+3) + rates_for_prioritised(j,Smartphone_users+1+k); % determine THE_TARGETED_RATES for cluster head
end
end

rates_for_prioritised(j,(2*Smartphone_users)+4) = sum(rates_for_prioritised(j,Smartphone_users+2: (2*Smartphone_users)+1));
[ resources_for_prioritised(j,Smartphone_users+2) ] = Smartphone_direct(rates_for_prioritised(j,(2*Smartphone_users)+3), PCHdB, CH_distance); % resources cluster head
if (rates_for_prioritised(j,(2*Smartphone_users)+3) > 0) && (resources_for_prioritised(j,Smartphone_users+2) == 0)
resources_for_prioritised(j,Smartphone_users+2) = 100 ;
end
resources_for_prioritised(j,Smartphone_users+3) = sum(resources_for_prioritised(j,1:Smartphone_users+2));
if (sum(resources_for_prioritised(j,Smartphone_users+3)) > 50) || (any(resources_for_prioritised(j,1:Smartphone_users) == 0))
resources_for_prioritised(j,Smartphone_users+3) = 0;
```

```
end
if j > (len_dd/2)
if (resources_for_prioritised(j,Smartphone_users+3) >= resources_for_prioritised(j-(len_dd/2),Smartphone_users+3)) && (resources_for_prioritised(j-(len_dd/2), Smartphone_users+3) > 0)
resources_for_prioritised(j,Smartphone_users+3) = 0;
elseif (resources_for_prioritised(j,Smartphone_users+3) < resources_for_prioritised (j-(len_dd/2),Smartphone_users+3)) && (resources_for_prioritised(j,Smartphone_users+3) > 0)
resources_for_prioritised(j-(len_dd/2),Smartphone_users+3) = 0;
end
end
end
doc_loc= 1;
for j = 1:1:len_dd
if resources_for_prioritised(j,Smartphone_users+3) == 0
to_del_dd(loc_dd) = j;
doc_loc= doc_loc+ 1;
end
end
if doc_loc> 1
rates_for_prioritised(to_del_dd,:) = [];
resources_for_prioritised(to_del_dd,:) = [];
end
[len_ddd,~] = size(rates_for_prioritised);
resources_for_prioritised_secure = resources_for_prioritised;
rates_for_prioritised_secure = rates_for_prioritised;
% find highest rate for prioritised smartphone and delete all lines with lower rates
for f = 7:-1:1
if (any(rates_for_prioritised(:,1) == f)) || (any(rates_for_prioritised(:,1) == f+7))
highest = f;
break
end
end
loc_bb = 1;
for f = 1:1:len_ddd
if (rates_for_prioritised(f,1) < highest) || ((rates_for_prioritised(f,1) > highest) && (rates_for_prioritised(f,1) < (highest+7)))
to_del_two(loc_bb) = f;
loc_bb = loc_bb + 1;
end
end
if loc_bb > 1
rates_for_prioritised(to_del_bb,:) = [];
resources_for_prioritised(to_del_bb,:) = [];
end
[len_dddd,~] = size(rates_for_prioritised);
P_smartphone_DB_min = min(rates_for_prioritised(:,1));
```

```
P_smartphone_DB_max = max(rates_for_prioritised(:,1));
% choose the least expensive combination
if len_dddd > 1
min_for_b = min(resources_for_prioritised(:,Smartphone_users+3));

[line_min_b, ~] = ind2sub(size(resources_for_prioritised),find(resources_for_prioritised==min_for_b));
[len_d5,~] = size(line_min_b);
for f = 1:1:len_d5
base_the_the_target(f,:) = rates_for_prioritised(line_min_b(f),:);
resources_base(f,:) = resources_for_prioritised(line_min_b(f),:);
end

else
base_the_target = rates_for_prioritised;
resources_base = resources_for_prioritised;
end
end
end
% Check if non-prioritised smartphones can be upgraded
% determine optimal combination for non-prioritised smartphones
% setup short combination table
for f = 2:1:Smartphone_users
x(f) = base_the_the_target(1,f);
if x(f) < 8
b(f) = x(f) + 7;
a(f) = x(f);
else
b(f) = x(f);
a(f) = x(f) - 7;
end
one(f) = a(f)+3;
if one(f) > 7
one(f) = 7;
end
two(f) = b(f)+3;
if two(f) > 14
two(f) = 14;
end
end
data_in = {[a(2):one(2) b(2):two(2)],[a(3):one(3) b(3):two(3)],[a(4):one(4) b(4):two(4)],[a(5):one(5) b(5):two(5)],[a(6):one(6) b(6):two(6)]};
sub_combination = combine_all(data_in{:});
[len_e,~] = size(sub_combination);
sub_combination_secure_1 = sub_combination;
% remove the combinations  that  are not valid
to_del_c = [];
loc_c = 1;
for f = 1:1:len_e
if ((~any(sub_combination(f,:) == a(2))) && (~any(sub_combination(f,:) == b(2))))
to_del_c(loc_c) = f;
loc_c = loc_c + 1;
```

```
end
end
sub_combination(to_del_c,:) = [];
sub_combination_secure_a = sub_combination;
[len_f,columns_f] = size(sub_combination);
if P_smartphone_DB_min == P_smartphone_DB_max% setup the bit rate table (rates_last) and resources table
for i = 1:1:len_f
rates_last(i,1) = base_the_the_target(1,1); % rate of prioritised smartphone
end
rates_terminal(:,2:1+columns_f) = sub_combination(:,1:columns_f);
rates_terminal(len_f,(2*Smartphone_users)+4) = 0;
else
for i = 1:1:len_f
rates_terminal(i,1) = highest; % rate of prioritised smartphone
end
for i = len_f+1:1:2*len_f
rates_terminal(i,1) = highest+7; % rate of prioritised smartphone
end
 rates_terminal(1:len_f,2:1+columns_f) = sub_combination(1:len_f,1:columns_f);
rates_terminal(len_f+1:2*len_f,2:1+columns_f) = sub_combination(1:len_f,1:columns_f)
rates_terminal(2*len_f,(2*Smartphone_users)+4) = 0;
len_f = len_f *2
end
rates_terminal_secure_a =  rates_terminal;
for j = 1:1:len_f
for k = 1:1:Smartphone_users
if ( rates_terminal(j,k) == 1)
if Smartphone_user_table(k,4+1) ~= 0
rates_terminal(j,Smartphone_users+1+k) = 0.1;
else
rates_terminal(j,Smartphone_users+1+k) = 0;
end
final_resources(j,k) = Smartphone_user_table(k,5);
elseif ( rates_terminal(j,k) == 2)
if Smartphone_user_table(k,4+2) ~= 0
rates_terminal(j,Smartphone_users+1+k) = 0.2;
else

rates_terminal(j,Smartphone_users+1+k) = 0;
end
final_resources(j,k) = Smartphone_user_table(k,6);
elseif ( rates_terminal(j,k) == 3)
if Smartphone_user_table(k,4+3) ~= 0
rates_terminal(j,Smartphone_users+1+k) = 0.3;
else
rates_terminal(j,Smartphone_users+1+k) = 0;
end
```

```
final_resources(j,k) = Smartphone_user_table(k,7);
elseif ( rates_terminal(j,k) == 4)
if Smartphone_user_table(k,4+4) ~= 0
rates_terminal(j,Smartphone_users+1+k) = 0.4;
else
rates_terminal(j,Smartphone_users+1+k) = 0;
end
final_resources(j,k) = Smartphone_user_table(k,8);
elseif ( rates_terminal(j,k) == 5)
if Smartphone_user_table(k,4+5) ~= 0
rates_terminal(j,Smartphone_users+1+k) = 0.8;
else
rates_terminal(j,Smartphone_users+1+k) = 0;
end
final_resources(j,k) = Smartphone_user_table(k,9);
elseif ( rates_terminal(j,k) == 6)
if Smartphone_user_table(k,4+6) ~= 0
rates_terminal(j,Smartphone_users+1+k) = 1.2;
else
rates_terminal(j,Smartphone_users+1+k) = 0;
end
final_resources(j,k) = Smartphone_user_table(k,10);
elseif ( rates_terminal(j,k) == 7)
if Smartphone_user_table(k,4+7) ~= 0
rates_terminal(j,Smartphone_users+1+k) = 2;
else
rates_terminal(j,Smartphone_users+1+k) = 0;
end
final_resources(j,k) = Smartphone_user_table(k,11);
elseif ( rates_terminal(j,k) == 8)
if Smartphone_user_table(k,4+8) ~= 0
rates_terminal(j,Smartphone_users+1+k) = 0.1;
else
rates_terminal(j,Smartphone_users+1+k) = 0;
end
final_resources(j,k) = Smartphone_user_table(k,19);
elseif ( rates_terminal(j,k) == 9)
if Smartphone_user_table(k,4+9) ~= 0
rates_terminal(j,Smartphone_users+1+k) = 0.2;
else
rates_terminal(j,Smartphone_users+1+k) = 0;
end
final_resources(j,k) = Smartphone_user_table(k,20);
elseif ( rates_terminal(j,k) == 10)
if Smartphone_user_table(k,4+10) ~= 0
rates_terminal(j,Smartphone_users+1+k) = 0.3;
else
rates_terminal(j,Smartphone_users+1+k) = 0;
end
```

```
final_resources(j,k) = Smartphone_user_table(k,21);
elseif ( rates_terminal(j,k) ==11)
if Smartphone_user_table(k,4+11) ~= 0
rates_terminal(j,Smartphone_users+1+k) = 0.4;
else
rates_terminal(j,Smartphone_users+1+k) = 0;
end
final_resources(j,k) = Smartphone_user_table(k,22);
elseif ( rates_terminal(j,k) == 12)
if Smartphone_user_table(k,4+12) ~= 0
rates_terminal(j,Smartphone_users+1+k) = 0.8;
else
rates_terminal(j,Smartphone_users+1+k) = 0;
end
final_resources(j,k) = Smartphone_user_table(k,23);
elseif ( rates_terminal(j,k) == 13)
if Smartphone_user_table(k,4+13) ~= 0
rates_terminal(j,Smartphone_users+1+k) = 1.2;
else
rates_terminal(j,Smartphone_users+1+k) = 0;
end
final_resources(j,k) = Smartphone_user_table(k,24);
elseif ( rates_terminal(j,k) == 14)
if Smartphone_user_table(k,4+14) ~= 0
rates_terminal(j,Smartphone_users+1+k) = 2;
else
rates_terminal(j,Smartphone_users+1+k) = 0;
end
final_resources(j,k) = Smartphone_user_table(k,25);
end

if  rates_terminal(j,k) >= 8
rates_terminal(j,(2*Smartphone_users)+3) =  rates_terminal(j,(2*Smartphone_users) +3) +  rates_terminal(j,Smartphone_users+1+k); % determine THE_TARGETED_RATES for cluster head
end
end

rates_terminal(j,(2*Smartphone_users)+4) = sum( rates_terminal(j, Smartphone_users+2: (2*Smartphone_users)+1));
[ final_resources(j,Smartphone_users+2) ] = Smartphone_direct( rates_terminal(j, (2*Smartphone_users)+3), PCHdB, CH_distance); % resources cluster head

if ( rates_terminal(j,(2*Smartphone_users)+3) > 0) && (final_resources(j, Smartphone_users+2) == 0)
final_resources(j,Smartphone_users+2) = 100 ;
end

final_resources(j,Smartphone_users+3) = sum(final_resources(j,1: Smartphone_users+2));
if (sum(final_resources(j,Smartphone_users+3)) > 50) || (any(final_resources(j,1:
```

```
Smartphone_users) == 0))
final_resources(j,Smartphone_users+3) = 0;
end
if j > (len_f/2)

if (final_resources(j,Smartphone_users+3) >= final_resources(j-(len_f/2), Smartphone_users+3)) && (final_resources(j-(len_f/2),Smartphone_users+3) > 0)
final_resources(j,Smartphone_users+3) = 0;
elseif (final_resources(j,Smartphone_users+3) < final_resources(j-(len_f/2), Smartphone_users+3)) && (final_resources(j,Smartphone_users+3) > 0)
final_resources(j-(len_f/2),Smartphone_users+3) = 0;
end
end
end
rates_terminal_secure_b =  rates_terminal;
final_resources_secure_b = final_resources;
[len_g,~] = size( rates_terminal);
[len_gg,~] = size(final_resources);
if len_g ~= len_gg
final_resources(len_g,9) = 0;
end
loc_d = 1;
for j = 1:1:len_g
if final_resources(j,Smartphone_users+3) == 0
to_del_d(loc_d) = j;
loc_d = loc_d + 1;
end
end
if loc_d > 1
rates_terminal(to_del_d,:) = [];
final_resources(to_del_d,:) = [];
end
[ h_length,~] = size( rates_terminal);
rates_terminal_secure_c =  rates_terminal;
final_resources_secure_c = final_resources;
resources_ideal = [];
rates_ideal = [];
if  h_length > 1
for d = 1:1:Smartphone_users-1
[~, start_for(1,d)] = find(abs(THE_TARGETED_RATES-base_the_the_target(1, Smartphone_users+2+d)) < 0.001);
end
n = 0; % for the lines
m = 1; % for the count
for_that = [];
doc_loc= 1;
for f = 1:1: h_length
flag = 0;
for_that(f,Smartphone_users) = 0;
for d = 1:1:Smartphone_users-1
```

```
if ( rates_terminal(f,Smartphone_users+2+d) > base_the_the_target(1, Smartphone_users+2+d))
for_that(f,d) = find(abs(THE_TARGETED_RATES-rates_terminal(f,Smartphone_users+2+d)) < 0.001) - start_for(1,d);
n = n + 1;
elseif ( rates_terminal(f,Smartphone_users+2+d) < base_the_the_target(1, Smartphone_users+2+d))
for_that(f,d) = -10;
n = n + 1;
end
for_that(f,Smartphone_users) = sum (for_that(f,1:Smartphone_users-1));
end
de_mos(m,1) = n;
m = m+1;
n = 0;
end
if doc_loc> 1
rates_terminal(to_del_dd,:) = [];
final_resources(to_del_dd,:) = [];
for_that(to_del_dd,:) = [];
end
[ h_length,~] = size( rates_terminal);
rates_terminal_secure_c1 =  rates_terminal;
final_resources_secure_c1 = final_resources;
for_that_secure_c1 = for_that;
de_mos_max_a = max(max(for_that(:,1:Smartphone_users-1))) %
if (de_mos_max_a > 2) && (one(2) < 7)
[  rates_terminal, final_resources, for_that, de_mos ] = Optimal_6_long_run_v02(a, aa, b, bb,Smartphone_user_table, base_the_target, THE_TARGETED_RATES, Smartphone_users, PCHdB, CH_distance, P_smartphone_DB_min, P_smartphone_DB_max, highest)
[ h_length,~] = size( rates_terminal);
end
rates_terminal_secure_cc =  rates_terminal;
final_resources_secure_cc = final_resources;
for_that_secure_cc = for_that;
de_mos_smartphones_b = max(de_mos(:,1));
for_that_max = max(for_that(:,Smartphone_users));
if for_that_max > 0
loc_e = 1;
for j = 1:1: h_length
if sum(for_that(j,1:Smartphone_users-1)~=0) < de_mos_smartphones_b
to_del_e(loc_e) = j;
loc_e = loc_e + 1;
end
end
if loc_e > 1
rates_terminal(to_del_e,:) = [];
final_resources(to_del_e,:) = [];
```

```
for_that(to_del_e,:) = [];
end
[len_i,~] = size( rates_terminal);
rates_terminal_secure_d =  rates_terminal;
final_resources_secure_d = final_resources;
for_that_secure_d = for_that;
candidate_1=  rates_terminal(1,:);
candidate_1_res= final_resources(1,:);
if len_i > 1
for f = 1:1:len_i-1
can_1(f,:) = candidate_1;
a = 1;
diff_can_1 = [0]
diff_can_2 = [0]
candidate_2 =  rates_terminal_secure_d(f+1,:)
candidate_2_res = final_resources_secure_d(f+1,:);
for d = Smartphone_users+2:1:(2*Smartphone_users)+1
if candidate_1(1,d) ~= candidate_2(1,d)
diff_can_1(a) = candidate_1(1,d)
d_can_1(f,a) = candidate_1(1,d)
diff_can_2(a) = candidate_2(1,d)
d_can_2(f,a) = candidate_2(1,d)
a = a + 1
end
end
if a > 1
count_d = 0
[len_i] = length(diff_can_1)
for g = 1:1:len_i
if diff_can_1(g) < diff_can_2(g)
count_d = count_d + 1
elseif diff_can_1(g) > diff_can_2(g)
count_d = count_d - 1
end
end
if len_i == 1
if count_d == 1
candidate_1= candidate_2
candidate_1_res= candidate_2_res;
end
elseif len_i == 2
if (count_d == 2) || ((count_d == 0) && (min(diff_can_1) < min(diff_can_2)))
candidate_1= candidate_2
candidate_1_res= candidate_2_res;
elseif ((count_d == 0) && (min(diff_can_1) == min(diff_can_2)) && (max(diff_can_1) == max(diff_can_2)))
if candidate_1_res(1,Smartphone_users+3) > candidate_2_res(1,Smartphone_users+3)
candidate_1= candidate_2
candidate_1_res= candidate_2_res;
end
```

```
end
elseif len_i == 3
if (count_d == 3) || ((count_d == -1) && (min(diff_can_1) < min(diff_can_2))) || ((count_d == -1) && (min(diff_can_1) == min(diff_can_2)) && (sum(diff_can_1(:)== max(diff_can_1(:)))) < (sum(diff_can_2(:)== max(diff_can_2(:)))) && (min(diff_can_2) == max(diff_can_2)) )...
((count_d == 1) && (min(diff_can_1) == min(diff_can_2)) && (max(diff_can_1) < max(diff_can_2)) )
candidate_1= candidate_2
candidate_1_res= candidate_2_res;
end
end
else
if candidate_1_res(1,Smartphone_users+3) > candidate_2_res(1,Smartphone_users+3)
candidate_1= candidate_2;
candidate_1_res= candidate_2_res;
end
end
end
end
rates_ideal = candidate_1;
resources_ideal = candidate_1_res;
else
resources_ideal = final_resources(1,:);
rates_ideal =  rates_terminal(1,:);
[len_k2,~] = size( rates_terminal);
if len_k2 > 1
for f = 1:1:len_k2
if final_resources(f,Smartphone_users+3) < resources_ideal(1,Smartphone_users+3)
resources_ideal = final_resources(f,:);
rates_ideal =  rates_terminal(f,:);
end
end
end
end
else
rates_ideal =  rates_terminal;
resources_ideal = final_resources;
end
end
function [  rates_terminal, final_resources, for_that, de_mos ] = Optimal_6_long_run(a, aa, b, bb,Smartphone_user_table, base_the_target, THE_TARGETED_RATES, Smartphone_users, PCHdB, CH_distance, P_smartphone_DB_min, P_smartphone_DB_max, highest)

data_in = {[a(2):7 b(2):14],[a(3):7 b(3):14],[a(4):7 b(4):14],[a(5):7 b(5):14],[a(6):7 b(6):14]};
sub_combination = combine_all(data_in{:});
[len_e,~] = size(sub_combination);
to_del_c = [];
```

```
loc_ = 1;
for f = 1:1:len_e
if ((~any(sub_combination(f,:) == a(2))) && (~any(sub_combination(f,:) == b(2))))
to_del_c(loc_) = f;
loc_ = loc_ + 1;
end
end
sub_combination(to_del_c,:) = [];
[len_f,columns_f] = size(sub_combination);
if P_smartphone_DB_min == P_smartphone_DB_max
for i = 1:1:len_f
rates_terminal(i,1) = base_the_the_target(1,1); % rate of prioritised SUE
end
rates_terminal(:,2:1+columns_f) = sub_combination(:,1:columns_f);
rates_terminal(len_f,(2*Smartphone_users)+4) = 0;
else
for i = 1:1:len_f
rates_terminal(i,1) = highest; % rate of priorotised smartphone
end
for i = len_f+1:1:2*len_f
rates_terminal(i,1) = highest+7; % rate of prioritised smartphone
end
rates_terminal(1:len_f,2:1+columns_f) = sub_combination(1:len_f,1:columns_f);
rates_terminal(len_f+1:2*len_f,2:1+columns_f) = sub_combination(1:len_f,1:
columns_f);
rates_terminal(2*len_f,(2*Smartphone_users)+4) = 0;
len_f = len_f *2;
end
rates_terminal_secure_c =  rates_terminal;
for j = 1:1:len_f
for k = 1:1:Smartphone_users
if ( rates_terminal(j,k) == 1)
if Smartphone_user_table(k,4+1) ~= 0
rates_terminal(j,Smartphone_users+1+k) = 0.1;
else
rates_terminal(j,Smartphone_users+1+k) = 0;
end
final_resources(j,k) = Smartphone_user_table(k,5);
elseif ( rates_terminal(j,k) == 2)
if Smartphone_user_table(k,4+2) ~= 0
rates_terminal(j,Smartphone_users+1+k) = 0.2;
else
rates_terminal(j,Smartphone_users+1+k) = 0;
end
final_resources(j,k) = Smartphone_user_table(k,6);
elseif ( rates_terminal(j,k) == 3)
if Smartphone_user_table(k,4+3) ~= 0
rates_terminal(j,Smartphone_users+1+k) = 0.3;
else
rates_terminal(j,Smartphone_users+1+k) = 0;
```

```
end
final_resources(j,k) = Smartphone_user_table(k,7);
elseif ( rates_terminal(j,k) == 4)
if Smartphone_user_table(k,4+4) ~= 0
rates_terminal(j,Smartphone_users+1+k) = 0.4;
else
rates_terminal(j,Smartphone_users+1+k) = 0;
end
final_resources(j,k) = Smartphone_user_table(k,8);
elseif ( rates_terminal(j,k) == 5)
if Smartphone_user_table(k,4+5) ~= 0
rates_terminal(j,Smartphone_users+1+k) = 0.8;
else
rates_terminal(j,Smartphone_users+1+k) = 0;
end
final_resources(j,k) = Smartphone_user_table(k,9);
elseif ( rates_terminal(j,k) == 6)
if Smartphone_user_table(k,4+6) ~= 0
rates_terminal(j,Smartphone_users+1+k) = 1.2;
else
rates_terminal(j,Smartphone_users+1+k) = 0;
end
final_resources(j,k) = Smartphone_user_table(k,10);
elseif ( rates_terminal(j,k) == 7)
if Smartphone_user_table(k,4+7) ~= 0
rates_terminal(j,Smartphone_users+1+k) = 2;
else
rates_terminal(j,Smartphone_users+1+k) = 0;
end
final_resources(j,k) = Smartphone_user_table(k,11);
elseif ( rates_terminal(j,k) == 8)
if Smartphone_user_table(k,4+8) ~= 0
rates_terminal(j,Smartphone_users+1+k) = 0.1;
else
rates_terminal(j,Smartphone_users+1+k) = 0;
end
final_resources(j,k) = Smartphone_user_table(k,19);
elseif ( rates_terminal(j,k) == 9)
if Smartphone_user_table(k,4+9) ~= 0
rates_terminal(j,Smartphone_users+1+k) = 0.2;
else
rates_terminal(j,Smartphone_users+1+k) = 0;
end
final_resources(j,k) = Smartphone_user_table(k,20);
elseif ( rates_terminal(j,k) == 10)
if Smartphone_user_table(k,4+10) ~= 0
rates_terminal(j,Smartphone_users+1+k) = 0.3;
else
rates_terminal(j,Smartphone_users+1+k) = 0;
```

```
end
final_resources(j,k) = Smartphone_user_table(k,21);
elseif ( rates_terminal(j,k) ==11)

if Smartphone_user_table(k,4+11) ~= 0
rates_terminal(j,Smartphone_users+1+k) = 0.4;
else
rates_terminal(j,Smartphone_users+1+k) = 0;
end
final_resources(j,k) = Smartphone_user_table(k,22);
elseif ( rates_terminal(j,k) == 12)
if Smartphone_user_table(k,4+12) ~= 0
rates_terminal(j,Smartphone_users+1+k) = 0.8;
else
rates_terminal(j,Smartphone_users+1+k) = 0;
end
final_resources(j,k) = Smartphone_user_table(k,23);
elseif ( rates_terminal(j,k) == 13)
if Smartphone_user_table(k,4+13) ~= 0
rates_terminal(j,Smartphone_users+1+k) = 1.2;
else
rates_terminal(j,Smartphone_users+1+k) = 0;
end
final_resources(j,k) = Smartphone_user_table(k,24);
elseif ( rates_terminal(j,k) == 14)
if Smartphone_user_table(k,4+14) ~= 0
rates_terminal(j,Smartphone_users+1+k) = 2;
else
rates_terminal(j,Smartphone_users+1+k) = 0;
end
final_resources(j,k) = Smartphone_user_table(k,25);
end
if  rates_terminal(j,k) >= 8
rates_terminal(j,(2*Smartphone_users)+3) =  rates_terminal(j,(2*Smartphone_users) +3)
    +  rates_terminal(j,Smartphone_users+1+k); % determine THE_TARGETED_RATES
    for cluster head
end
end

rates_terminal(j,(2*Smartphone_users)+4) = sum( rates_terminal(j,
Smartphone_users+2: (2*Smartphone_users)+1));

[ final_resources(j,Smartphone_users+2) ] = Smartphone_direct( rates_terminal(j,
(2*Smartphone_users)+3), PCHdB, CH_distance); % resources cluster head
if ( rates_terminal(j,(2*Smartphone_users)+3) > 0) && (final_resources(j,
Smartphone_users+2) == 0)
final_resources(j,Smartphone_users+2) = 100 ;
end
final_resources(j,Smartphone_users+3) = sum(final_resources(j,1:
Smartphone_users+2));
```

```
if (sum(final_resources(j,Smartphone_users+3)) > 50) || (any(final_resources(j,1:Smartphone_users) == 0))
final_resources(j,Smartphone_users+3) = 0;
end
if j > (len_f/2)
if (final_resources(j,Smartphone_users+3) >= final_resources(j-(len_f/2),Smartphone_users+3)) && (final_resources(j-(len_f/2),Smartphone_users+3) > 0)
final_resources(j,Smartphone_users+3) = 0;

elseif (final_resources(j,Smartphone_users+3) < final_resources(j-(len_f/2),Smartphone_users+3)) && (final_resources(j,Smartphone_users+3) > 0)
final_resources(j-(len_f/2),Smartphone_users+3) = 0;
end
end
end
rates_terminal_secure_b =  rates_terminal;
final_resources_secure_b = final_resources;
[len_g,~] = size( rates_terminal);
loc_d = 1;
for j = 1:1:len_g
if final_resources(j,Smartphone_users+3) == 0
to_del_d(loc_d) = j;
loc_d = loc_d + 1;
end
end
if loc_d > 1
rates_terminal(to_del_d,:) = [];
final_resources(to_del_d,:) = [];
end
[ h_length,~] = size( rates_terminal);
rates_terminal_secure_c =  rates_terminal;
final_resources_secure_c = final_resources;
for d = 1:1:Smartphone_users-1
[~, start_for(1,d)] = find(abs(THE_TARGETED_RATES- rates_terminal(1,Smartphone_users+2+d)) < 0.001);
start_rate(1,d) =  rates_terminal(1,Smartphone_users+2+d);
end
n = 0; % Lines
m = 1; % count
for_that = [];
Enhancement_best = [];
for f = 1:1: h_length
for_that(f,Smartphone_users) = 0;
for d = 1:1:Smartphone_users-1

if ( rates_terminal(f,Smartphone_users+2+d) >  rates_terminal(1,Smartphone_users+2+d))
for_that(f,d) = find(abs(THE_TARGETED_RATES-rates_terminal(f,Smartphone_users+2+d)) <
```

```
0.001) - start_for(1,d);
n = n + 1;
elseif ( rates_terminal(f,Smartphone_users+2+d) <  rates_terminal(1,
Smartphone_users+2+d))
for_that(f,d) = -10;
n = n + 1;
end
for_that(f,Smartphone_users) = sum (for_that(f,1:Smartphone_users-1));
end
de_mos(m,1) = n;
m = m+1;
n = 0;
end
\de_mos_max_a = max(max(for_that(:,1:Smartphone_users-1)));
end
```