Architecture Design for Disaster Resilient Management Network Using D2D Technology

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I would like to dedicate this thesis to my loving parents, my family!

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Abstract

Huge damages from natural disasters, such as earthquakes, floods, landslide, tsunamis, have been reported in recent years, claiming many lives, rendering millions homeless and causing huge financial losses worldwide. The lack of effective communication between the public rescue/safety agencies, rescue teams, first responders and trapped survivors/victims makes the situation even worse. Factors like dysfunctional communication networks, limited communications capacity, limited resources/services, data transformation and effective evaluation, energy, and power deficiency cause unnecessary hindrance in rescue and recovery services during a disaster. The new wireless communication technologies are needed to enhance life-saving capabilities and rescue services. In general, in order to improve societal resilience towards natural catastrophes and develop effective communication infrastructure, innovative approaches need to be initiated to provide improved quality, better connectivity in the events of natural and human disasters.

In this thesis, a disaster resilient network architecture is proposed and analysed using multi-hop communications, clustering, energy harvesting, throughput optimization, reliability enhancement, adaptive selection, and low latency communications. It also examines the importance of mode selection, power management, frequency and time resource allocation to realize the promises of Long-term Evolution (LTE) Device to Device (D2D) communication. In particular, to support resilient and energy efficient communication in disaster-affected areas.

This research is examined by thorough and vigorous simulations and validated through mathematical modelling. Overall, the impact of

this research is twofold: i) it provides new technologies for effective inter- and intra-agency coordination system during a disaster event by establishing a stronger and resilient communication; and ii) It offers a potential solution for stakeholders such as governments, rescue teams, and general public with new informed information on how to establish effective policies to cope with challenges before, during and after the disaster events.

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Acronyms

AP	Access Point
BS	Base Station
CH	Cluster Head
CM	Cluster Members
CTS	Clear-to-Send
DSRC	Dedicated Short Range Communication
DSC	Drone Small Cells
ECD	Emergency Channel Demand
5G	5th Generation Mobile Network
GPRS	Global Positioning System
GSM	Global System for Mobile
HPPP	Homogeneous Poisson Point Process
IP	Internet Protocol
IoT	Internet of Things
LAN	Local Area Network
LoS	Line of Sight

LTE	Long Term Evolution
MAC	Medium Access Control
M2M	Machine-to-Machine
MATLAB	Matrix Laboratory
MIMO	Multiple-input Multiple-output
MDRU	Movable and Deployable Resource Units
NLoS	Non-Light-of-Sight
NTT	Nippon Telegraph And Telephone Corporation
OBU	On-board Units
ProS	Proximity Services
PE	Power Splitting
PS	Public Safety
QoE	Quality of Experience
QoS	Quality of Service
RG	Resource Groups
RTS	Ready-to-Send
RF	Radio Frequency
RAT	Radio Access Technology
RSU	Road-side Unit
RSR	Received Signal Strength
SWIPT	Simultaneous Wireless Information and Power Transfer
SINR	Signal to interference Noise Ratio

TDMA	Time Division Multiple Access
TS	Time Switching
3GPP	Third Generation Partnership Project
TCP	Transmission Control Protocol
UDP	User Datagram Protocol
UER	User Equipment Relay
UERCH	User Equipment Relay and Cluster Head
UMTS	Universal Mobile Telecommunications Systems
UE	User Equipment
UMTS	Universal Mobile Telecommunications System
V2I	Vehicle-to-Infrastructure
V2V	Vehicle-to-Vehicle
VANET	Vehicular Ad-hoc Network
WLAN	Wireless Local Area Network
WEH	Wireless Energy Harvesting

Chapter 1

Introduction

1.1 Introduction

Information and communication technologies (ICT) provide vital services and systems for our daily lives as well as in emergency and disaster situations. Many people around the world are adversely affected by various unforeseen disasters such as earthquakes, tsunami, volcanic eruptions and floods. Unfortunately, the number of such disasters are on a rise worldwide and has increased substantially over the second half of the twentieth century. Disasters and emergency crisis are usually unpredicted events that cause panic conditions in the civilian and affect existing resources. The need for communication and other types of information exchange services is at its peak after such drastic events. The communication infrastructure is often damaged to large extents, making services unavailable or at least heavily congested. In disaster situations, communication system have been developed to endure services and network connectivity in different manner. In such situations, neither these helpless people are able to communicate with their relatives nor rescue teams to help them. Furthermore, it is also difficult for rescue teams to communicate with each other in order to provide effective assistance to the people who are spread over the disaster affected area. There are numerous approaches available to maximize availability: redundancy, reliability, repairability, recoverability and robustness of information communication system.

In recent years, the focus of research in disaster communication system has been on designing architecture that allows affected people in disaster situations to communicate with outside area and rescue teams. However, most of the present disaster communication systems rely on an existing network infrastructure and fail to provide services because of physical destruction of network equipment. An effective disaster response operation should provide help and rescue to the victims at the right time. Asia has been struck frequently with various disasters in the last decade, one would remember the 9.1-richter earthquake that hit the wide area of Japan on 11th March 2011 Noguchi (2012), which resulted in an incredible giant tsunami spell on the seashores of the whole Pacific area. Recent earthquakes of Italy, Iran, Nepal, and New Zealand destroyed huge number of buildings and vast amount of facilities over cities, town, and villages. This alter us to think that disaster may spell us at any scale at any time without premonition and on the other hand this evokes discussion how an efficient, reliable and resilient disaster communication architecture design in place could have helped in preventing and minimizing the loss of lives and property.

The next generation public safety network (PSN), with its mission-critical aspect and the ever increasing demand for rich-content-based applications, requires a standard shift not only in sharing and managing the connectivity, but also in designing the architecture. Whereas commercial wireless networks are evolving at a high pace to sophisticated standards, such as Long Term Evolution (LTE), the PSNs has not gone through such an evolution mainly due to lack of commercial incentives. PSN communications still largely use traditional land mobile radio system standards, such as Project 25 (P25) and terrestrial trunked radio (TETRA) Sohul et al. (2016). These systems have been in use for about more than 20 years. They are mature and reliable in supporting critical communication applications. However, they are not designed to support higher bandwidth applications, because they are mostly based on narrowband system. Academia and research communities are working on gap, and in particular, the LTE mobile radio technology has widely been envisaged as a basic technology for the evolution of PSN communication systems Fantacci et al. (2016). The 3GPP Release 12 introduces the support to Device to Device (D2D) or direct-mode communications in LTE, enabling Peer-to-Peer (P2P) transmissions between devices in proximity Astely et al. (2013).

LTE is now growing to the challenge of addressing numerous concerns (e.g., cellular networks capacity, ultra-high bandwidth, ultra-low latency, massive numbers of connections, fast mobility, and diverse spectrum access) that speed up the pace toward 5G. Moreover, LTE is expected to be an important part of the 5G solution for future networks and to play a vital role in advancing public safety (PS) communications. In the United States, LTE has been chosen up as the next appropriate communication technology to support PSNs, and it is likely to be the same elsewhere in the world too. Thus, several vendors (e.g., Ericsson, Nokia-Alcatel, Huawei, Cisco, Motorola, Thales) are now starting to propose LTE-based PSN solutions, and some of them have been put to real field experimentation Favraud et al. (2016).

1.2 Problem Statement

The communications technologies provide very important capabilities to PSN in various operational scenarios, where timely coordination is crucial, fixed communications may not be available and support for mobility. Therefore, wireless broadband networks are essential to many sectors of the society, and thus they should be robust to resist several types of failures. The malfunction of crucial infrastructures such as the cellular network, Internet, smart grids and power breakdown resulting from natural disasters (e.g., earthquakes, flood and hurricanes) would have devastating impact on the common operation of the society. In large-scale and complex networks, numerous links can cause extensive connectivity losses and affect many mission-critical applications and services that public safety agencies rely on. Frequently occurring large-scale natural disasters have been reported to cause great damage in recent years, claiming many people's lives, rendering millions people homeless, and causing huge financial loss.

In the emergency scenarios, like the aftermath of disaster, the first 24 to 72 hours are tend to be a very chaotic as well as critical period for instant rescue and lifesaving activities. For this reason, a fast communication system must be deployed in the disaster area to allow a fast cooperation among the first responders and survivors.

ICT service stupendously increases just after the events, when people from the affected zones desperately seek to communicate with friends and family both inside and outside of the disaster stricken zones. Therefore, these states instigate serious traffic congestion in both fixed-line and mobile telephone services. If new site set-ups, the costs of set-up, operating, maintaining activities and human resources reaches beyond the limit. From the traditional disaster communication infrastructure we learned that, increasing the number of sites means multiple the amount of cost. Apart from high cost, the requirement of the double infrastructures during critical situation leads many other technical issues such as, reliability and the major challenges of power, energy efficiency, bandwidth limitation, and communication connectivity still remain a concern.

1.3 Research Aims and Objectives

The aim of this thesis is to design disaster resilient network architecture system that is able to cope with the hazardous conditions of an emergency situation where the communication infrastructure is not sufficient to support the rescue teams and victims. The speed of the intervention by the public safety agencies is of utmost importance for the outcome of the rescue operations. For this reasons the ambition of this thesis is twofold: i) the analysis and the development of self-organizing autonomous systems that are capable of rapidly covering the disaster area in order to re-establish the network connectivity; ii) study and design of autonomous systems that will enable the end-user devices, owned by both the survivors and the rescue teams, to create spontaneous communication networks that will facilitate the cooperation during the rescue operations.

Alongside addressing the main issues highlighted above, the ultimate goal is to design a disaster resilient network architecture which includes the integration of modern computing technologies and also offer effective provision in regards to disaster communication and management system.

“**Architecture design for resilient management network using D2D technology”**

This research is focused on designing and development of secure and generic architecture (artefacts) for disaster communication. Fast and effective response to disaster is desirable. Moreover availability, reliability, robustness and recovery are the most important features required due to unpredictable situations which are common in the disaster areas. It is essential to provide adaptive and efficient connectivity with sufficient QoS between the relief organizations and the victims. Furthermore, the development of systems able to deal with above mentioned problems which needs a complete architecture that will help to analysis and the planning of the future emergency systems. This thesis, in fact, proposes new architectural designs for the deployment of new devices that will have self-organizing properties and will be able to self-configure in order to face the difficulties in an unknown environment of a post disaster scenario. This is the basic motivation behind designing of disaster-resilient communication network and management system.

Considering the scope above, the main research question of this thesis has been underlined in the next subsection.

1.3.1 Key Research Questions

In order to propose new architectural designs, some of the key research questions that have to be addressed in this thesis are:

1.4 Research Objectives

1. To examine the challenges and constraints within traditional ICT disaster architecture and uncover the primary context of disaster communication failures.
2. To analyse the next generation of wireless technologies suitable for disaster communication system.
3. To examine the applicability of D2D technology, new communication approaches will be designed to tackle safety and emergency concerns where conventional methods of communication would not be available.
4. To utilize relay communication (single or multi-hop) to extend coverage area for information sharing during disaster.

5. To examine mode selection strategy for D2D communication suitability during disaster and analyse energy harvesting, energy efficiency and capacity during communication.

6. To enhance disaster communication framework using Unmanned Aerial Vehicles (UAVs) communication in the context of 5G.

1.5 Thesis outline and contributions

In this thesis, the focus is how to improve the connectivity and performance of device to device communication which enabled cellular systems by means of proper design and coordination of radio resource management techniques. Specifically, we recognize the importance of mode selection, power management and frequency/time resource allocation to realize the promises of D2D communication. The outline of the thesis, together with the publications supporting the contributions, is as follows:

Chapter 2, details an in-depth literature review on disaster management communication network. It discusses the challenges and issues while designing the network architecture, details the factors that caused unnecessary hindrance to the previous disaster system response operations. Moreover, this chapter presenting the challenges, services, features and requirement of a robust disaster management communication network by exploiting future based wireless technologies. This chapter includes part of the material in:

- K. Ali, H. X. Nguyen, Q. T. Vien, and P. Shah, "Disaster Management Communication Networks: Challenges and Architecture Design," *Pervasive Computing and Communication Workshops (PerCom)*, USA, Mar. 2015.

- Kamran Ali, Huan X. Nguyen, Purav Shah, Quoc-Tuan Vien and Enver Ever,"Internet of Things (IoT) Considerations, Requirements, and Architectures for Disaster Management System," in book *EAI/Springer Innovations in Communication and Computing*, 2018.

Chapter 3, we introduce the D2D technology, focusing on the context of D2D technology integrated in cellular systems. Potential usages that might be promoted by cellular user proximity are listed. To support these usages, we analyse general functions that need to be provided by LTE D2D. Moreover, we present an in-depth discussion on the main resource management techniques for D2D-enabled networks, together with single and multi-hop relay techniques. The content of this chapter is based on:

- K. Ali, H. X. Nguyen, P. Shah, Q. T. Vien, and N. Bhuvanasundaram, "Architecture for Public Safety Network Using D2D Communication," in *Proc. IEEE Wireless Communications and Networking Conference (WCNC)*, Doha, Apr. 2016.

Chapter 4, D2D communications can increase the spectral and energy efficiency by taking advantage of the proximity, reuse and hop gains when radio resources are properly allocated to the cellular and D2D systems. This chapter investigates multi-hop communications for enhancing the capacity of the D2D communications, Energy Efficiency and Spectral Efficiency in public safety partial coverage scenarios. The content of this chapter is based on:

- Kamran Ali, Huan X. Nguyen, Purav Shah, Quoc-Tuan Vien and Enver Ever,"D2D Multi-hop relaying Services Towards Disaster Communication System," in *Proc. IEEE International Workshop on 5G Networks for Public Safety and Disaster Management (IWNDP)*, Limassol, May 2017.

Chapter 5, the first section discuss the adaptive context to exploit the full potential of D2D transmission modes. We determine the outage probability of a user equipment relay that operates in D2D mode that harvests energy from radio frequency signal via base station and later uses harvested energy for D2D communications.

In the second section, we present a channel-opportunistic architecture that leverages D2D communications and opportunistic clustering techniques. We therefore propose a coalition formation algorithm to form the clusters in the most energy-efficient way. In particular, the proposed algorithm is to form the clusters among all the UEs (User Equipment) in a way to reduce the average energy consumption. This chapter is based on:

- K. Ali, H. X. Nguyen, P. Shah, and Q. T. Vien,"Energy efficient and scalable D2D architecture design for public safety network," in *Proc. Advanced Communication Systems and Information Security (ACOSIS)*, Marrakech , Oct. 2016.

- Kamran Ali, Huan X. Nguyen, Quoc-Tuan Vien, Purav Shah and Zheng Chu," Disaster Management System Using D2D Communication With Power Transfer and Clustering Techniques," in *IEEE Access,* vol. PP, no. 99, pp. 1–1, 2018.

Chapter 6, a drone based cellular infrastructure to revive necessary communications for out-of-coverage UE who is in the disaster area is proposed. In particular, a matching game algorithm is proposed using one-to-many approach wherein several Drone Small Cells (DSCs) are deployed to match different UEs to reach a stable connection with optimal throughput. In addition, a Medium Access Control (MAC) framework is then developed to optimize emergency and high priority communications initiated from the rescue workers and vulnerable individuals.

- Kamran Ali, Huan X. Nguyen, Quoc-Tuan Vien, Purav Shah and Mohsin Raza,"Deployment of Drone Based Small Cells for Public Safety Communication System," (submitted to IEEE Systems Journal) 2018.

Chapter 7, Finally, in this chapter, we conclude the thesis with a summary of the main contributions and a discussion on potential directions for future work.

The summary of the research issues, existing solutions and original contribution of the thesis in disaster communication architecture system is graphically presented in Fig. 1.1

1.6 Publications

- K. Ali, Huan X. Nguyen, Quoc-Tuan Vien, Purav Shah, M. Raza, and Vishnu V. Paranthaman "Towards Efficient Public Safety Communication Network Management, 5G and Emerging Technologies, " *IEEE Communication Magazine* (under review)
- K. Ali, Huan X. Nguyen, Quoc-Tuan Vien, Purav Shah and M. Raza,"Deployment of Drone Based Small Cells for Public Safety Communication System" *IEEE Systems Journal* (under review)
- K. Ali, Huan X. Nguyen, Quoc-Tuan Vien, Purav Shah and Z. Chu,"Clustering Techniques Deployment for D2D Energy Harvesting Relay Communication in Disaster Architecture System"in IEEE Access, Jan. 2018.
- K. Ali , Huan X. Nguyen, Quoc-Tuan Vien, and Purav Shah,"Internet of Things (IoT) Considerations, Requirements, and Architectures for Disaster Management System." *In: Performability in Internet of Things. Springer International Publishing. , page 111-125, 2018, pp.111-125.*
- K. Ali, Huan X. Nguyen, Purav Shah, Quoc-Tuan Vien, and Enver Ever,"D2D Multi-hop relaying Services Towards Disaster Communication System"in *Proc. 2017 24th International Conference on Telecommunications (ICT)*, Limassol, Cyprus, May 2017.
- K. Ali, H. X. Nguyen, P. Shah, and Q. T. Vien, 'Energy Efficient And Scalable D2D Architecture Design for Public Safety Network," in *Proc. International Conference on Advanced Communication Systems and Information Security (ACOSIS'16)*, Marrakesh, Morocco, Oct. 2016.
- K. Ali, H. X. Nguyen, P. Shah, Q. T. Vien, and N. Bhuvanasundaram, "Architecture for Public Safety Network Using D2D Communication," in *Proc. IEEE Wireless Communications and Networking Conference (WCNC)*, Doha, Apr. 2016.

- K. Ali, H. X. Nguyen, Q. T. Vien, and P. Shah "Disaster Management Communication Networks: Challenges and Architecture Design," *Pervasive Computing and Communication Workshops (PerCom)*, USA, Mar. 2015.

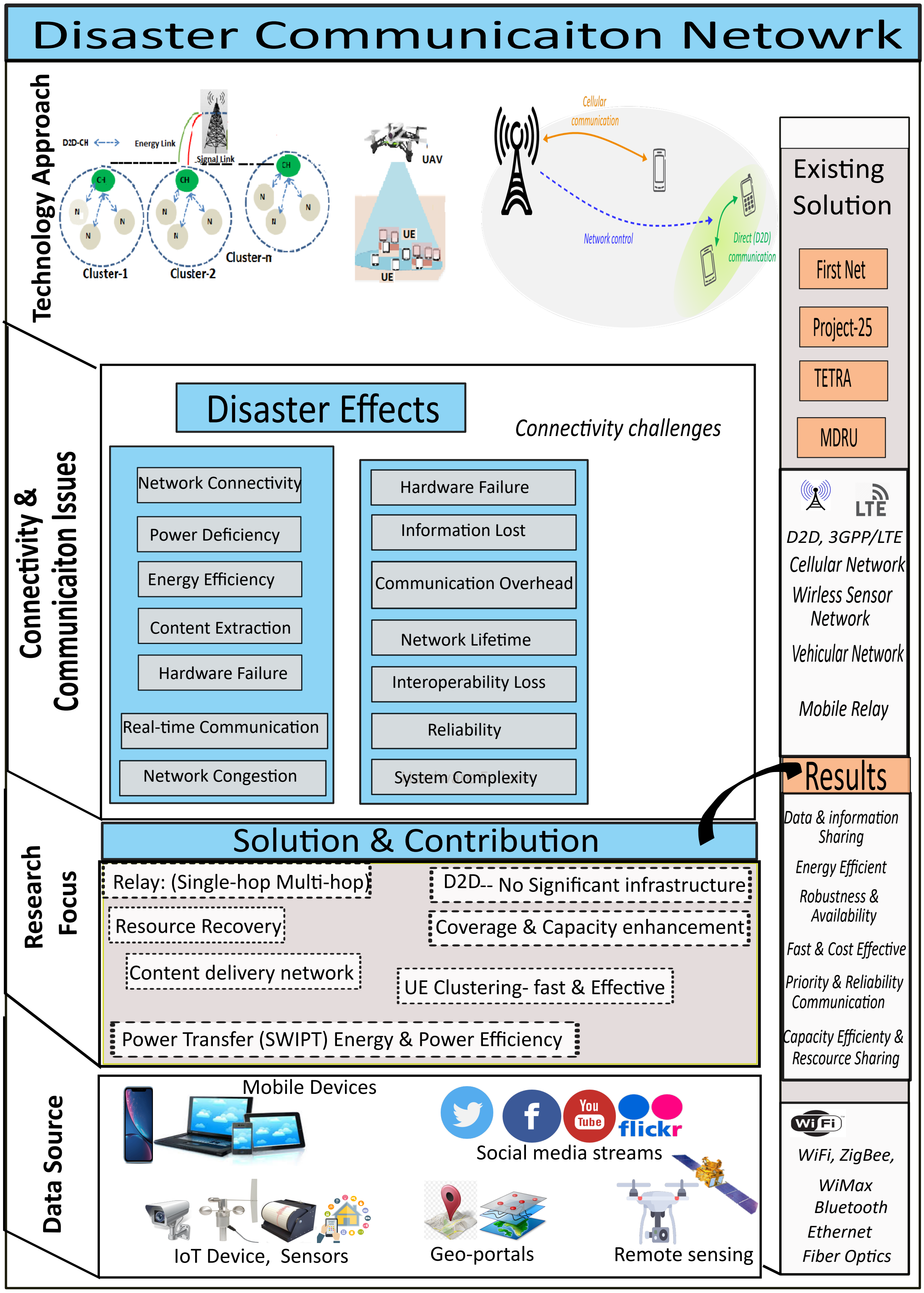


Figure 1.1: The summary of the issues, existing solutions and original contributions for disaster communication architecture system

Chapter 2

Background

This chapter gives the background to the underlying concepts delineated in details in the forthcoming chapters. The aim of this chapter is to highlight the key concepts of DMS, LTE, LTE-PS, D2D communication (i.e. mode selection/energy efficiency/resource allocation), UAV, energy harvesting and their importance with effective applications in public safety areas. As a forerunner to the following chapters setting the scene and providing an in-depth insight into the key issues to be addressed.

2.1 Background

Public safety networks (PSN) are wireless communication networks established by first responders during the need for critical communications. The communication capabilities provided by the PSN should manage all the difficulties created by the challenging situation that the first responders face in the disaster area. In fact, the critical infrastructures like energy and communication stations are often degraded or totally destroyed by the catastrophic event. Keeping all the above facts, this chapter first presents the background of different technologies integrated within the PSN.

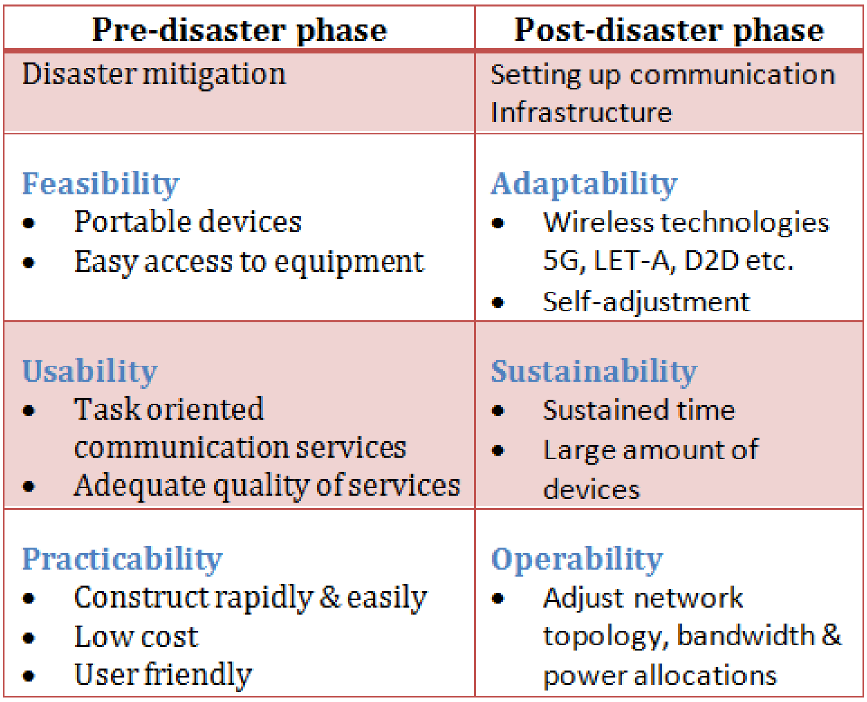
Today, wireless broadband networks are essential to many sectors of the society, and thus they should be robust to resist several types of failures. The malfunction of crucial infrastructures such as the cellular network, the Internet, smart grids and power breakdown resulting from natural disasters (e.g., earthquakes, flood and hurricanes) would have devastating impacts on the common operation of the society. In large-scale and complex networks, numerous links can cause extensive connectivity losses and affect many mission-critical applications and services Habib et al. (2013) that public safety agencies rely on. Frequently occurring large-scale natural disasters have been reported to cause great damage in recent years, claiming many people's lives, rendering millions people homeless, and causing huge financial loss.

The natural disasters and emergency crisis are usually unexpected events that cause panic situations in the civilian population and affect existing resources. Typically, public safety officers and responders include law enforcement, firefighters, emergency medical personnel, military organizations, volunteers groups, and other local and national organizations. The aim of these organizations and personnel is to protect people and assets, and respond as soon as possible to the disaster location, in order to provide medical attention and organize rescue operations. The public safety agencies can rapidly respond to the routine events like fire in residential buildings or car accidents. However, large-scale unexpected events a number of challenges that can strain the public safety agencies, raising a lot of issues in organizing the cooperation among all the active organizations and in creating fast and reliable communication networks. The existing PSNs are unfortunately unable to satisfy all the requirements of a public safety operation in an emergency scenario Sohul et al. (2016). In addition, the public safety systems must take into account different management strategies depending on the specific environment characteristics Baldini et al. (2014).

Communications is an essential element in various operational situations and at different stages of the hierarchy of public safety. In this type of scenario, communication capabilities need to be provided in very challenging environments, where critical infrastructures (e.g. base stations) are often degraded or destroyed by the impact of the catastrophic event. Despite this, public safety responders should be able to exchange information in a timely manner to coordinate the relief efforts and to develop situational awareness. Timely information sharing and the development of shared situational awareness therefore critical tasks and Public safety communication plays an important role throughout disaster response and recovery. In large-scale natural disasters, numerous different public safety organizations may be involved with different information technology and communication systems. At the same time, the commercial communications infrastructure and resources that are still usable, have to be exploited to alert and communicate with the civilian population.

2.2 Disaster Management System

Disaster management system (DMS) consist of two phases including pre-disaster and post-disaster as shown in Table. 2.1. The pre-disaster phase involves disaster mitigation whereas its focus is on disaster communication connectivity and recovery operation in the affected areas. The post-disaster phase covers setting up of communication infrastructure, locating and rescuing the victims by providing basic needs. An efficient disaster communication is strongly based on the post-disaster phase because it depends on the technologies and the available equipment that can be used by the affected people on the ground as well as the first responders. The victims should be able to use the available technologies as fast as possible to communicate their location and whereabouts to the first responders. Mobile phones might be the first thing carried by most victims or volunteers in disaster situation. It is easy and ready to use without the need of deploying any additional infrastructure, and hence using mobile phones as terminals saves both cost and time. Notebook and tablet PC, are also good options considering their portable size and good transceiver capabilities. The interest of research is to investigate current technologies that empower a reliable and rapid rescue operation in a disaster situation. Figure 2.2 highlights the key challenges and some features with requirements that should be met by a DMS. Furthermore, a disaster communication system should provide some basic communication services with the related main features as listed in Fig. 2.2 Ali et al. (2015)Tanha et al. (2016)Kumbhar et al. (2017).The services that a PSN must supply include: voice , video streaming, data connectivity, messaging and security services. In the current PSN, messaging and voice-based communication systems provide narrowband data services. However, it has become evident that the mobile users also need high speed broadband data services and applications in disaster situation



Pre-disaster phase	Post-disaster phase
Disaster mitigation	Setting up communication Infrastructure
Feasibility • Portable devices • Easy access to equipment	**Adaptability** • Wireless technologies 5G, LET-A, D2D etc. • Self-adjustment
Usability • Task oriented communication services • Adequate quality of services	**Sustainability** • Sustained time • Large amount of devices
Practicability • Construct rapidly & easily • Low cost • User friendly	**Operability** • Adjust network topology, bandwidth & power allocations

Figure 2.1: Disaster Communication Management

for better and quick rescue operation.

Note that broadband data services and features allow developing more efficient disaster communication system. In the case of data connectivity and messaging services, an important requirement is the bandwidth available to support the application working during disaster rescue teams. Many good numbers of investigation, exploration and study efforts have been carried out on disaster communication based architectures and applied technologies Huang and Lien (2012)Rawat et al. (2015)Noguchi (2012)Altay et al. (2016). But due to the climate change and among other reasons, natural disasters have increased significantly over the years which not only costs assets, communication infrastructure destruction but also fear and loss of human lives Fantacci et al. (2016). Numerous solutions have been presented effectively to sustain communication after a disaster. Moreover, capacity, coverage enhancements and performance gains during disaster and critical communication were also addressed in many proposals and research works Lee and Choi (2017)Ali et al. (2018).

The 4G networks are now moving towards maturity and making the re-

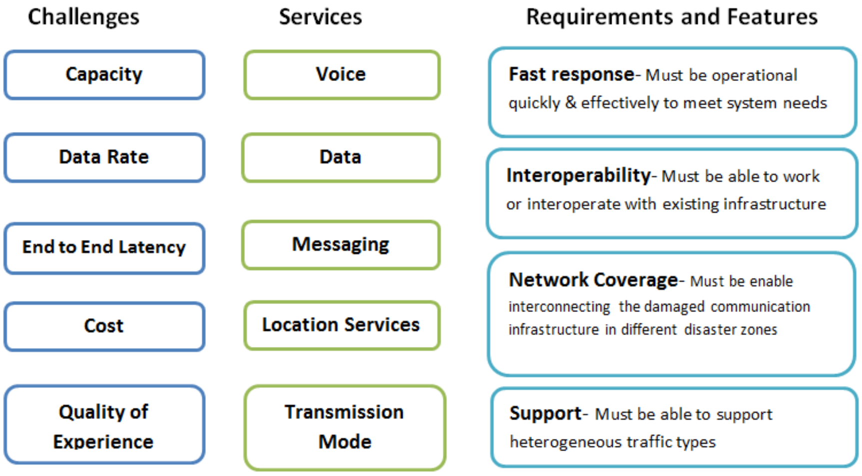


Figure 2.2: DMS Challenges, Services and Requirements

searchers to explicit new generation of wireless network with enormously large bandwidth and with vast devices connectivity. With respect to this the technologies that enable a rapid recovery, sustainability and efficient adaptability of wireless devices for disaster communication are presented below.

2.3 Technology Selection

After a disaster, restoring communications is always the first priority since, without communication, sending rescue personnel into the disaster area is dangerous and futile. Moreover, victims might be trapped in the collapsed building or covered by debris and the easiest way to locate them or for them to connect to the outside world and call for help is through mobile communications. Wireless communications play a fundamental role in disaster communication system and security operations, since appropriate communications have a strong impact on the efficiency and responsiveness of emergency services. Disaster communication architecture systems can benefit from recent advancements in wireless communication technologies especially mobile technology and devices. The ever growing number of mobile devices makes them an essential component of critical communication system.

2.3.1 Long Term Evolution Mobile Network

The evolution of wireless networks process is an ongoing research. There is always a need for high data rates, reduced packet latency or delay, high spectral efficiency and lower cost. The 3GPP Long Term Evolution (LTE) is one of the choices for next-generation wireless networks. LTE can be defined as an evolution for both Universal Mobile Telecommunications System (UMTS) and Code Division Multiple Access (CDMA). LTE is designed to provide a peak data rate because LTE is an all Internet Protocol (IP) based technology that is capable of providing data throughput 300 Mbit/s for downlink (DL) and 75 Mbit/s for uplink(UL). Furthermore to ensure high mobility at speed up to 350 km/h also anticipated supporting voice and real-time service quality without interruption Ergen (2009.3.) in LTE.

The NTT DoCoMo's proposed concept for Release 12 onward which consists of two aspects: i) Integration of wide and local area enhancement, and ii) efficient utilization of both lower and higher frequency bands through frequency-separated deployments between wide and local areas Kishiyama et al. (2012). The authors emphasizes on local area network technologies that will continue to evolve and will play more important role in the future. Fig. 2.3 shows the common specifications between wide and local area in terms of a fundamental LTE radio interface.

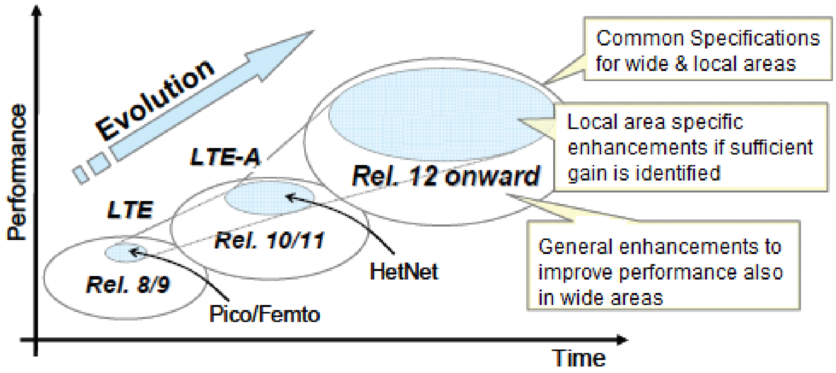


Figure 2.3: Integrated Part of General LTE Enhancements

2.3.1.1 Long Term Evolution and Public Safety

LTE is being widely deployed as the global mobile broadband standard. Perhaps the main benefit in the use of LTE for public safety is having large-scale deployment of LTE, which allows less expensive equipment based on unified standards. These standards can be adopted by all public safety agencies and organizations globally, thus sharing scale with non-public safety applications of LTE. Public safety networks are today undergoing a transition, from voice and low-bandwidth data applications carried on 700 MHz P25 narrowband networks to more advanced data-intensive applications supported by a 700 MHz LTE broadband network overlay. For public safety agencies, the result of combining the two networks is obvious: a unified broadband/narrowband communications infrastructure featuring the strengths of both technologies and on-going access to the continual advances being made with commercial cellular technologies and networks.

In March 2010, the FCC took things one step further by releasing the National Broadband Plan (NBP), which made significant recommendations for improving access to broadband communications across America. The plan included a recommendation for the utilization of 10 MHz of dedicated 700 MHz spectrum in the upper D block for creation and deployment of a nationwide, interoperable public safety broadband wireless network Testing (March 2018). The allocation is illustrated in Fig. 2.4

2.3.1.2 Public Safety Standardisation

In early 2013-2014, a lot of discussion and opinions presented for standardisation set-up but finally, late in 2014, it was decided that the required standardisation work will be done within 3GPP in such a way that the requirements of public safety functionalities covered.

LTE was defined within 3GPP Releases 8 and 9, LTE-Advanced (4G) in Releases 10 and 11. This was a major piece of work, followed by a stable period without new major standardisation efforts. 3GPP Releases 12 and13 were the first to addressing Public Safety specific requirements, and this work is on-going with Release 14. Further functionalities and enhancements are planned for Release 15, and it is expected that new refinements and enhancements will be needed

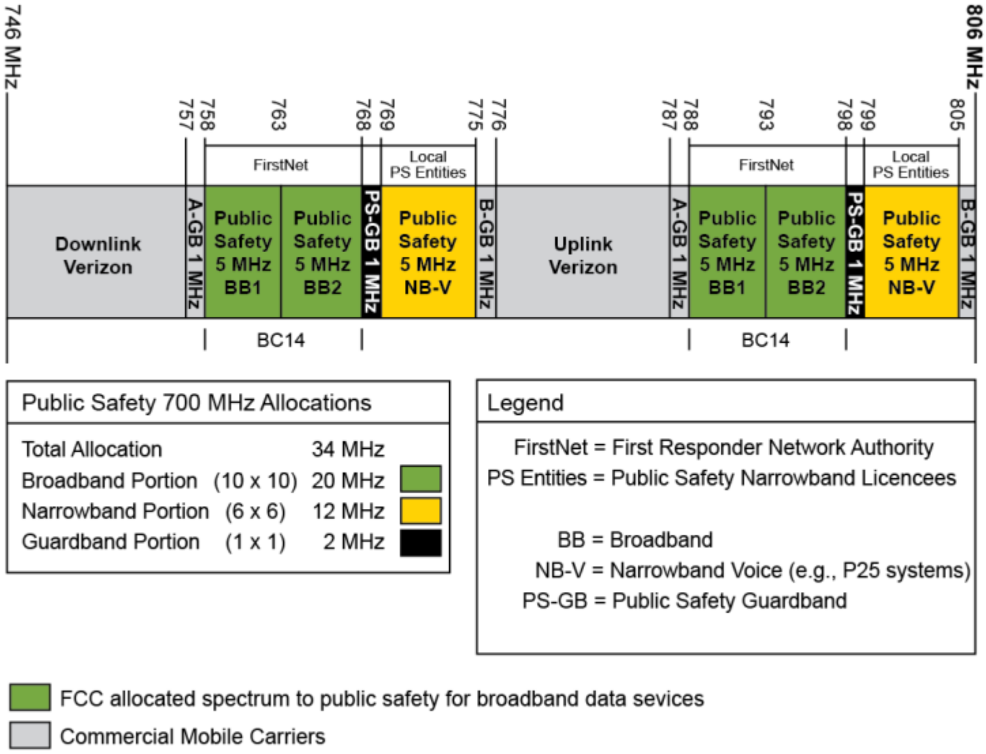


Figure 2.4: Public Safety Spectrum Allocation in the 700 MHz Band Testing (March 2018)

in future Releases as shown in Fig. 2.5 The next programme of 3GPP standardisation effort focusing on 5G and the Internet of Things (IoT) has already started. Releases 15 and 16 will begin to define 5G and IoT. Part of Public Safety functionality initially included in Release 14 has been shifted to these later Releases. Public Safety lacks priority when compared to 5G, but providing there is continued support, the expectation is that 3GPP will be able to complete the required functionality for Public Safety solutions.

The reason for the Public Safety standardisation work is simple: Public Safety users have communications needs that are not addressed by standards defined for consumer use. Group calls and direct device-to-device communication are the main Public Safety functionalities that are not included in 3GPP Releases 10 and 11 (LTE), and this triggered the need for additional standardisation on top of those Releases. This is not just adding some new features in 3GPP Releases,

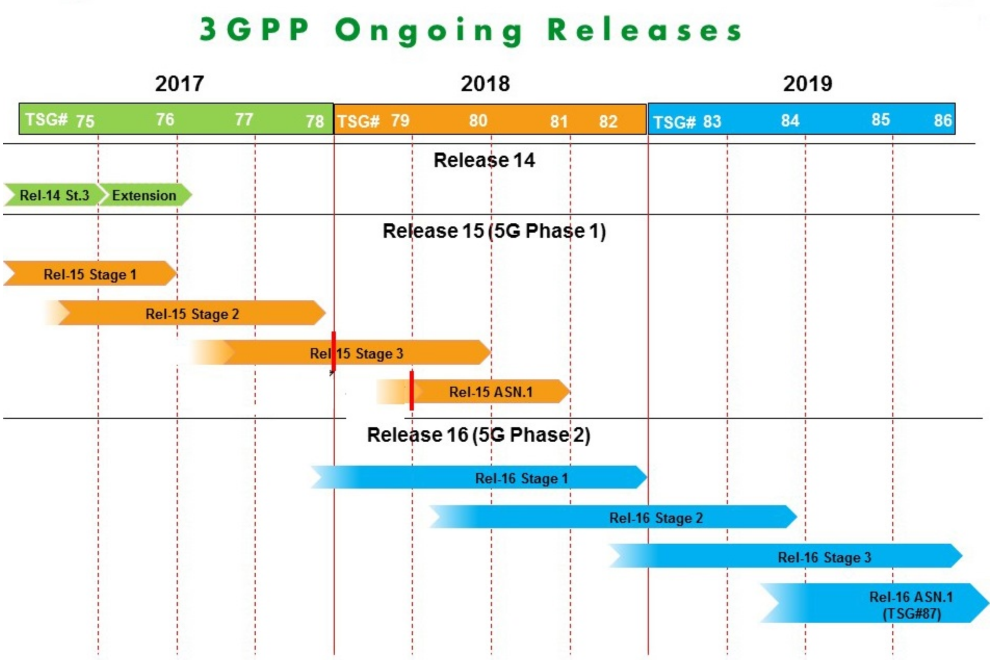


Figure 2.5: 3GPP Ongoing Releases time graph Seidel (Published on May 9, 2017)

but also creating some basic mechanisms which are needed to support Public Safety functionalities, like creating multicast and broadcast mechanisms needed for group calls or multimedia sessions.

The following are the listed one-by-on PS related standardisation items 3GPP (access July 2018)TCCA:

- **GCSE - Group Call System Enablers (Rel12):** This standardisation item is a collection of different mechanisms to provide both unicast transmissions and multicast transmissions for group communication.

- **ProSe - Proximity Services (Rel12-Rel14,. . .):** This standardisation item defines the architecture and radio interface for direct device-to-device communication.

- **IOPS - Isolated E-UTRAN Operations for Public Safety (Rel13-Rel14):** The high service availability requirements of Public Safety need base stations to deliver service autonomously during a break in connection between the base station and the core network.

- **MCS - Mission Critical Services (Rel13-Rel14,. . .):** Mission-critical applications required to deliver mission critical services for Public Safety users (MCPTT, MCData, MCVideo) need a generic common set of system capabilities in order to deliver the service to end users.
- **MCPTT – Mission Critical Push To Talk (Rel13-Rel14,. . .):** This standardisation item defines the application needed for delivering voice services for Public Safety users.
- **Interworking with Legacy PMR Systems (Rel15,. . .):** Existing narrowband Public Safety implementations will be used for the foreseeable future in parallel with new broadband based implementations, so Public Safety users require interworking between narrowband and broadband systems. This standardisation item defines the required interworking functionality.

It gives an idea that the standardisation of Public Safety functionalities will constantly evolve in order to enhance the service and include new mechanisms that will be beneficial to Public Safety operations and these need to be placed within forthcoming 3GPP releases.

2.3.2 Device-to-Device Communication

As stated earlier, due to the critical nature of the different emergency communications, public safety requires that the network supports diverse traffic in a robust environment. Some of this robustness is provided by LTE through standardization; other aspects result from careful network planning. In general, robustness goes beyond just cell and capacity planning, it demands that alternative paths be available in the event of congestion and resources outages. When part of the public safety network fails, the remainder of the network must continue to provide services to the greatest extent possible. The LTE transport infrastructure must support such continued communications. The way to accomplish this will likely involve LTE network level enhancements and it may incorporate what is known as *direct communications (e.g. Device-to-Device).*

Device-to-Device (D2D) communication refers to a radio technology that enables devices to communicate directly with each other, that is without routing the data paths through a network infrastructure. The classification of D2D communication can be based on the association of the cellular infrastructure in the set-up of the direct link, and on the spectrum in which the direct communication occurs.

In *self-organized D2D communication*, the synchronization between the radio interfaces is controlled by the users themselves. This method is similar to traditional ad-hoc networks and works on the unlicensed spectrum. It is typically motivated by its limited overhead and easy deployment, and finds application when the cellular infrastructure is not operative (e.g., in case of natural disaster).

On the other hand, in *network-assisted D2D communication*, the base station (BS) assists the direct data-transmission by means of control signaling and resource management. In this case, the network can manage all communications in order to mitigate the possible mutual interference. One disadvantage of this coordination is that it might require high signaling overhead and complex centralized resource management. Different levels of network support can also be assumed, with the goal of achieving a good trade-off between complexity/signaling overhead and guaranteed performance. For example, D2D users can be supported by the network only during the discovery phase, and then they autonomously schedule their transmissions and select the radio resources Mach et al. (2015).

The D2D based communications can be further classified based on how users access the spectrum. This classification is as illustrated in Fig. 2.6 and described as follows:

- **Out-band D2D:** when D2D users communicate over the unlicensed spectrum. While this approach avoids D2D communications to interfere with the traditional cellular communications, D2D communications may suffer from the uncontrolled nature of the unlicensed spectrum.

- **In-band D2D:** In this case, the D2D users utilize the licensed spectrum of the cellular operator. So, Base Station (BS) has a high control over the D2D links, with a resulting of higher assurance of communication performance, compared to out-band D2D.

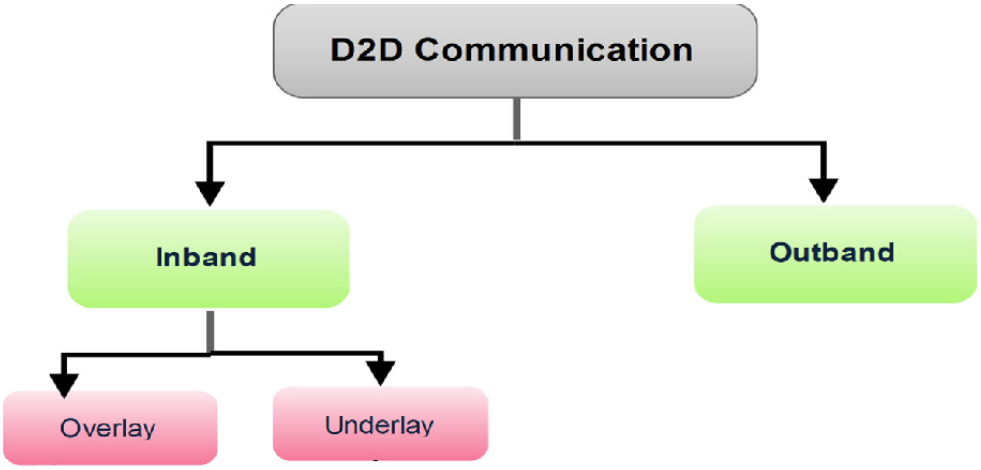


Figure 2.6: D2D communication classification on the bases of spectrum use

In-band D2D communication can further branch into two subcategories. i) *Underlay in-band D2D* (shared mode): D2D and cellular users share the same frequency bands in order to increase the spectrum efficiency of the network. ii) *Overlay in-band D2D* (dedicated mode): D2D and cellular users transmit over non-overlapping frequency bands. Although the overlay mode works best in reducing interference, it results in the underutilization of the frequency resource.

This thesis focuses on in-band network-assisted D2D communication, which is believed to be the most innovative concept in the context of short-distance wireless communications Ali et al. (2016b). The out-band and self-organized D2D communications have been studied since decades ago, and currently there exist several protocols and standards for them. Examples of out-band D2D technologies commonly used are Bluetooth and Wi-Fi Direct, both working in the unlicensed Industrial, Scientific, and Medical (ISM) bands. Moreover, both Bluetooth and Wi-Fi Direct require physical pairing among the devices. For in-band D2D communication, this process might in the future be transparent to the users and activated directly by the network when needed; for example, to offload data from the BS during disaster communication or in crowded areas.

Thus, self-organized unlicensed D2D technology is commonly interested by the low overhead and easy deployment that does not need any modification at the BS and cellular infrastructure. Nevertheless, it has some boundaries related to manual device pairing and possible poor user experience. These limitations are overwhelmed with in-band D2D communication since it is foreseen to utilize the advanced management features of cellular infrastructure to progress the communication throughput, power efficiency, security, and reliability which are considered in all the Public safety network architectures and frameworks discussed further in chapters 3, 4, 5 and 6.

D2D communication is considered as a key enabling technology in future cellular networks and thus, it has become an intriguing topic for research Apostolos et al. (2016). It refers to a state-of-the-art technology that enables User Equipment (UEs) to communicate directly with each other without using the access network (i.e. eNodeB). One of the most vital functions of D2D communication is the proximity service (ProSe) Lien et al. (2016a). This is indeed an inspiring technique for critical communications, e.g. in public safety or emergency situations. Feasibility study for D2D services is presented in Fig. 2.7 with the purpose of recognizing use cases and the potential requirement for discovery and communications between UEs that are in proximity, including network operator control or direct.

- **In-coverage**: This scenario indicates that all the considered UEs are within eNB coverage (in-coverage UEs) to receive services/signals from an eNB.
- **Partial-coverage:** This scenario indicates that some UEs are within eNB coverage, while other UEs are outside eNB coverage.
- **Out-of-coverage:** This scenario indicates that all the considered UEs are outside eNB coverage (out-of-coverage UEs) and cannot receive services/signals from an eNB.
- **D2D-based relay:** D2D communication is useful not only for local communication but also for communication between a BS and out-of-coverage user equipment (UE). This facility can be enabled by D2D-based relay Lien et al. (2016a) , an out-of-coverage UE can communicate with a neighbor UE via D2D communication; the later UE becomes a relay to the BS as shown in Fig. 2.8.

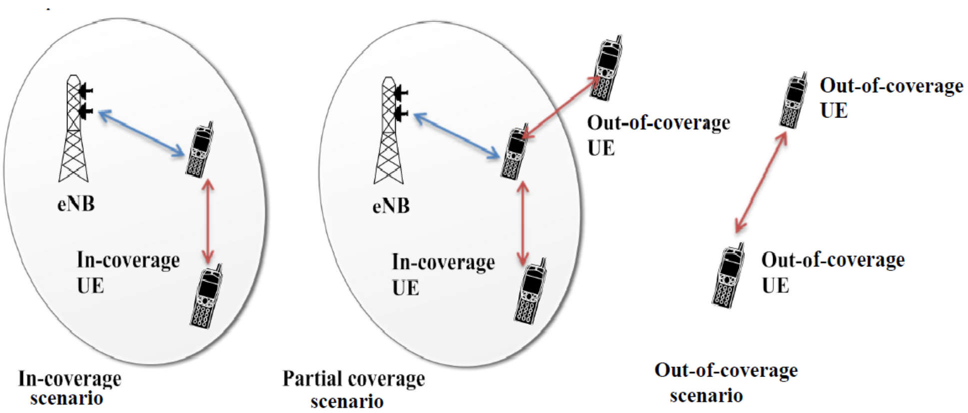


Figure 2.7: D2D proximity service (ProSe) support scenarios

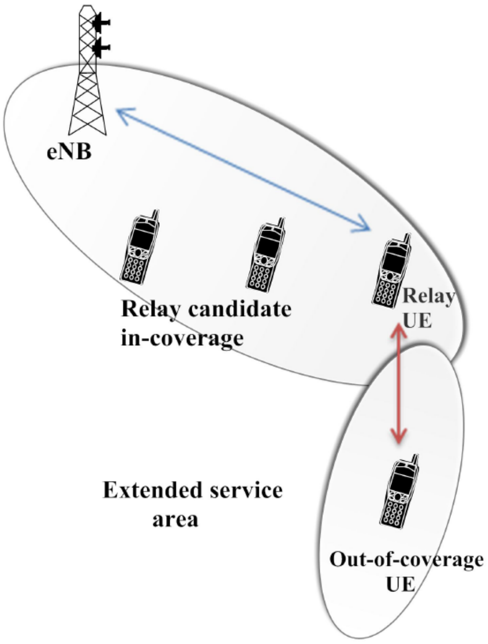


Figure 2.8: D2D relay for extended out-of-coverage area

2.3.2.1 D2D Technology Applications

The thesis presents D2D communication as an essential part of the PS and cellular network. Qualcomm made the first effort to introduce D2D communication in a cellular network with the system FlashLinQ Wu et al. (2013). FlashLinQ is a synchronous peer-to-peer wireless network architecture that permits cellular devices to automatically discover other devices and communicate directly without the need for intermediary infrastructure. FlashLinQ represents a well-organized technique for timing synchronization, peer discovery, and link management based on OFDMA technology, and the aim of Qualcomm was to adapt FlashLinQ to the radio interface of the LTE.

The study of D2D technology combined into cellular networks was boosted by the request from different governments to use a direct connection for public safety purposes as part of LTE cellular network. The academia and telecommunication companies responded to this interest, but likewise, the 3GPP standardization group became progressively active in investigating D2D communication for Proximity-based Services. In particular, Release 12 of 3GPP standards classifies use cases Cmara and Nikaein (2015) and technical requirements for discovery and communication between users that are in physical proximity, including studies on network operator control, authentication, authorization, and regulatory aspects. Since Release 12, D2D communication within LTE system has been improved in Releases 13 and 14 with numerous features, moving from applications related to public safety and commercial communication to recent vehicle-to-vehicle communications Lien et al. (2016b),Lien et al. (2016a).

In this thesis the disaster management system utilizing D2D communications alone with different approaches. For instance, in an underlay D2D network, an underlay UE enforces interference to the cellular network. One possible solution is that the cellular network can accept a settlement from the underlay D2D network, which is considered as an incentive to share the spectrum with the D2D UE nodes Chu et al. (2017). The author of Liu et al. (2017) proposed a suitable solution for disaster management. A Stackelberg game was proved to be an appropriate candidate to formulate the decision making in the interference pricing process [13]. Likewise, it is not practical to adopt that the UE always has enough power to transmit its own information. Therefore, it needs to harvest power for future operations (i.e., wireless information transfer). The UE is also willing to pay a certain price to the BS for energy service. Again, a Stackelberg game can be considered a good tool to exploit the hierarchical energy interaction between the cellular and D2D networks.

The regular research on architecture enhancements and radio resource management aspects for D2D enabled PS cellular networks are further motivated by the forecasts on the opportunities that D2D communication will bring to the critical and emergencies networks. In the remaining of this section, an overview on mode selection, resource allocation and , power control for D2D-enabled networks, with some examples of relevant solutions in the literature.

2.3.2.2 D2D in PS Networks

Device to Device communications for disaster scenarios: In disaster, the effective use of the radio resources is of extreme importance with the goal of serving a large number of affected people to collect information from different nodes in the disaster zone. In this context, D2D communication will be effective as for example, a D2D-based solution allows an efficient spectrum allocation without adding any further delay in content uploading for the UEs.

As discussed earlier that D2D offers a wide range of advantages from offload cellular traffic, reduced battery consumption, much higher data-rate to novel applications. In particular, D2D communications are of great interest in scenarios, where there is a high density of devices sharing the scarce cellular radio resources, e.g., in public safety and disaster scenarios where the network coverage and the connectivity are limited with the network infrastructure having been damaged. A recent review of key requirements, technology challenges, and solution approaches for enabling D2D to meet the requirements for public protection and disaster relief is presented in Fodor et al. (2014). In work Militano et al. (2015) explores the possibility of D2D communication between UEs in proximity to each other to minimize the radio resource needed to upload multimedia content to the base station (eNodeB). The reference scenario is a single cell in a LTE-A system, where multiple UEs aim at uploading some data content to a central server or to the Cloud as shown in Militano et al. (2015). Such a D2D-based solution allows an efficient spectrum allocation without adding any delay in content uploading for the UEs. Authors claim that in comparison to a standard LTE uploading scheme, the proposed D2D-based solution is more effective as it decreases the average number of RBs (Resource Blocks) required in a data uploading process without affecting the standard uploading time given by the LTE system. Moreover, it provides a more effective management of the battery life as compared to the traditional LTE.

The schedulers that are often implemented in LTE systems (e.g., best Channel Quality Indicator (BCQI), Proportionally Fair (PF) and Round Robin (RR)) mostly target the best resources utilization for increasing fairness, throughput and bandwidth efficiency and assign them more promptly and faster to the users. However, in disaster scenarios, it is required to design smarter resource scheduling to prevent the loss of connectivity and resulting isolation of first responders located inside buildings or tunnels. This problem is addressed in Gomez et al. (2014) and different scheduling disciplines in 5G Systems for emergency communications, especially in post-disaster phase are provided.

The D2D communication in emergency systems requires considering radio resource management techniques to make the best use of this technology. The radio resource management approaches for D2D communication in PS networks into three main categories: i) Mode selection, that is, deciding if a user pair should communicate directly or via the BS; ii) Power control, that is, setting the power level of the transmitting nodes; iii) Time/frequency resource allocation, that is, assigning the physical resource blocks (RBs) to be used by each communication.

Mode selection:

Mode selection is the strategy of choosing whether two UEs should communicate through a direct link (using dedicated or shared resources) or via the BS. The optimal mode selection depends on the performance measure to optimize (e.g., sum rate, transmission power, energy consumption), and on the information available when making the decision (e.g., physical distance between UEs, channel quality of the links, interference level).

The path loss techniques are the most intuitive mode selection practice which is directly related to the physical distance between the nodes. In Xing and Hakola (2010), for example, the D2D mode is activated if the path loss of the direct D2D link is smaller than a given threshold. A mode selection method that accounts for the path loss of both the D2D and the cellular link is proposed in ElSawy et al. (2014). Here, D2D mode is chosen if the ratio of the two path losses is below a given threshold, and the threshold depends on the desired traffic offloading from the BS (the larger the threshold, the more user pairs are forced to communicate in D2D mode). Another example of distance-dependent mode selection can be found in Ye and Zhang (2015). Here, the authors define a guard-zone based mode selection, and the potential D2D links decide whether to operate in underlay D2D or cellular mode based on the distance from the transmitter to the BS.

In most of the present works, the mode selection algorithms either require channel state information at the centralized decision maker (e.g., the BS), or assume some signalling mechanism to share information among the nodes Akkarajitsakul et al. (2012),Yu et al. (2011). However, implementing a central controller with complete channel and network knowledge is impractical, as recently emphasized in Maghsudi and Niyato (2017).

From the above literature review, we conclude that there are several design issues to consider in PS network. For example, what channel information is needed, how often this information should be updated, how much per/energy required, how resource blacks should be managed and which communication mode between two UEs should be feasible. In particular, the timescale for the mode selection cannot be too coarse because the wireless channel might change rapidly. The below Fig. 2.9 illustrates the common performance metrics of D2D in PS networks.

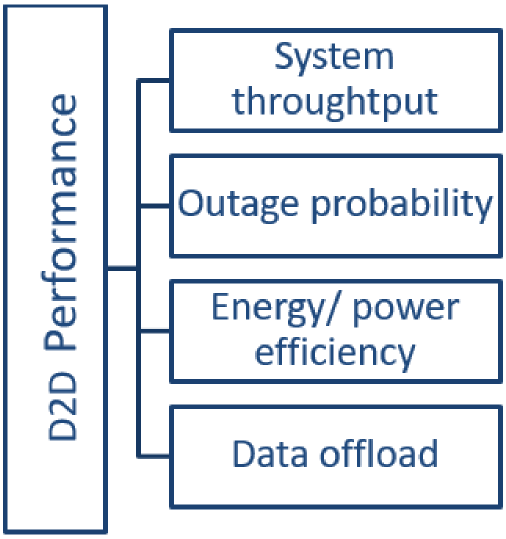


Figure 2.9: Common performance metrics of D2D Network

Power/Energy Efficiency:

The basic need for evolving broadband PS services capable systems is to provide access to cellular services when the portion or infrastructure of the network entity become unavailable due to some emergency situation. For the evolution of such systems, spectral efficiency and extended battery life are two important aspects of communication that need to be focused on rigorously. The D2D communications can be a key technique in providing services to those UE that suffer lack of network coverage. D2D communications can improve network efficiency by increasing the spectral reuse and energy efficiency while reducing transmission delay and congestion in cellular networks.

In this thesis, to enhance the link quality, relay-based transmission has been considered in later chapters. For instance, the 3GPP standard has defined two types of relays which are: fixed and mobile user relays. The idea of using D2D relaying information was originally proposed in Lin et al. (2000) Wu et al. (2001) and it was shown that the cell coverage and throughput can be improved significantly. However, together with the privacy problem, the power consumption at user equipment relay (UER) has been an issue since the UER needs to use its own power to forward the information of other UEs. This problem can be complemented by using the energy harvesting (EH) technology Yang et al. (2016)–Ali et al. (2018) which enables devices to harvest energy from their surrounding environments.

A secure wireless powered D2D communication in the presence of the multiple eavesdroppers presented, where a smart hybrid BS in cellular network not only charges for the D2D transmitter to guarantee power efficiency for the D2D network, but also serves as a cooperative jammer (CJ) to interfere with the eavesdroppers Chu et al. (2017b). Although the cellular networks share their own spectrum with the D2D underlay network, both of them may not belong to the same service provider. Thus, the D2D transmitter charges for the energy services released by the hybrid BS. The authors formulated two Stackelberg game formulations to exploit the hierarchical interaction between the BS and the D2D transmitter with/without energy trading. The associated Stackelberg equilibriums of the formulated games are derived in terms of closed-form solutions which

which highlights the importance of the energy trading interaction between the cellular and D2D networks and presented in Chu et al. (2017b).

Designing efficient energy-harvesting communication systems is a relatively new research topic especially in PS architecture. The harvesting energy from the environment is a promising technique for future communication systems. It allows, at least theoretically, the construction and the operation of perpetually powered communication networks. Solar, wind, and vibration are commonly suggested sources for energy harvesting at the transmit nodes. This energy can be alternatively provided by wireless devices since radio frequency (RF) signals can carry energy that is used as a vehicle for transporting information. Based on this reason, simultaneous wireless information and power transfer (SWIPT) is a key technique for harvesting energy and is a promising solution for the energy in critical communication network Ding et al. (2014b). In Xia et al. (2013)-Krikidis (2015), relay strategies have been investigated to distribute the harvested energy to multiple destinations and can be used in disaster communication approaches.

In SWIPT, information and power transfer is done over wireless medium simultaneously instead of making these separately. In addition to providing a reliable alternative to powering communication networks solely with batteries or with cables, SWIPT capabilities bring increased mobility and prolong network lifetime during disaster communication. Two practical schemes for SWIPT, namely *time switching* (TS) and *power splitting* (PS), are proposed in Zhang and Ho (2013)-Zhou et al. (2013).

Time Switching: If TS is employed, the receiver switches in time between information decoding and energy harvesting. In this case, the signal splitting is performed in the time domain and thus the entire signal received in one time slot is used either for information decoding or power transfer as shown Fig 2.10a.

Power Splitting: The PS technique achieve SWIPT by splitting the received signal in two streams of different power levels using a PS components, one signal stream is sent to the rectenna circuit for energy harvesting and the other is converted to baseband for information decoding as shown Fig 2.10b.

In the context of EH communication network, the authors Maso et al. (2014) proposed a method to harvest wireless energy by using the cyclic prefix from the OFDM signal. Huang and Lau (2014), the "power beacons" is defined as extra

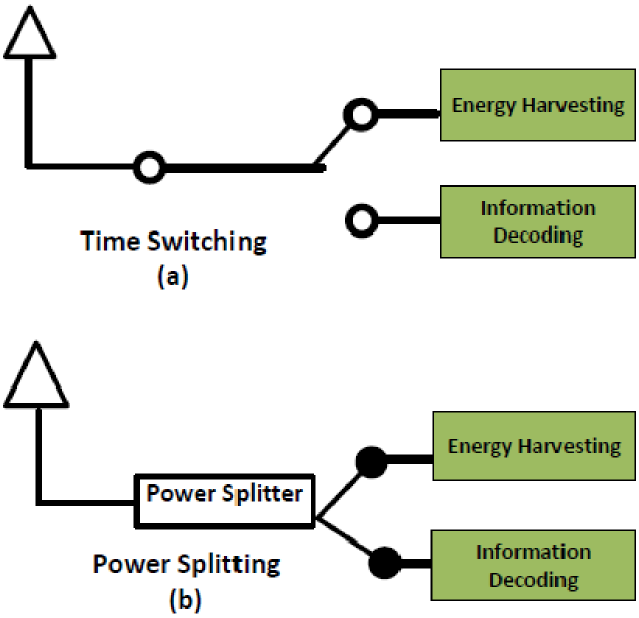


Figure 2.10: SWIPT Transmission Techniques.

energy transmitting nodes, and the feasible region for the BS density and the transmit power is provided under an outage constraint.

A special case of SWIPT with particular interest for PS networks is the SWIPT with energy/information relaying. In this network structure, a battery-less relay node extracts both information and energy from the source signal, and then uses the harvested energy to forward the source signal to a destination. In Nasir et al. (2013), the authors study the performance of a three-node Amplify-and-Forward (AF) relay channel, where the relay node employs TS/PS to power the relaying link. This work is extended in Nasir et al. (2014) for a Decode-and-Forward (DF) relay channel and the throughput performance is analysed in closed form for both TS/PS techniques. A three-node relay channel with direct link, which combines TS-SWIPT with the dynamic Decode-and-Forward (DDF) protocol, is analysed in Ishibashi (2014).

In the context of D2D communication with energy harvesting, the performance of EH D2D communication in a cognitive network is recently investigated in Sakr and Hossain (2015) for different spectrum access policies. However, most of the prior work were based on fixed relay location and they ignored the UER spatial distribution, which significantly affects the throughput and outage performance of D2D transmission. Besides, there is no general framework that analyses the performance of energy harvesting cellular network which takes into account both the EH process and relay spatial location Yang et al. (2016).

One of the most important concerns in disaster communication system is intra-cell interference in narrowband communication systems. In the environment of 4G systems, the intra-cell interference is not a big concern as uplink transmissions are allocated to orthogonal resources. The power control mechanism mostly compensates for path loss and fast scheduling procedures are taking over the role of the power control to increase the user data rate Khan (2009).

The most intuitive way to reduce the interference from D2D communications to cellular communications is to limit the transmission power of D2D users Yu et al. (2009). The impression is to set the power of the D2D transmitter such that the performance degradation in terms of SINR reduction and the cellular users does not exceed a certain threshold. Likewise, the authors of Oduola et al. (2014) mitigate the interference from the D2D transmissions by reducing their power with a back-off parameter. Because limiting the D2D power translates into shortening the distance range for D2D communication, the authors also adjust the power of the cellular users to help to compensate for the interference.

In a real system, the inter-cell interference triggered by together D2D and cellular users in neighbouring cells must also be wisely controlled. The multi-cell scenario is analyzed in Ramezani-Kebrya et al. (2017). Here, the authors improve the transmission power of a cellular user and a D2D pair so as to maximize their sum rate.

Numerous LTE schemes of power control for multi-cell D2D-enabled structures are discussed in Xing and Hakola (2010). The approach is mostly based on simulations and shows exciting visions into the impact of the different approaches. For example, although the fixed transmission power scheme is very simple, it does not work well for D2D communications because of the possibly large dynamic variety of the D2D SINR (that is, it might provide too good performance for some users and too bad performance for some others), though the closed loop LTE power control with a dynamic tuning step seems more suitable. In Tang et al. (2016), the authors study an underlay multi-cell D2D network operating in a Rayleigh fading channel. They intend a power allocation technique that allocates transmission powers to both cellular and D2D users to maximize the probability of successful communication.

Resulting from the above-mentioned works, the authors accomplish that the standalone power control scheme is not sufficient to efficiently handle the interference, and it needs to be complemented by mode selection and resource scheduling during communication.

Resource Allocation:

The resources assignment in PS networks is important not only to exploit the possible frequency diversity among the channels, but also to increase the spectral efficiency by proper resource reuse. As discussed earlier, D2D communication is a promising concept used to improve user experience and enhance resource utilization in critical situations, enabling two close-by D2D devices to establish a direct local link and bypass a base station Corson et al. (2010).

The devices with the D2D capability can connect with others by using the cellular resources such as channels and resources blocks (RBs) allocated by the base station. It allows D2D devices in proximity of each other to start a direct local link and bypass the BS. This permits two proximal D2D devices transmit data with low transmission power, resulting in better data rates and low delays. The 3GPP integrates D2D communication into the Long Term Evolution-Advanced (LTE-A) system and prospects for the benefits such as D2D communication is operated in the licensed spectrum, operators can manage the radio resources carefully so as to minimize the interference and maximize the performance of the LTE-A system. In addition, the proximity of two D2D devices promises a better data rate with low latency, and low energy consumption. By reducing transmission power, the interference between D2D devices can also decrease. Consequently, it is possible for a PS networks to reuse the transmission resources simultaneously within the same cell Fodor et al. (2012). Furthermore, D2D communication can likewise achieve cellular data offloading, multi-hop relay, and prolong battery lifetime during critical communication scenarios. Generally, the proximity-based D2D technique can be applied to various important fields, such as public safety, and social networking, location-based services, and network offloading during public safety situations.

In the scholarly work Zulhasnine et al. (2010), design a resource sharing strategy for throughput maximization where a single D2D pair can exploit all possible cellular resources while guaranteeing the quality of communication. Game theoretical approaches are also mostly used to design and analyse resource allocation schemes Song et al. (2014). For instance, the authors of Huang et al. (2015b) model the resource allocation issues for multi-cell D2D networks as a non-cooperative game, in which the BSs are the players, and each BS can charge the D2D users for reusing the cellular resources. The analysis is based on the simplified model with only one D2D pair located in the overlapping area of neighbouring cells, and assumes that the BSs know the channel state information of all involved links.

2.3.3 Unmanned Aerial Vehicles

Aerial platforms, such as drones, balloons, quadcopters or gliders are expected to have an important role in the next generation of mobile networks. Because of their flexibility, adaptability, and mobility capabilities, these platforms can be deployed in a wide range of situations, ranging from providing connectivity, extending coverage or providing extra capacity whenever unexpected high traffic demands, a big event takes place, supplying the necessary communication infrastructure in case of an emergency, or bringing service in rural and isolated area or any hard-to-reach areas. Recently, the use of drones as small cell base station to support ground cellular networks has received substantial attention. Because of these reasons, the deployment of drones in mobile communication networks has seen an increased attention recently Erdelj et al. (2017),Wang et al. (2016),Kalantari et al. (2016).

Enabled by recent technological advancement and open-source hardware and software initiatives, UAVs have found several key applications recently Villasenor (2014)-Koh (2013). Amazon, for example, claims that seeing its Prime Air order delivery UAVs in the sky is expected to be as conventional as seeing mail trucks on the road within the next few years Mohammed et al. (2014). Google and Facebook have been examining the use of a network of high-altitude balloons and drones A. Abdulsalam and Zhang (2014.) over specific population centers for providing broadband connectivity. Such solar-powered drones are capable of flying several years without refueling. UAVs are having self organization capabilities, which are invaluable for quickly delivering broadband connectivity at times and locations where most needed, through an agile, low-cost, and ubiquitous communication infrastructure. Due to their high mobility and low cost, UAVs have found a wide range of applications like, for instance, public safety, search and rescue missions and disaster recovery systems Valavanis and Vachtsevanos (2015). Multiple UAVs, in fact, can be utilized to create self-organizing flying swarms, specially designed for rescue operations Kalantari et al. (2016) Bekmezci et al. (2013). Aerial ad-hoc networks provide the advantage to be deployable also on critical scenarios where terrestrial mobile devices might not operate, however their implementation is challenging from the point of view of communication network protocols, of mobility management and of coverage lifetime.

Early uses of UAV were characterized by use of a single large UAV for a task. In these systems the UAV based communication network, therefore, consisted of just one aerial node and one or more ground nodes. Today most public and civil applications can be carried out more efficiently with multi UAV systems. In a multi-UAV system, the UAVs are smaller and less expensive and work in a coordinated manner. In most multi-UAV systems, the communication network, proving communication among UAVs and between the UAVs and the ground nodes, becomes an important constituent. These UAVs can be configured to provide services co-operatively and extend the network coverage by acting as relays. The degree of mobility of UAVs depends on the application. For instance, in providing communication over an earthquake struck area the UAVs would hover over the area of operation and the links would be slow dynamic Gupta et al. (2016).

In terms of communication needs, single UAV systems would have to maintain links with the control station(s), base stations, servers and also provide access functionality. This puts a heavy constraint on the limited battery power and bandwidth. In a multi-UAV system, only one or two UAVs may connect to control and servers and feed the other UAVs. This way most UAVs just have to sustain the mesh structure and can easily offer access functions for calls, video and data. Multi-UAV systems also turn out to be less expensive to acquire, maintain and operate than their larger counterparts. As shown through their experiments by Mergenthaler et al. in Morgenthaler et al. (2012), adding more UAVs to the network can relatively easily extend communication umbrella provided by a multi-UAV system. Missions are generally completed more speedily, efficiently and at lower cost with small UAV systems as compared to a single UAV system Sahingoz (2013). In their work Huang et al. (2010) the authors explain how in opportunistic networks multi-UAVs find a path even if two end points are not directly connected leading to completion of missions. In their work on Multi-UAV cooperative search in Yang et al. (2007) the authors describe how multi-UAV systems complete searches faster and are robust to loss of some UAVs. Advantages of multi-UAV networks are leading to their increasing use in civilian applicationsDaniel and Wietfeld (2011).

2.3.3.1 D2D-Enhanced UAV Information Dissemination

D2D communication is an effective technology for capacity enhancement in terrestrial communication systems Asadi et al. (2014b). The key idea is to offload the BS by allowing direct communications amongst nearby mobile terminals. For UAV-aided communication systems, D2D communication is predictable to play an significant role by providing the supplementary benefits such as UAV energy saving, lower capacity, quick deployment condition for UAV wireless backhaul, etc. Numerous current D2D techniques for terrestrial communication systems, such as those on interference mitigation and spectrum sharing, can be directly applied in UAV-aided communications, particularly in the scenario to support ubiquitous cellular coverage as shown in Fig. 2.11. On the other hand, new D2D communication techniques could be created by exploiting the unique characteristics of UAV-aided communications. The chapter 6 presents the concept of the D2D-enhanced UAV information dissemination, which aims to achieve efficient connectivity and information dissemination to a large number of ground nodes by exploiting both D2D communications and the UAV mobility in disaster communication network.

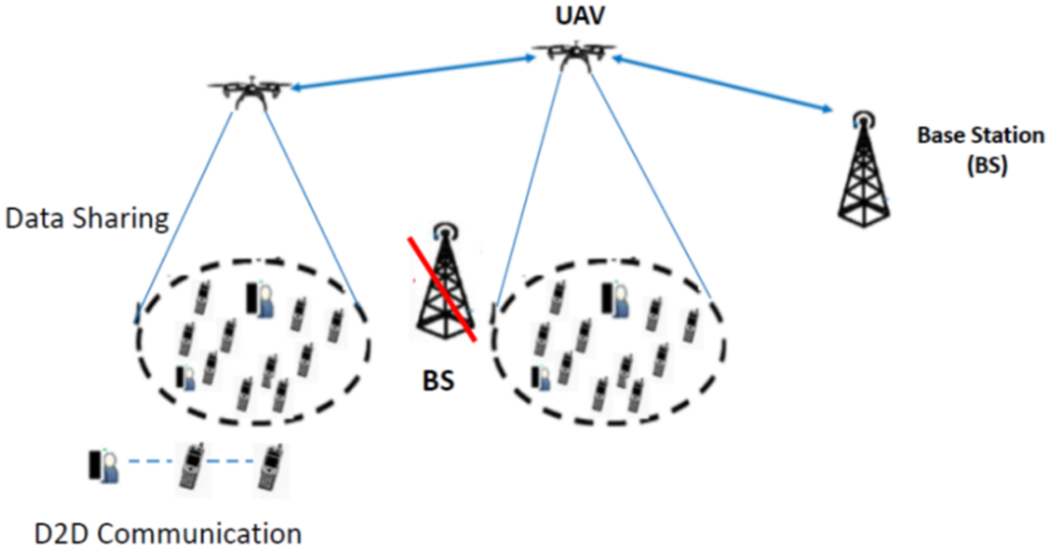


Figure 2.11: UAV-aided wireless communication use cases

As shown in Fig. 2.11 , the scenario where one UAV flies over a certain area where communication is disturbed because of disaster situation. UAV can be used to distribute a common file to a large number of ground nodes. One simple approach to realise this is by letting the UAV repeatedly transmit the same data as it flies over different ground nodes, until all of them successfully receive the information. It is not difficult to see that such a scheme requires substantial UAV retransmissions, and its performance is essentially limited by the ground terminals which experience the weakest channel.

From the above Fig. 2.11, it is observed that the UAV broadcasts the appropriately data to the ground nodes. Each node has only limited wireless connectivity with the UAV, it is very likely that some of the nodes would be able to successfully receive data. Later ground nodes exchange their respectively received data via D2D communications, until all the nodes receive data successfully. This approach expressively decreases the number of UAV retransmissions and as well as a result the total flying time of the UAV, which saves its energy and is particularly useful for small UAVs with limited on board energy Zeng et al. (2016).

One of the main lack in this field is the absence of a generic architecture for the design of the next-generation wireless devices that is able to face with an emergency scenario. These devices need to be provided with self-organizing and self-configuring capability, since they must deal with an emergency scenario that is in general unknown. Furthermore, an emergency scenario has the characteristic of shortage in communication infrastructure. For this reason the public safety agencies need a temporary communication network that is capable of fast deployment with autonomous configuration ability in order to help victims and the rescue operations. The use of UAV and D2D are the prominent solutions for a fast creation of support communication networks.

2.4 Emergency Situation Peculiarities

In numerous reports from emergency management agencies, the first 72h aftermath the occurrence of a disaster also referred as “Golden 72 hours” Lien et al. (2009), are considered the most critical hours to organize first response actions and to save human lives Kuntze et al. (2012). In this emergency context, a key role is played by the communication network that must be fully operative in order to enable rescue teams to coordinate operations and to keep the population informed. Unfortunately, this requirement is far to be guaranteed by terrestrial communication infrastructures, whose fragility has been confirmed by most of recent (catastrophic) events worldwide.

This thesis distinguishes the main characteristics of disaster (e.g. unpredictability, limited resources, hardware failure, interoperability loss, system complexity, network connectivity, power deficiency, dynamic changing environment and etc..). Given these communication challenges, there is strong motivation towards the realization of backup communication systems that are able to quickly self-deploy in the aftermath of an emergency and ensure temporary network services in the affected area. One main issue is established by the occurrence of network partitions caused by damages to the communication components (e.g. base stations), and by the lack of adequate self-healing capabilities of devices and of the infrastructure. A dramatic evidence of this fact was provided by the Japan earthquake in 2011. Network bandwidth constitutes also a key issue since peak traffic demands generated by mobile devices owned by survivors or by rescue teams during disaster example found in Italy earthquakes. The cellular infrastructure was not fully damaged, but its functionalities were severely compromised by the exceptional traffic load generated by end-users so that both conventional and emergency communication services could not be supported Bbc.com (2016). Moreover, some area can have insufficient presence of cellular base stations and other traditional communication infrastructure, like in Nepal, where after the earthquake that had a magnitude of 7.8 Manesh Shrestha (2015), teams from all over the world thronged Nepal for offering rescue and relief services, but they had communications difficulties for the rescue operations due to the intermittent connectivity provided by the actual network infrastructure Bhattacharjee et al. (2016).

2.4.1 Communication Challenges

To overcome the communication boundaries produced by the emergency situation, most of disaster relief organizations depend on alternative mission-critical communication systems (e.g. TETRA and TEDS Nouri et al. (2007) in Europe). However, the utilization of such technologies are limited to specific applications and is not suitable to create large-scale emergency networks, due to the technological limitations in terms of coverage, bandwidth, and interoperability with their define devices. Moreover, due to the mobility of the nodes, the network topology is continuously varying. Most of the researches on wireless systems have investigated how to deploy wireless networks with self-configuration and self-healing capabilities, in order to promise facility continuity in case of communication failures of specific network components during disaster Zhang et al. (2013).

We have highlighted some of the areas in which we can present our contribution and proposed a reliable, efficient and robust network. The cube depicted in Fig. 2.12 a holistic view of our research work. The communication networks recognized during an emergency can be mostly categorized into two types: infrastructure based and infrastructure-free. The infrastructure networks are based on the assumption that the communication infrastructure remains active also after the disaster, i.e. cellular networks and users of local area networks. These kinds of solutions are, though, difficult to preserve after a disaster where the commu-

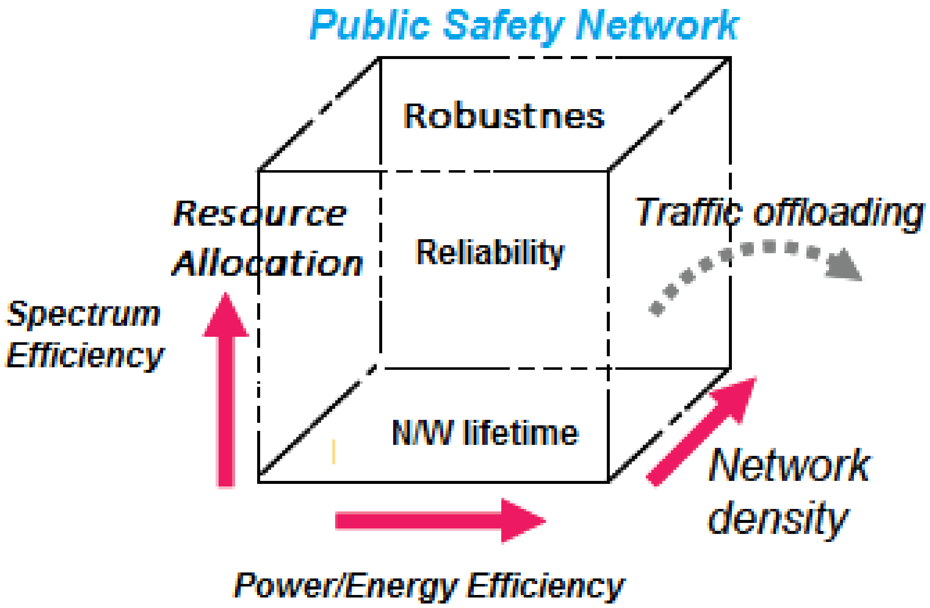


Figure 2.12: Holistic View of Research

nications infrastructure is seriously damaged. The infrastructure-free approaches have, instead, more flexibility and can restore damaged communication networks where response operations can be established in an ad-hoc manner. However, besides the well-known results from the literature on hop and Multi-hop relay, this thesis actually proposed solution discussed in later chapters on the bases of different technologies for example, ad hoc networks, 3GPP-LTE with device to device communication approach, movable base stations with aerial unmanned vehicles (drones), clustering of nodes and energy harvesting ability along with proposed algorithms for better connectivity and communication. Fig. 2.13 below shows the overall concept of this research and thesis which includes all major technologies that are an integral part of the PS framework. Parts of the framework in Fig. 2.13 appear in forerunner chapters of the thesis.

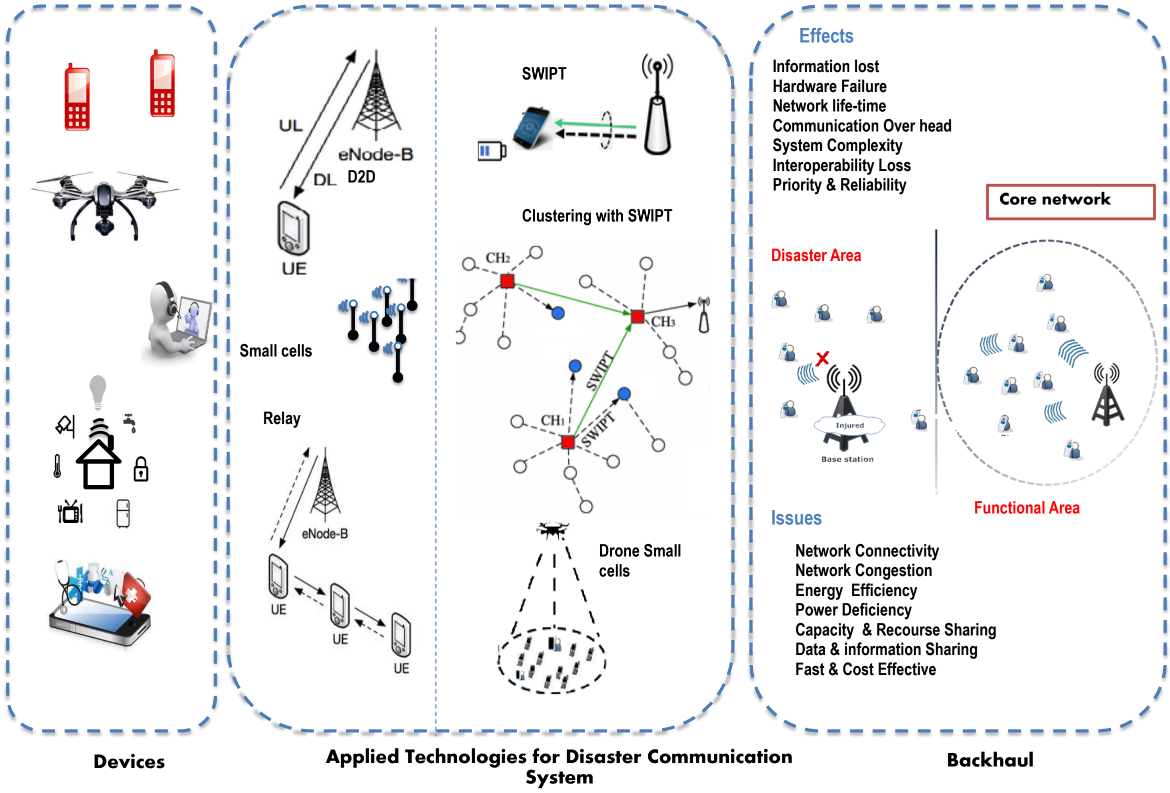


Figure 2.13: Centric View and Methodologies

2.5 TAXONOMY

In this section, the thematic taxonomy is presented for networking aspects for disaster communication system. The taxonomy identifies and categorizes key attributes essential for the basic preparation concept and development of system architecture for disaster communications. As demonstrated in Fig. 2.14, the taxonomy at the top level is categorized into the two attributes, i.e., pre-disaster and post-disaster phases. The purpose behind forming the taxonomy is to provide an overall understanding of the appropriate communications with strong impact on efficiency and responsiveness of emergency services. We classify it with numerous related attributes for critical communication to develop robust and sustainable system. The taxonomy is the reflection of the proposed solution for efficient, reliable and low latency communications network uses multitude of technologies to improve existing systems.

There are two main concerns regarding communications in disasters. The first is related to the pre-disaster communications when disaster warnings need to be transmitted efficiently to citizens and to aid rescue operations. The second is related to post-disaster when there is lack of communication access for the emergency response operations due to the destruction of various communication mediums.

2.5.1 Pre-disaster Phase

Early Warning System

Early warning system generates simple and clear messages containing valuable information to provide accurate responses for minimizing causalities and infrastructure damage. Early warning system depends on communication systems so that it can span to the regional and national level. Monitoring for a warning involves observation and detection of the factors that are distributed and interconnected and indicates the likelihood of a disaster occurrence. A potential threat warning is triggered for the system to analysis. Threat analysis and dissemination of the information over the network plays a key role in ensuring people and communities at risk obtain precise warnings in advance of approaching disaster and enabling inter-organizational coordination through required information exchange. Multiple communication mediums are utilized to ensure wider accessibility for warning and saving people at risk. Communications concerns for early warning system are the capacity, efficiency, and reliability of data transfer networks. It is very important as well as challenging to efficiently perform different network management activities such as identifying, configuring, monitoring and troubleshooting network devices. User-friendly accessibility is extremely important for early warning systems to ensure unrestricted access to the people in need.

Communication Resources

Infrastructure-based networks utilize multiple access points distributed throughout a given area, to provide connection to mobile terminals. The performance of infrastructure-based networks is comparatively much better than other adhoc networks. Long-range communication systems use satellite and other high-

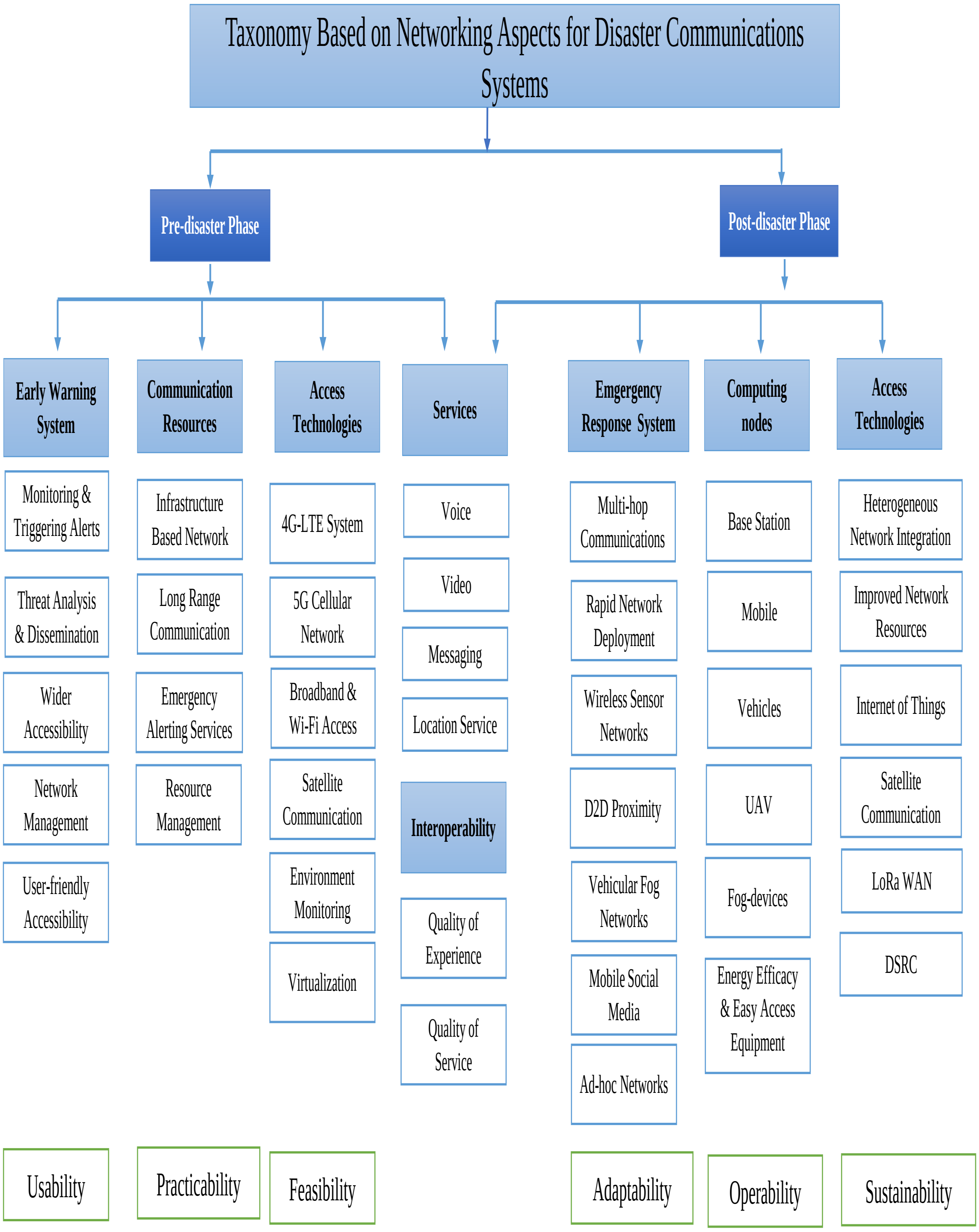


Figure 2.14: Taxonomy of Disaster Communication Architecture system

frequency communication systems that support beyond the line of sight operations. Authorized organizations require to disseminate warnings and coordinate with each other and other public systems through some dedicated communication service. Emergency alerts are mainly transmitted via terrestrial and satellite television and radio broadcasting, which requires different communication channels. In order to improve the performance of the network, resource management techniques need to be applied to ensure proper usage of bandwidth, storage capacity, etc. Resource management includes the identification and coordination of various network devices that can assist in efficient and reliable communications.

Access Technologies

LTE provides communications with wide area mobility, improved interactivity and on the go multimedia services. 4G LTE technologies are widely used by major telecom operators globally. With its high speed and low latency features, users are able to operate applications such as social networks, banking, maps, browsing, etc. in addition to traditional voice calls and SMS services. 4G is gradually replaced by 5G, which is the fifth generation of cellular mobile communications. This shift will drastically change the usage of technology by providing faster and more reliable services. These cellular mobile communications with its wide access to the people can be utilized for early warnings and disaster alerts. Satellites are not vulnerable to damage from disasters, which make them the only wireless communication infrastructure that can reliably be utilized in disasters. Though the main concern is the cost of satellite bandwidth but establishing a communications infrastructure in a disastrous area might comparatively cost more. Continuous, accurate and high-resolution environment monitoring is of great importance for disaster management and early warning systems. The inter-linked network of environmental monitoring sensors can aggregate and disseminate a great deal of useful information for early warning systems. Virtualization methods are making the networks more accessible and reliable by and identifying bandwidth controls and managing the workloads.

Services

One of the promising technologies that will support the disaster architectures and is being considered in the future standard Long Term Evolution Release 13 and beyond, is device-to-device communications. D2D can be used for different proximity-based services where the users locate their neighbours and benefit from various services like social apps, messaging, alert messages, location services.

Interoperability

The communication networks used during disaster management processes have a number of issues which includes the following,

- Interoperability of communication devices and protocols between authorized organizations/emergency responders.
- Network congestions and network speed differences.

Disaster situations are a challenge for network operators because they result in an extraordinary large number of calls being opened simultaneously compared to normal operating conditions. The Quality of Service (QoS) and Quality of Experience (QoE) for the end user can be widely affected by peak loads and result in severe degradation, basically due to congestion on bottlenecks inside the network. In disaster situations, however, a high reliability of the connections is in particular required. To minimize the loss of human lives and infrastructure damage, a disaster communication network has to ensure a strict Quality of Service (QoS) mechanism for better performance with limited network resources. A strict time constraint is also required to be maintained to ensure fast and reliable communications.

2.5.2 Post-disaster Phase

An effective post-disaster phase depends on the technologies (and tools) available that can be used by the affected people on the ground as well as the professional first responders. The affected people should be able to use the available technologies as fast as possible to communicate their location and whereabouts to the first responders present.

Emergency response system

Emergency response system is the capability to reduce the impact and consequences of an incident or major disaster by securing the affected area, and issues as appropriate, safely diverting the public from hazards, providing security support to other response operations and sustaining operations from response through recovery of communication network. To act effectively in disaster situations requires sharing and using information effectively: collecting, collating, analyzing, and then deploying it promptly and in a useful form. Use of information and communication technologies in emergency responses is a persistent challenge that requires constant attention. The rapid advancement of communication technologies that has occurred during the last decade has changed the way emergency communications are performed. In this taxonomy, multi-hop communication, wireless sensor network, D2D proximity, vehicular for network, mobile social media, and ad-hoc networks considered from adaptability point of view.

Computing Nodes

In disaster, the devices have limited energy and processing capabilities, which make them unsuitable for computing-in-intensive tasks. However, resources-contained can be provided extra energy from energy harvesting to increase their capabilities during disaster operation. Computing nodes includes BS, mobile, vehicles, UAVs, fog-devices etc.

Access Technologies

Various computing paradigms are used in disaster communication to provide different services depending on diverse application requirements. These paradigms can be categorized into heterogeneous network, devices proximity, LoRa WAN, DSRC, D2D. The end user can access the services using both wireless and wired access technologies. Telecommunication network operators with the assistance of heterogeneous network can deploy new services for victim and rescue teams rapidly from the nearby BS.

Chapter 3

Relay-assisted Multi-hop D2D Communication For Public Safety Networks

D2D communication has been proposed as an underlay to the LTE networks as a means of harvesting the proximity, frequency reuse and hop gains. However, the D2D communication can also serve as a technology for providing public safety and disaster relief services. This chapter investigates the performance of the network architecture by utilizing the relay assisted transmission which can effectively enhance the capacity and power saving of the network. Specifically, it has been found that D2D communications can increase the spectral and energy efficiency by taking advantage of the proximity, reuse and hop gains when radio resources are properly allocated to the cellular and D2D systems. In particular, a distance based strategy is proposed to reduce the computational complexity and power transmission. The achievable capacity is derived so as to maintain the outage probability constraints of both cellular and D2D systems. Furthermore, multi-hop communications investigated for enhancing the capacity of the D2D communications, energy efficiency and spectral efficiency in public safety partial coverage scenarios.

3.1 Introduction

The topic of D2D communication is enormously popular Yang et al. (2016); however, only few works have been done to propose network architecture level in order to incorporate D2D communication. The proposed system explicits the concept of D2D technology application and presents a disaster communication network architecture for the public safety network scenario. The architecture allows sufficient and resourceful connectivity between the functional and non-functional areas in which victims, rescue teams, and other services can carry on communication in the affected locations. The overall system tends to provide reliability, availability, and reduce the complexity by using modern technology of D2D and relay assisted network. Subsequently, the relay assisted concept of transmission in a disaster can effectively enhance the capacity of the D2D system. Furthermore, power efficiency for D2D system increases as the number of hops increases as discussed in result section of this chapter.

The public safety networks ought to be reliable, resilient and secure while meeting other stringent functionality requirements in terms of service accessibility, end-to-end performance and device characteristics with radio coverage. Network recovery/restores, network infrastructure to their original status or else to a certain level of the availability even temporarily to provide the users with basic communication services after a disaster. Keeping the above facts in mind, the research community proposed disaster resilient networks on the basis of earlier disasters experiences and related projects around the world. The common goal of all efforts is to design network architectures and provide solutions that are resilient to disaster. Network resiliency and recovery from disasters can be tackled with multiple approaches:

Nippon Telegraph and Telephone Corporation (NTT) Sakano et al. (2013) proposed a disaster resilient network architecture using specially designed, movable and deployable resource units (MDRUs), transportable container that accommodates modularized equipment for networking, information processing, and storage. The architecture is based on layers named network facility, network, and platform layers. Accordingly, each MDRU forms a wireless access network around it to reach customer premises equipment. Existing optical fibers can be used for connecting the MDRU to nationwide networks if they are found not damaged in the disaster area. In Ohyama et al. (2012) the authors described how vehicles could be used as network nodes in temporary disaster information networks. The basic observation behind the ideas presented is the fact of Dedicated Short Range Communication (DSRC) systems which is gradually coming into practical use in some countries. Both mobile roadside units (RSUs) and vehicular on-board units (OBUs) are used as network nodes in a multi-hop network, while end users are using regular smart phones. The system was designed to use a variety of protocols for vehicular applications. The authors in Hasegawa et al. (2013) presented how to use white space which is temporally unused licensed frequency. The IEEE standard 802.22 based wireless regional area network (WRAN) was discussed and a prototype was proposed using television white space. The basic components of the prototype are a MAC control unit, a transceiver (TRX) unit, a radio frequency (RF) controller and a global positioning system (GPS) receiver. The proposed prototype can be used as an alternative line or backhaul line in the cellular systems. Additionally, the features of the system are flexible channel usage and long-range wireless communication availability as they employ dynamic spectrum access under television white space channel and QoS management.

In last few years, we have witnessed some development in research related to disaster communication management. Several systems that are currently in place for allowing people to communicate during emergency and critical situations include M-Urgency and SafeCity. In M-Urgency Krishnamoorthy and Agrawala (2011), users can use either iOS or Android to stream live reports over the cellular network to a local public safety answering point. Moreover, it delivers real-time position through GPS or Wi-Fi fingerprint to confirm an appropriate help for victims. SafeCity SafeCity allows receiving live mobile video stream of crimes and crises situations.

However, in disaster situation, the existing emergency response systems need the network infrastructure to be operative. Due to physical damage to cellular BSs or network congestion, communication infrastructures may not be available to users in disaster areas. In such a situation, communication becomes difficult between victims and rescue teams. Some existing technologies Gupta and Jha (2015) overcome this problem by permitting to create ad-hoc communication networks during a disaster. For instance, Wi-Fi Direct in Camps-Mur et al. (2013) enables ad-hoc communication; however, its key mechanisms do not support legacy Wi-Fi devices but only Wi-Fi Direct-certified devices. During recent earthquakes of Italy, Nepal, and New Zealand, Facebook activated its Safety Check feature to enable people to give quick safety status updates to their family and friends SafetyCheck (2016.). Popular social media tools like Twitter and Facebook were flooded with messages for requests and help.

It was observed that, local people had little capacity to gather and arrange a large amount of information arriving. However, D2D communication can effectively exploit the radio resources with the goal of serving a large number of affected people to collect the information from different nodes in disaster zone Asadi et al. (2014a). Authors in Baldini et al. (2014) explicate the functions of cognitive radio (CR) that provides spectrum sensing, spectrum management, spectrum sharing and spectrum mobility. These CR functions enable the flexibility needed during disaster management in the affected zones where fixed communication infrastructures may be damaged.

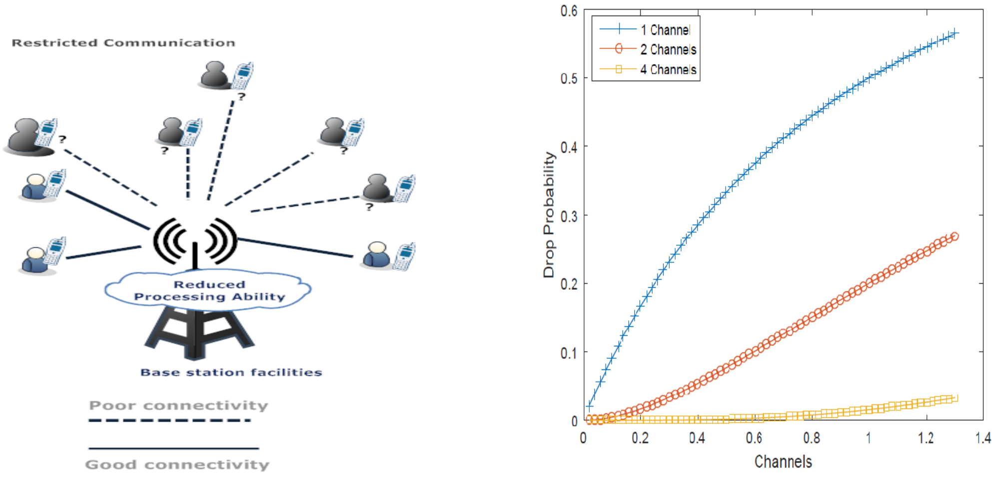
The goal of this chapter is to evaluate the benefits of using relay-assisted transmission and multi-hop communication techniques in extending the coverage area of active base station in public safety partial coverage area. By using multi-hop, it is possible to connect the source (faraway UE) to the destination with the intervention of other UEs acting as temporary wireless relay. The power efficiency for D2D system increases as the number of relay hops increases, which implies the relay-assisted D2D system is a power saving system. Also energy efficiency and spectral efficiency performance of D2D have been evaluated since for emergency situations efficient energy and spectral resources utilization are critical.

3.2 System Description

3.3 Scenario 1

Basically, there are two possible situations that can be set up for emergency communication networks including: i) partially damaged BS and ii) fully damaged

BS. Fig. 3.1 is the schematic of situation (i), in which BS is partially injured because of disaster so it has only limited accesses and processing ability. Therefore, mobile phones and internet access will be congested in affected areas and difficulties with regular communications are observed as shown in Fig. 3.1(a). Due to the reduced processing ability of BS, call dropping problem intensifies. The call dropping is caused by lack of available radio channels and network capacity which varies unpredictably. Service requests stupendously increase just after the event when people from the affected zones desperately seek to communicate with both inside and outside of the disaster-stricken zones. These states instigate serious traffic congestion. So, keeping in mind channels and call traffic congestion, the experiment is performed on the basis of some assumptions to see how it affects the transmission. It is particularly important to understand the traffic volume at peak times when the loss probability, denoted by B, can be given by ErlangB:



(a) Reduced Processing Ability of BS

(b) Variation of Drop-Call Probability and Traffic Intensity with Channel

Figure 3.1: Partially Damaged BS

$$B = \frac{A^N/N!}{\sum_{k=0}^{N} A^k/k!} \tag{3.1}$$

where denotes the, A = offered traffic intensity in Erlang and N = denotes the available number of channels. It can be seen in Fig.(b)3.1, if traffic intensity increases the call drop probability rises but if we increase the number of channels drop call probability decreases which later stables the communication process.

3.3.1 System Architecture

Considering situation (ii), as shown in Fig. 3.2 BS is fully injured and UEs have no radio resource. Utilizing the relaying concept the UEs can be selected from the functional area to perform like a mobile relay. In Fig. 3.2, all the UE devices located in a non-functional BS area or disaster area (i.e. region (A)) and have no radio signals but they have the capacity to communicate with each other through one-hop or multi-hop routes from functional area (i.e. region (B) . Once the relay node (R) has been selected, the system can be able to transmit radio signal to the non-functional area (i.e. region (A)). For example, in Fig. 3.2, UE1 receiving radio signal can now be connected with BS in the functional area and start transmitting signals to its neighboured UEs in the non-functional area.. This relaying node can not only increase the system capacity but also

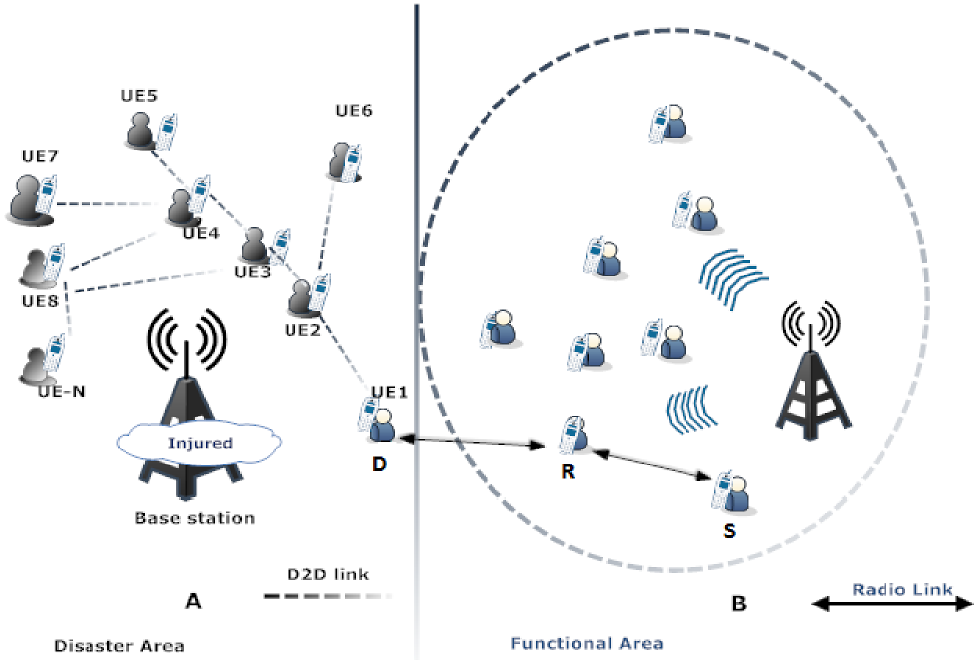


Figure 3.2: D2D communication concept with relay node.

reduce the transmission power for mobile host and extend the system coverage area. Here, D2D users must ensure their transmission does not cause a specific level of interference that leads to failure of the cellular link. For instance, the interference can be caused by the spectrum sharing between cellular and D2D (see Fig. 3.2). In this chapter, the propagation channel model contains pathloss and Rayleigh fading δ_{ji}. Therefore, the received power at a typical receiver from the i node in system j is $P_j\delta_{ji} \mid X_{ji} \mid^{-\alpha}$, where P_j is the transmission power of user set j, α is the pathloss exponent, $\mid X_{ji} \mid$ is the distance between the transmitter and receiver of user i in system j. For Rayleigh fading δ_{ji}, it has an exponential distribution with unit mean. In the interference situation, we consider the interference nodes in user set j can be modelled by marked Poisson Point process (MPPP), which is denoted as $\prod_j = (X_{ji}, \delta_{ji})$. Since the interference is caused by spectrum sharing between cellular and D2D systems, the signal to interference plus-noise ratio (SINR) at a receiver in system k can be given by Wen et al. (2013)

$$SINR_k = \frac{P_k\delta_{k0}R_k^{-\alpha}}{\sum_{j\neq k}\sum_{X_{ji}\in\prod_j} P_j\delta_{ji} \mid X_{ji} \mid^{-\alpha} + N_0} \tag{3.2}$$

where P_k is transmission power, δ_{k0} is fading factor link between the desired transmitter and receiver of system k, N_0 is the thermal noise power and R_k is the distance between the transmitter and the receiver node (which can be either BS, D2D or relay node) of system k.

The successful transmission of system k can be possible when $SINR_k \geq \upsilon_k$, where υ_k is the target $SINR$ for system k. The probability of successful transmission is represented as Lee et al. (2010):

$$P(SINR_k \geq \upsilon_k) = exp\{-\zeta_k \sum_{j\in\Phi} \gamma_{kj}\lambda_j\} \tag{3.3}$$

where $\gamma_{kj} = (P_j/P_k)^{2/\alpha}$, $C_\alpha = (2\pi/\alpha)\,\Gamma(2/\alpha)\Gamma(1-2/\alpha)$ with Gamma function $\Gamma(x) = \int_0^\infty y^{x-1}e^{-y}dy$ and $\zeta_k = C_\alpha R_k^2 \upsilon_k^{2/\alpha}$. Therefore, the outage probability of cellular system can be expressed as, Wen et al. (2013)

$$P_c^0(\lambda_c, \lambda_d) = 1 - \left[exp\left\{-\zeta_c(\lambda_c + \gamma_{dc}^{-1}\lambda_d)\right\}\right] \tag{3.4}$$

where $\zeta_c = C_\alpha R_c^2 \upsilon_c^{2\alpha}$. Equation 3.4 becomes

$$P_c^0(\lambda_c, \lambda_d) = 1 - \left[exp\left\{C_\alpha R_c^2 \upsilon_c^{2/\alpha}(\lambda_c + \gamma_{dc}^{-1}\lambda_d)\right\}\right] \tag{3.5}$$

$$= 1 - [exp\left\{(2\pi/\alpha)\,\Gamma(2/\alpha)\Gamma(1-2/\alpha)R_c^2\upsilon_c^{2/\alpha}(\lambda_c + \gamma_{dc}^{-1}\lambda_d)\right\}].$$

Finally, after putting the values of $\Gamma(x)$ in the above equation, the probability is:

$$= 1 - [exp\left\{(2\pi/\alpha)\,(\int_0^\infty y^{2\pi/\alpha-1}e^{-y}dy)\right.$$
$$(\int_0^\infty y^{2\pi/\alpha-1}e^{-y}dy)R_c^2\upsilon_c^{2/\alpha}(\lambda_c + \gamma_{dc}^{-1}\lambda_d\}]$$

The outage probability of the end-to-end transmission can be expressed as below:

$$P_d^0(\lambda_c, \lambda_d) = 1 - [exp\{-\zeta_{dr}(\lambda_d + \gamma_{dc}\lambda_c)\}]^N \tag{3.6}$$

where P_c and P_d are the power of cellular and D2D users, $\zeta_{dr} = C_\alpha(R_d/N)^2\upsilon_d^{2/\alpha}$ and $\gamma_d = (P_c/P_d)^{2/\alpha}$. Here, υ_d and R_d are the target SINR and the end-to-end distance of D2D , respectively..

Since the relay system operates in time-division duplexing mode, only one node can work at the same time. The relay n can decode the codeword transmitted from the relay $(n-1)$ the capacity of D2D relay system is defined as in Wen et al. (2013), i.e.:

$$C_{D2D} = \lambda_d.\frac{1}{N}\int_0^\infty \frac{1}{1+v}e^{-\zeta_{dr}(\lambda_d+\gamma_{dc}\lambda_c)}dv \tag{3.7}$$

where λ_d and λ_c are the spatial density of D2D and cellular system , respectively. In the non-functional areas ((see region A in Fig. 3.2), the relay distance $R_r = R_d/N$ decreases as the number of hops N increases. The power ratio of cellular and D2D systems, i.e. $\gamma_{dc} = (P_c/P_d)^{2/\alpha}$, has a significant impact on the interference level and system capacity. In order to achieve the transmission capacity for the N-hop relay system, the transmit power and spatial density of the D2D system should be designed for the D2D users. The outage probability constraints the spatial density of the D2D system can given by:

$$\lambda_d \leq min(\gamma_{dc}\xi_c, \xi_d) - \gamma_{dc}\lambda_c \tag{3.8}$$

where $\xi_c = -\frac{ln(1-\theta_c)}{\zeta_c}$ and $\xi_d = -\frac{ln(1-\theta_d)}{N\zeta_{dr}}$. When λ_d satisfies Eq. (3.8), the capacity of the D2D system increases as λ_d increases.

The optimal spatial density is affected by the power ratio of the cellular and D2D system. As λ_d increases, γ_{dc} increases, leading the capacity of D2D system (C_{D2D}) to increase. When λ_d decreases γ_{dc} increases, leading the capacity of D2D system to decrease. The optimal transmit power and spatial density of the D2D system can be given by Wen et al. (2013):

$$P_d = (\gamma_{dc})^{-\frac{\alpha}{2}} P_c = (\xi_c/\xi_d)^{\frac{\alpha}{2}} P_c \tag{3.9}$$

$$\lambda_d = \xi_d(1 - \lambda_c/\xi_c) \tag{3.10}$$

where $\xi_c = \frac{ln(1-\theta_c)}{\zeta_c}$ and $\xi_d = \frac{ln(1-\theta_c)}{N\zeta_{dr}}$. Therefore, relay assisted D2D transmission can benefit from better coverage and high power efficiency. Substitute Eq. (3.9) and (3.10) into (3.8), here the achievable transmission capacity of D2D relay system is obtain as:

$$C_{D2D} = (1 - \frac{\lambda_c}{\xi_c}).\frac{-ln(1-\theta_d)}{C_\alpha R_d^2 V_d^{2/\alpha}} \int_0^\infty \frac{1}{1+v}(1-\theta_d)^{\frac{(v/v_d)^{2/\alpha}}{N}} dv \tag{3.11}$$

The Eq. (3.11) represents the achievable transmission capacity increases as the number of relay hops N increases.

3.3.2 Simulation Results

In this section, we evaluate the performance of multi-hop D2D system by numerical simulations. We consider a single cell situation illustrated in Fig. 3.2 where the cellular users and D2D user are randomly distributed. Some important parameters are listed in Table 3.1.

Table 3.1: Simulation parameters.

Parameters	**Explanations**	**Settings**
λ_c	Cellular spatial density	1×10^{-5}
λ_d	D2D spatial density	3.3×10^{-4}
R_c	Cellular transmit distance	1km
R_d	D2D transmit distance	10m
υ_c	Cellular target SINR	3dB
υ_d	D2D target SINR	3dB
α	pathloss exponent	4

In this section, we provide results to analyze the multi-hop D2D system performance in the non-functional area. From Fig. 3.3 we can see the trend of capacity with the number of relays hops, when the number of relay hops is small ($N \leq 3$), D2D system capacity increases quickly as N increases. This has been observed because the increase of relay hops shortens the transmission distance in large scale, which brings high multi-cast diversity gain. However, when the number of relay hops becomes large ($e.g. N \geq 5$), the decrease in relay distance is not noticeable, but the risk of transmission failure increases in relay mode. Consequently, it results in an inconsiderable increase of the achievable transmission capacity. Furthermore, with high cellular spatial density, more relay hops are required to achieve the same system capacity. This is due to the fact that increasing relay hops can effectively reduce the transmit power of each node, which reduces the interference between D2D and cellular users of the functional and non-functional area. Hence, the multi-hop D2D system can support high D2D spatial density and results in high transmission capacity.

Figure 3.4 illustrates the effect of cellular spatial density λ_d on both cellular and D2D systems. Increasing the λ_d has a stronger effect on the D2D system compared to that of the cellular system. In Fig. 3.4, the outage probability of both systems is plotted against the cellular spatial density λ_d. It can be seen that there is an exponential increase in the outage probability of both systems when the cellular spatial density increases. However, λ_d is shown to have more impacts on the cellular system when compared to the D2D system. Also, an improved outage performance is achieved in the D2D system over the cellular system with

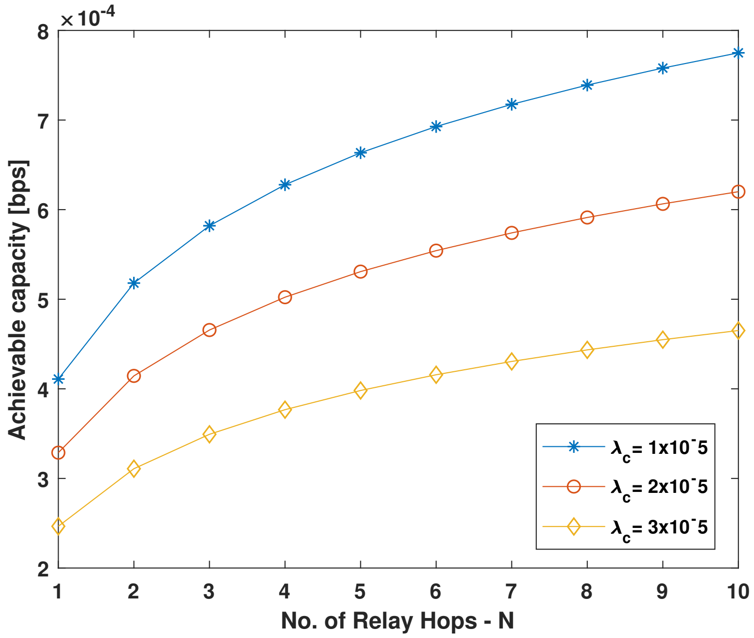


Figure 3.3: Multi-hop D2D system capacity and number of relay hops

respect to λ_d.

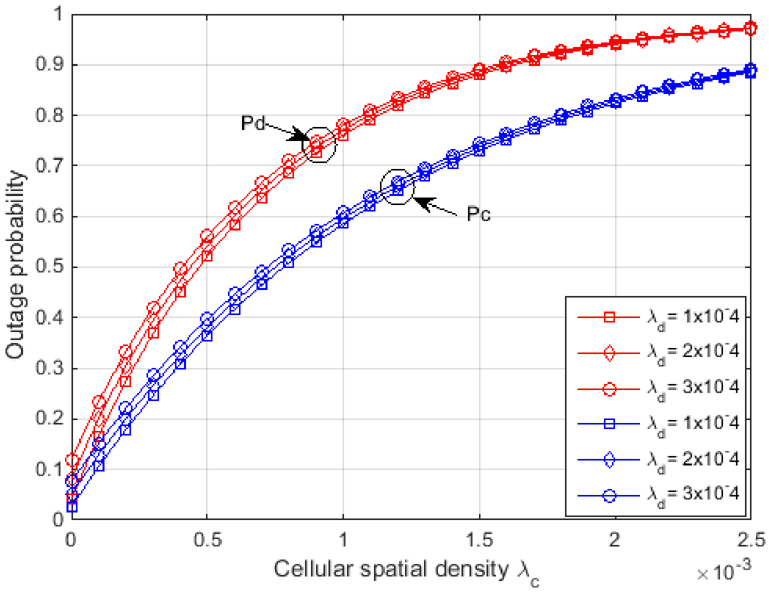


Figure 3.4: Outage parbability Vs cellular spatial density

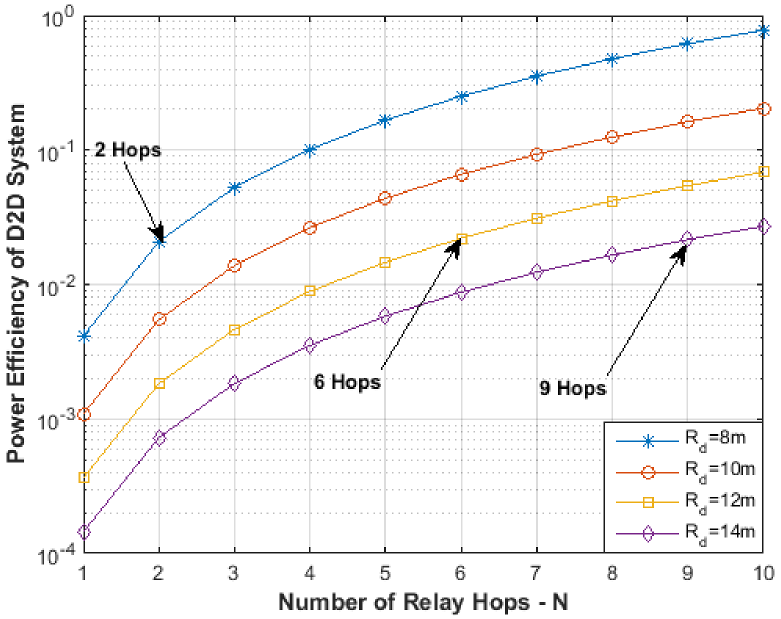


Figure 3.5: Power efficiency performance of multi-hop D2D system

As the power consumption can be one of the main constraints in a disaster area, Fig. 3.5 shows the power efficiency of the multi-hop D2D system. According to the proposed architecture, the power efficiency is defined as the ratio of throughput and transmit power. In D2D communication, if the transmitter is far away from the receiver, transmission via a direct link consumes much power. While with relaying, increasing the number of relay hops can effectively enhance power efficiency, because the required power of each relay link decreases considerably. Therefore, the proposed relay assisted architecture of D2D communication system can be regarded as a power saving system, especially when the D2D users are far away from each other in disaster situations.

3.4 Scenario 2

The disaster situation as shown in Fig. 3.6 is considered, where one BS is transmitting at full power while in lower zone BS are non-functional. As discussed in introduction section, in emergency situations users located in the non-functional area can benefit from D2D UE proximity services. D2D relay allows multi-hop links to be formed between two D2D devices or between the cellular infrastructure and an endpoint UE. Moreover, it is known that the D2D with UE relay enhances data throughput of edge-user and can be used to connect far-away UEs with cellular coverage to the BS which supports the extension of cellular coverage.

In this chapter, the scenario of multi-hop D2D communication with two modes is considered.

- Mode-1. Four predefined paths (section:4.2.2) in which UEs intend to exchange information with each other using multi-hop D2D and extend communication from coverage area to non-functional area.
- Mode-2. Using multi-hop D2D communication to cover non-functional area and exchange information.

Routing in wireless multi-hop communication is a well-addressed research area and it has been studied extensively in the past Sachs et al. (2010)Yuan et al. (2014). Subsequently, several algorithms have been designed and proposed for supporting D2D communication. However, these algorithms are subject to their specific characteristics and may apply to specific scenarios.

Considering the situation in Fig. 3.6 two algorithms named shortest path routing and interference-aware routing are studied and on the basis of the given matrices the shortest path routing algorithm is implemented for given situation.

3.4.1 Shortest-Path-Routing Algorithm

In Shortest-Path-Routing (SPR), each D2D UE is assumed to know its location through GPS and other wireless localisation means (i.e. wireless fingerprinting and triangulation) Yuan et al. (2014). The step-by-step D2D algorithm presented to achieve shortest path routing from a generic UE pair. The SPR algorithm from a soure UE A to a destination UE B includes the following steps:

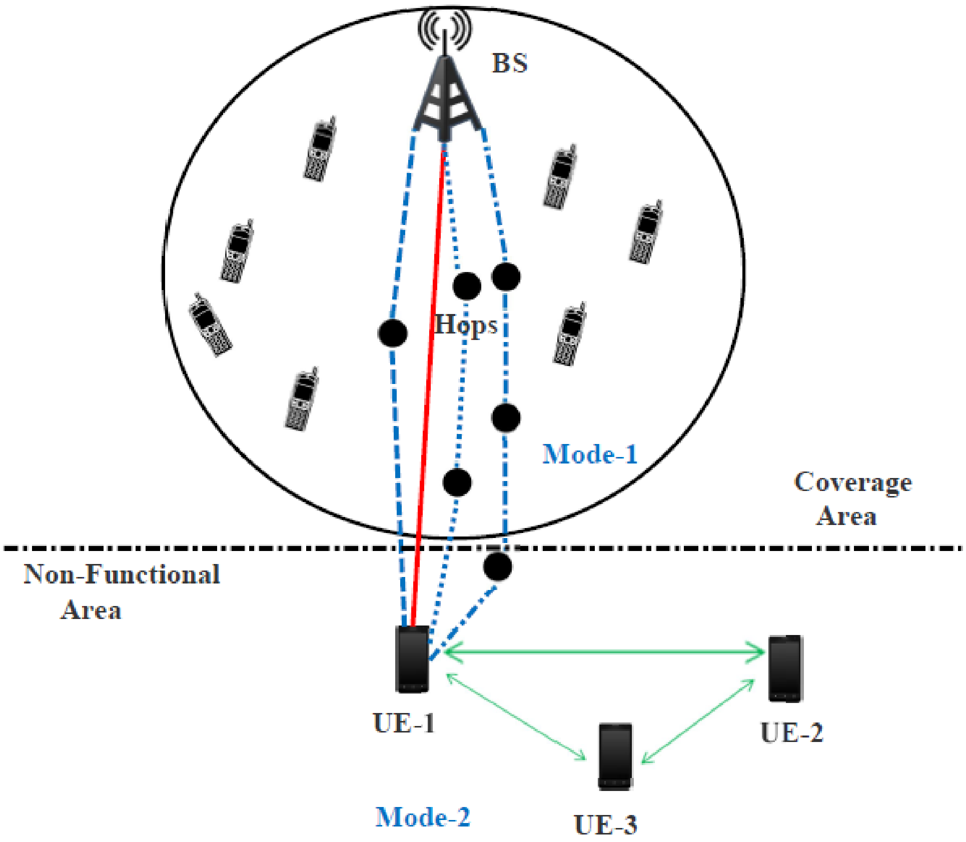


Figure 3.6: System Model for D2D Extended Out-of-Coverage Scenarios.

- Node A detects which of its neighbouring UEs can successfully transmit to node B with some arbitrary that it needs to satisfy for successful connection.
- Then node A sends a relay request to all the neighbouring UEs in its communication range.
- After receiving information about potential relay UEs, node A sends a data packet to the relay that is the closest to the node B.

This process will continue until the destination UE is reached.

3.4.2 Network Configuration

The D2D underlying a cellular network situation Fig. 3.6 is considered for communication purpose where UE_1 intends to communicate with active BS which is nearer to its position. In mode-1 UE_1 is located in the non-functional area and tries to connect with the BS directly or by using different UEs as relays. Moreover, for simplicity four different pathways have been predefined as follows:

- Path-1. Direct communication with BS (0-hop)) not possible because of the distance.
- Path-2. Communication with BS using one UE as relay (2-hop).
- Path-3. Communication with BS using two UEs as relay (3-hops).
- Path-4. Communication with BS using three UEs as relay (4-hops).

Each communication hop is occurring in different time frames Tf_{p_t,l_n,h_o}, where p_t, l_n and h_o denote the, path number, link number for a specific route and hop number within specific link respectively. Let us assume that every communication link L_{p_t,l_n} is composed by H hops h_{p_t,l_n,h_o}. So, every hop which is h_{p_t,l_n,h_o} from the same route resides a different time frame resource. Subsequently, interferences are only possible with the same hops h_{p_t,l_n,h_o} duration from the different routes. Here, SPR algorithm is adopted for simulation purpose. The path selection combines SPR with channel quality information so that the route selected for communication will contain nodes with the best channel that follows SPR rules.

3.4.3 Energy Efficiency and Spectral Efficiency

Energy efficiency (EE) and spectral efficiency (SE) have become two of the dynamic requirements in the design of future public safety communications. Due to the expected limitations in energy and spectral resources during emergency situations, we need to use D2D communication in such a way to increase the cellular spectrum efficiency. This can be performed and controlled with proper interference management and resource allocation. As show in Fig. 3.6, every communication path within a route is independent follows in different time slots, we can present capacity of mode-1 in link l C_{1,l_n} as in Babun et al. (2015), i.e.

$$C_{1,l_n} = \sum_{i=1}^{N} B_w \log_2 \left(1 + SINR_{l_n,i}\right) \tag{3.12}$$

where B_w is communication bandwidth and $SINR_{l_n,i}$ is the signal-to-interference-plus-noise ratio for every hop i within the link l_n. As noise can be considered negligible, $SINR_{l_n,i}$ becomes signal-to-interference-ratio $SIR_{l_n,i}$ which can be calculated by

$$SIR_{l_n,i} = \frac{P_d r_{l_n,i}}{I_t r_{l_n,i}} \tag{3.13}$$

where $P_d r_{l_n,i}$ and $I_t r_{l_n,i}$ are D2D communication received power and received power with interference in hop i and link l_n respectively. At the end, total capacity for all multi-hop communications in mode-1, will define EE and SE performance for multi-hop D2D communications in our model. The overall instantaneous transmission vector for energy efficiency $EE(1, l_n)$ comprised by the EE elements from every link L_{1,l_n} is defined by equation (3.14):

$$EE_{1,l_n} = \frac{C_{1,l_n}}{H p_{tx}^{ue}} \tag{3.14}$$

where H represents the number of hops on every link L_{1,l_n} and p_{tx}^{ue} the maximum transmission power of the UE. In the same manner, we present SE vector for mode-1 as

$$SE_{1,l} = \frac{C_{1,l_n}}{B_w}. \tag{3.15}$$

In mode-2, it is assumed that the distance between UE_1 and UE_2 is d_u and UE_3 is in the middle of both $d_u/2$. The transmission power of UE_t, t = 1,2,3 is P_{ue} and channel gain between UE_t and BS is C_{gt}.

In this mode, the coverage is extended for the non-functional area and UE_1 and UE_2 will exchange information via UE_3 within two time slots. In the first time slot both UE_1 and UE_2 transmits to UE_3 at the same time. The received signal at UE_3 is

$$y_{M_2} = \sqrt{P_{ue}/2}\,(C_{gt_1} x_1 + C_{gt_2} x_2) + n \tag{3.16}$$

where x_t, $t = 1, 2$, is the transmitted data from UE_t and n is the additive Gaussian noise at UE_3. The energy efficiency for mode-2 is calculated as in Wei et al.

(2016),

$$\begin{aligned} EE &= \mathbb{E}_{C_{gt1,0},C_{gt2,0}}\{ee\} \\ &\geq \frac{2B_w}{3P_{ue}}\left[1+\frac{1}{SNR}\log_2(1+SNR)-\log_2 e\right]. \end{aligned} \tag{3.17}$$

3.5 Simulation Results

The simulation results to show the performance of an efficient resource management using multi-hop D2D communication. As BS knows every channel in the field, it can easily determine which node can perform best in the area. In order to select relay shortest path toward BS we used SPR algorithm. Table 3.2 represents the parameters used to evaluate EE and SE. In Fig. 3.7, the energy efficiency as a function of spectral efficiency for variations in resource groups (RG). Simulation results show that increasing the size of RGs will benefit both energy efficiency and spectral efficiency of the multi-hop D2D transmissions. Energy efficiency rises for the same UE transmission power. This is due to the fact that UE act as a relay which influences the system capacity to improve due to the shorter communication path, which results in better channel conditions. Also, these results show that the use of shorter D2D links while increasing the number of hops guarantee or even improve the QoS. The spectral efficiency increases when using a higher number of RGs for the same number of hops. This is due to the fact that the size of RGs increase is associated with bandwidth increase (Table 3.2).

Table 3.2: Simluation Parameters

Parameters	**Values**
System Bandwidth	[2 3 4 5 10 12] MHz
Carrier Frequency	700MHz
Subfram duration	1 ms
UE Max. Trans.power	23 dBm
Min Distance UE2UE	3 m
Resource Groups (RGs)	6 14 25 50 75 100

However, when using a higher number of hops, we also notice that energy efficiency is bounded by a certain limit. This limitation is due to higher aggregate

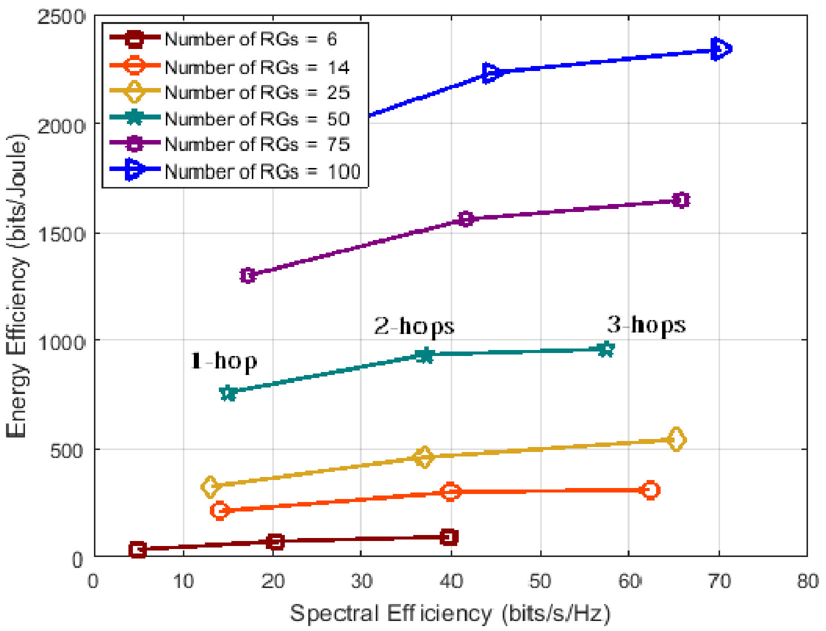


Figure 3.7: Energy efficiency performance vs spectral efficiency while increasing resource group number

interference effects in multi-hops communications.

The Fig. 3.8 and Fig. 3.9 shows the energy efficiency and spectral efficiency versus a number of hops for different size of RGs. It is observed that energy efficiency have dramatical improvements with a higher number of hops for every mode of communication whereas spectral efficiency has nearly double changed for every mode of communication. This confirms the first observations.

Figure 3.10 shows the simulation result of the energy efficiency of the mode-2 and quantify the performance of the D2D multi-hop communication with various D2D distance settings. It is observed that, when the distance between the UEs are less, the energy efficiency is high and as the distance between the UEs increases the EE decreases. The rate at which the EE decreases depends upon the available bandwidth. The energy efficiency at 10m for 20Mhz bandwidth is (approximately) 2 times greater than 10Mhz bandwidth. Even through the EE drops exponentially as the bandwidth is reduced, still, the performance of our proposed network is better and considerable for communication in critical situations.

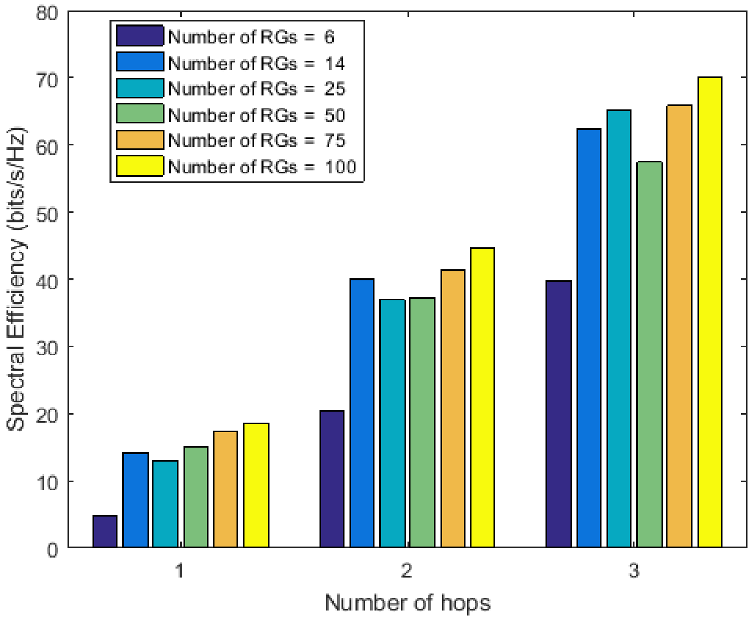


Figure 3.8: Spectral efficiency as a function of number of hops for different resource group values

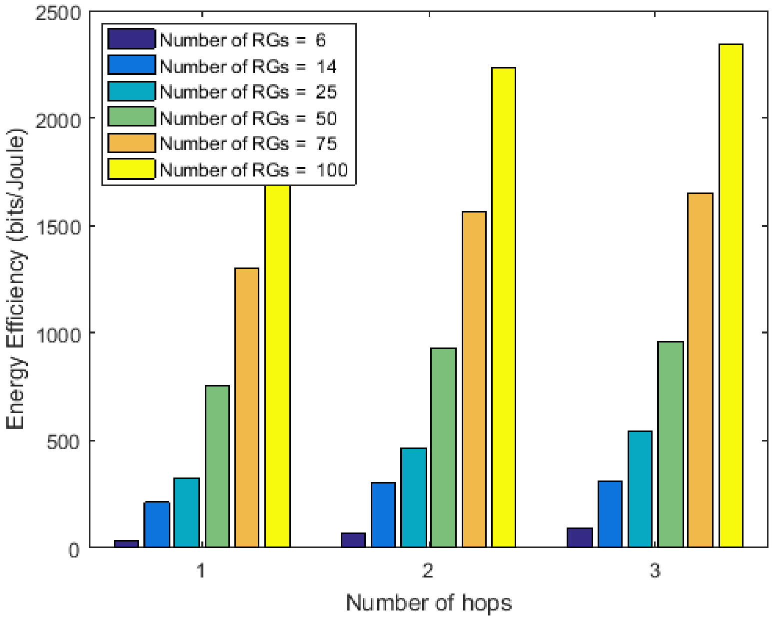


Figure 3.9: Energy efficiency as a function of number of hops for different resource group values

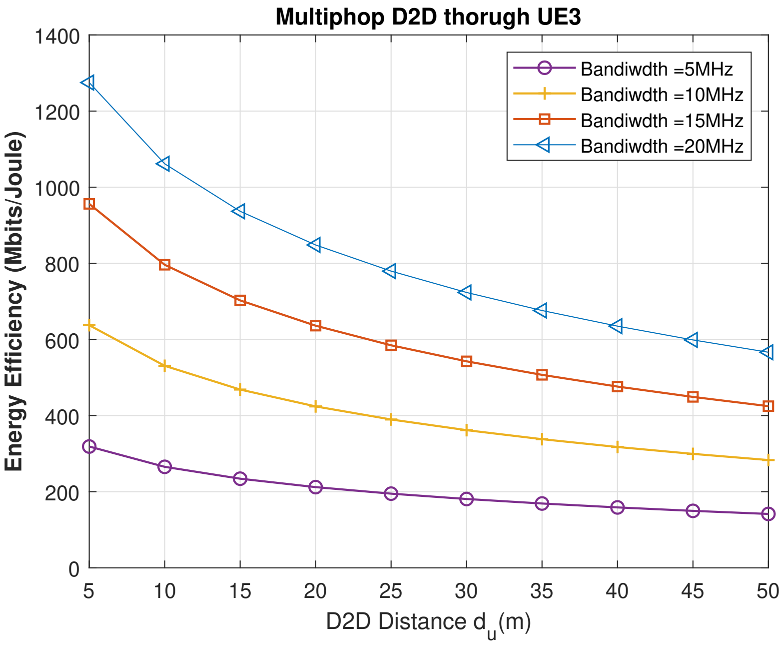


Figure 3.10: Multi-hop D2D communication in non-coverage area

3.6 Summary

This chapter highlighted the concept of D2D communications and its applications with potential benefits in disaster situations. State-of-the-art research works on D2D communication was discussed and a way to protect communication system was proposed at the time of disaster. Having proposed PS network architecture using D2D and reuse resources of cellular users near the BS, the optimization of spatial density and transmit power capacity to the multi-hop D2D system in the non-functional area was analysed with the help of the relay-assisted network. The results show that the proposed architecture enhances the performance of the D2D network, both in system and power efficiency. These were preliminary results with many challenges yet to be investigated. Therefore, next chapter is the extension of the same relay assisted work with SPR algorithm to select the best and quickest path for better performance. The multi-hop D2D communications underlaying cellular networks will be considered to enhance data capacity, energy efficiency and spectral efficiency in public safety partial coverage situation.

Chapter 4

D2D Communication With Power Transfer and Clustering Techniques

As described in the aforementioned chapter that D2D communications as an underlay to cellular networks can not only increase the system capacity and energy efficiency but also enable national security and public safety services. The key requirement for such services is to provide alternative access to cellular networks when they are partially or fully damaged due to a natural disaster. This chapter employs energy harvesting (EH) at the relay (R) with simultaneous wireless information and power transfer (SWIPT) to prolong the lifetime of energy constrained network. In particular, it considers a user equipment relay that harvests energy from the radio frequency signal via a base station and use harvested energy for D2D communications. In addition, a clustering technique is integrated with D2D communications into cellular networks such that communication services are maintained when the cellular infrastructure becomes partially dysfunctional. Simulation results show that our proposed EH based D2D clustering model performs efficiently in terms of coverage, energy efficiency, and cluster formation to extend the communication area. Moreover, a novel concept of power transfer in D2D clustering with user equipment relay and cluster head (UERCH) is proposed to provide a new framework to handle critical and emergency situations. The proposed approach is shown to provide significant energy saving for both mobile users and clustering heads to survive in emergency and disaster situations.

4.1 Introduction

Recently, it has been observed in Italy, Nepal, and New Zealand that due to the earthquakes most of the existing networks were completely destroyed in the disaster areas. This affected local people significantly and made the first responders' tasks very difficult. A large number of victims were trapped in the disaster zones for several days. Such big-scale disasters require a public safety network system that can operate efficiently in disaster situations. The research community has attempted to propose various disaster-resilient networks on the basis of earlier disasters experiences and related projects around the world. The common goal of all the efforts is to design network architectures and provide solutions that are resilient to disasters.

During those above disaster situations, Facebook activated its Safety Check feature to enable people to give quick safety status updates to their family and friend during the disaster. Popular social media tools like Twitter and Facebook were flooded with messages for requests and help. It was observed that on the disaster sites, local people had little capacity to gather and arrange a large amount of information coming in. This has led to the demand to investigate the limitations of the cellular networks to handle the traffic in those critical situations. Fortunately, D2D communication effectively uses the radio resources with the goal of serving a large number of affected people to collect information from different nodes in the disaster zone Asadi et al. (2014a). In Hunukumbure et al. (2013), the authors developed a prototype, namely Relay by Smartphone, of D2D relaying smartphone that enables sending out emergency messages from disconnected areas and sharing of information between people gathered in evacuation centres. In Nishiyama et al. (2014) a novel D2D based messaging solution to overcome the UE power limitation issues faced by cellular radio access technologies in disaster situations was presented. The proposed D2D messaging mechanism was compared with the default Random Access Channel (RACH) based messaging mechanism. However, in this work, the RACH based power consumption was not explicitly modelled for various radio access technologies (e.g., Global System for Mobile Communications (GSM), Universal Mobile Telecommunications Systems (UMTS) and Long-Term Evolution (LTE)), and therefore further study is needed to evaluate the power consumption.

According to the requirement of public safety network, wireless networks are an ideal choice for disaster relief operations as wireless networks do not need any pre-existing infrastructure to be set up and are easy to operate in critical situations. However, energy management is a big concern for such infrastructure. Therefore, some recent studies have considered energy harvesting through the RF signals in wireless cooperative networks. In Chalise et al. (2012), the authors considered a multiple-input multiple-output (MIMO) relay system and studied the trade-off between the energy transfer and the information rate to achieve the optimal source and relay precoding. However, they assumed that the relay has its own internal energy source and does not need external charging. In contrast to Chalise et al. (2012), this paper considers that the relay also relies on external wireless charging through the RF signal from the source node. The authors of Lee (2014) presented hybrid power transfer architecture with power relay. Airships, helicopters, and balloons are used to transfer power wirelessly through inductive power transfer to big communication devices and through microwave power transfer to small communication devices. Differently, the efficient and practically workable BS and relay to transfer energy wirelessly to the destinations are considered for communication.

The work in Li et al. (2015) investigated renewable energy enabled base station (REBS) and pre-equipped energy harvesting devices, performing in wireless mesh network fashion, for post-disaster communication scenarios. Particularly, the authors focused on optimizing data traffic throughput with the lowest weighted energy consumption, in which they proposed an off-line energy efficient scheme using the expectation of traffic demands. In addition, for better energy consumption and management in future cellular networks, the authors in Nahas et al. (2014) proposed a new algorithm to help in reducing the energy consumption of heterogeneous LTE network (HetNet) using macro and micro base stations and cell zooming. The solution is carried out through introducing new cell sizes (micro, pico and femto cells) with various capacities, coverage areas, and lower power consumption by operating all together existing base stations in a heterogeneous network. However, the existing scholarly works have focussed mainly on reducing the energy consumption of BS via HetNet and cell zooming, whereas in this chapter extended communication links in the disaster area presented by adopting EH-D2D technique and a clustering method. The authors Vien et al. (2017) explore and analysis the current wireless networks for energy efficient, particularly the base stations by which terminals access services from the network. The research article discusses the approach being taken in the Mobile VCE project and presented novel approaches to reducing the energy consumption of wireless links, particularly in improving the design and operation of wireless base stations. Moreover, the authors Han et al. (2011) investigated the security at the physical layer in cooperative wireless networks (CWNs) where the data transmission between nodes can be realised via either direct transmission or relaying transmission schemes. The authors particularly optimized the optimal scheme amongst several DT and RT to achieve lowest secrecy outage probability. In Sakano et al. (2016), resource unit concept called Movable and Deployable Resource Unit (MDRU) was presented by Nippon Telegraph and Telephone (NTT) Corp. The idea of MDRU is to transport a complete resource unit to the disaster site and deploy recovery network. However, the cost of making an MDRU is very high, and the MDRU deployment may not be practical considering that spectrum and energy resource in a disaster area is significantly limited while the demand of network connectivity, capacity and power often increase with time during and after a disaster.

In Altay et al. (2016), the authors proposed a standalone eNode-B architecture, which deploys its own integrated virtual evolved packet core (EPC) to ensure service without backhaul connection. The proposed standalone eNode-Bs are also designed to establish backhaul connection with each other to extend the coverage without the need for a central EPC structure. The concept of eNode-B not only offers better interoperability but also increase functionality in terms of transmitting data especially in emergency situations and disaster scenarios. However, the work in Altay et al. (2016) did not address the power consumption issue during the disaster events. In Xiao et al. (2010), the effect of the relay mobility was addressed, where the authors considered the coverage and capacity extensions by mobile relays and the influence of mobility on the probability of route establishment and the expected availability duration. However, this work limits their scope to point-to-point communication with a single cell in the idealized circular coverage area, whereas here in this chapter the communication links across the entire network of multi-cell multihop discussed where the network coverage is extended beyond a single cell using D2D relay links. Additionly the authors Chu et al. (2017a) explore disaster-recovery communications applying two-cell cooperative D2D communications. Specifically, one cell is in a healthy area, while the other is in a disaster area. A UE in the healthy area aims to assist a UE during disaster to recover wirless information transfer via an energy harvesting relay. In the healthy area, the cellular BS shares the spectrum with the UE, however, both of them may belong to different service providers. Thus, the UE pays an amount of role as incentive to the BS as part of two processes: energy trading and interference pricing. The research articulated these two processes as two Stackelberg games and the outcome help providing a sustainable framework for disaster recovery.

4.2 System Model And Our Approach

Mobile communications with D2D proximity have unique topographies which are valuable in disaster and emergency situations. As long as BS is up and running or an ad-hoc process can manage to provide reliable communications (relay system), wireless links can be easily established between users within its coverage area or with extended options.

4.2.1 Disaster Management Architecture

The public safety scenario as shown in Fig. 4.1, where a source (i.e., BS) with a fixed energy supply desires to transmit its information to a destination located in the out of coverage area. Due to the barrier between the source and destination or direct link distance, the source cannot directly transmit its signals to the destination; thus it asks a relay to assist its information transmission via D2D communication proximity services since the destination is in a disaster area where direct communication is not possible. However, because of the selfish nature, or lack of energy supply, the relay needs to harvest energy before being able to help. Throughout this chapter, the following set of assumptions are considered.

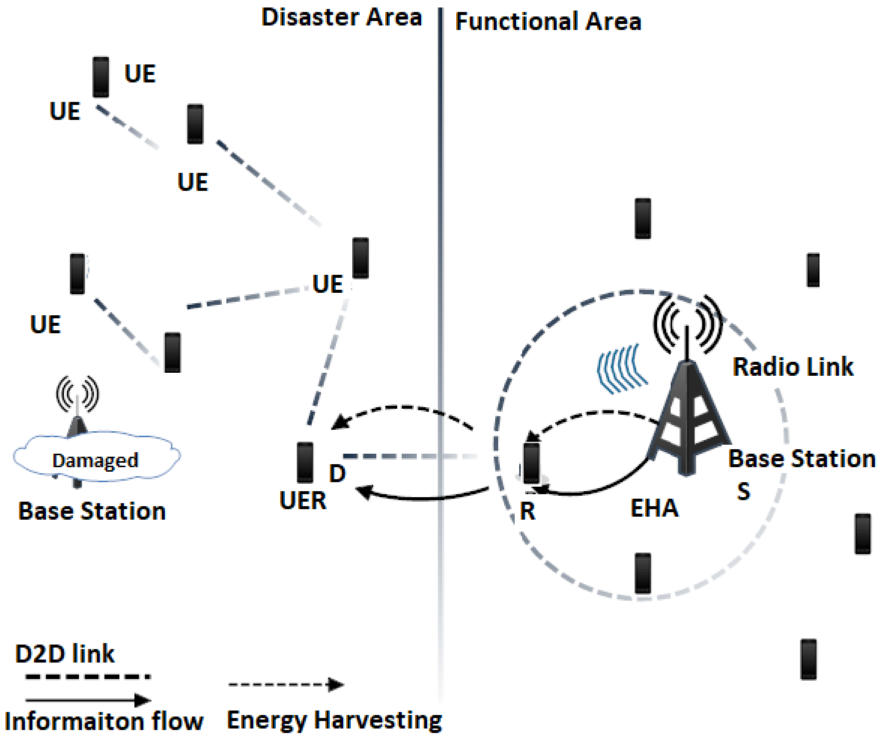


Figure 4.1: Energy harvesting concept in disaster situation.

Assumption 1 *A wireless D2D communication system is considered, where the information is transferred from source S to destination node D, through intermediate relay node R as shown in Fig. 4.1. The destination node D can then act as a User Equipment Relay (UER) node in another hop in the disaster area. Further, UER acts as a cluster head (UERCH) in clustering formation phase.*

Assumption 2 *The intermediate node R is an energy constrained node. It first harvests energy from the S then uses the harvested energy as a source of transmit power to forward the source information to the destination.*

Assumption 3 *Relay node is selected to forward the signals and energy to the destination only if it has sufficient energy or is able to harvest energy from* *the source. Amongst the different relaying protocols, Decode and Forward (DF) scheme is chosen at the relay node.*

4.2.2 Time Switching based protocol

The TS based protocol is adopted at the relay, where T denote the block time in which a certain block of information is transmitted from the *source* node to the *destination* node with TS ratios α_1, α_2 and α_3 where $\alpha_1 + \alpha_2 + \alpha_3 = 1$. During the first time slot with duration of $\alpha_1 T$, the source transfers energy to the relay. In the second time slot $\alpha_2 T$, the source transmits a signal to the relay while in $\alpha_3 T$ the relay forwards signals to the destination. There is no direct link between the source and the destination node.

Assume that in relay network the total bandwidth is divided into N orthogonal sub-carriers, $n \in N = 1, 2, 3, \ldots\ldots..N$ and the network comprises two wireless links i.e., source to relay and relay to destination links as h_n^{SR} and h_n^{RD}, respectively. Further assume that $h_n^{SR} \propto d_{SR}^{\alpha}$ and $h_n^{RD} \propto d_{RD}^{\alpha}$ where α is the pathloss exponent and d_{SR} and d_{RD} are the distances between source and relay and between relay and destination, respectively. The energy harvested at the relay during the first time slot can be expressed as Zhou et al. (2013):

$$E = \alpha_1 T \zeta \sum_{n=1}^{N} p_n^{S,1} \mid h_n^{SR} \mid^2 \tag{4.1}$$

where $p_n^{S,1}$ represents the transmit power of the source (i.e., BS) over n^{th} sub-carrier for energy transfer and ζ denotes EH efficiency. To maximize harvested energy at the relay, the source should assign all available power over the sub-carrier that has a maximum channel value of $\mid h_n^{SR} \mid^2$ for $n \in N$. Ee have, Therefore,

$$E = \alpha_1 G \tag{4.2}$$

where

$$G = T \zeta P \max_n \mid h_n^{SR} \mid^2 \tag{4.3}$$

and P represents the maximum transmit power of the source for both energy and information transmission. We have $P \geq \sum_{n=1}^{N} p_n^{S,1}$. Then, the source transmits signals to the relay over N sub-carrier in the second time slot. After receiving the signals relay decodes the signals, redistributes the decoded signals over different sub-carriers and forwards the signals to destination. Therefore, the maximum achievable end-to-end data rate of DF relay network is obtained as Huang et al. (2015a)

$$C = min\left[\alpha_2 \sum_{n=1}^{N} \log_2(1 + p_n^{S,2}\gamma_n^{SR}), \alpha_3 \sum_{n=1}^{N} \log_2(1 + p_n^{R}\gamma_n^{RD})\right] \tag{4.4}$$

where $p_n^{S,2}$ and p_n^R represent the transmit power of source and relay over n^{th} sub-carrier for information transmission, respectively; $\gamma_n^{SR} =\mid h_n^{SR} \mid^2 /\sigma_R^2$ and $\gamma_n^{RD} =\mid h_n^{RD} \mid^2 /\sigma_D^2$. Here, noise powers over each sub-carrier at relay and destination are represented by σ_R^2 and σ_D^2, respectively. It is also noticed from Nasir et al. (2013) and Ding et al. (2014a) that the harvested energy in the first time slot should be larger than or equal to the consumed energy for information transmission at the relay i.e,

$$E \geq \alpha_3 T \sum_{n=1}^{N} p_n^R. \tag{4.5}$$

Note that there are possibly numerous nodes between source and destination, which are candidates to perform as a relaying node. Here the right identification of the best relay is important before information and energy transfer.

Relay node selection has already been discussed in our earlier work. It is assumed that the BS knows every channel in the field. So, it can simply determine which node can act better in the area. In order to harvest energy, the received power of a relay from its nearby BS should not be small. The area around the BS called *energy harvesting area (EHA)*, which is a circle with the radius R_{ha} centered at BS as shown in the Fig. 4.1 and the R_{ha} is given by

$$P_r = P_{bs}\left(\frac{d_o}{d}\right)^{\nu}$$

$d_o = 1$ which is close in reference distance

$$P_r = P_{bs}\left(\frac{1}{d}\right)^{\nu}$$

$$P_r = P_{bs}(\frac{1}{d^\nu})$$

$$d^\nu = P_{bs}(\frac{1}{P_r})$$

$$d^\nu = (\frac{P_t}{P_r})$$

For our case harvertable range is up to where $P_r \geq B_w$. So, by replaying $P_r = B_w \Rightarrow d$ becomes radius (R_{ha}) of harvesting range.

$$R_{ha}^\nu = (\frac{P_bs}{B_w})$$

$$R_{ha} = (\frac{\zeta P_{bs}}{B_w})^{1/\nu} \tag{4.6}$$

where $\zeta \in (0, 1)$ is the energy harvesting efficiency factor of UE, P_{bs} transmit power of the BS, B_w is the energy harvesting threshold to activate the EH circuit and ν is path loss exponent in EH transfer link.

4.2.3 Network Configuration

As shown in Fig. 4.1, a cellular network which consists of BS capable of performing wireless power transfer and relay that can harvest energy from their nearby BS is considered. It is assume that the distribution of the BS in the network follows homogeneous Poisson Point Process (PPP) Φ_{bs} with spatial density λ_{bs} and UEs are also distributed according to a homogeneous PPP Φ_{ue} with spatial density λ_{ue} while relay spatial density is λ_r. The transmit powers of a BS, relay and UE are P_{bs}, P_r and P_{ue}, respectively. When a relay has sufficient harvested energy then it can help the BS to forward the information to another hop in the non-functional area node in DF manner and with the signal-to-interference ratio (SIR). The node acts as a UER and the communication between a relay and the destination UE is taken place between two user devices, which is D2D communication. As it is known that, UEs can not communicate with a BS for their own data so, it is also assumed that each UER receives the data for itself with probability p_{rc} and p_r is the probability that a UE can support other UEs as a UER. Moreover, when a UER does not need to receive its own data and has the amount of harvested energy exceeding $E_{ue} = NB_w$, the UER can help another UE using E_{ue}. Load ρ_{bs}, as BS using the same spectrum at any random time slot, is expressed as Yang et al. (2014)

$$\rho_{bs} = \frac{p_{rc}\lambda_r}{\lambda_{bs}N}. \tag{4.7}$$

4.2.4 Outage Probability for Mode Selection

Applying relaying techniques to D2D communication scenarios has attracted much attention recently due to its ability to enhance D2D coverage and reliability. End-to-end outage probability is investigated here to confirm whether D2D technology could be a preferable option or not in our scenario (mode selection). First, lets determine the outage probability of an UER that operates in D2D mode. The distance between BS and R is d_1 and the distance between R and an intended UER is d_2, the outage probability of D2D mode can be presented as Yang et al. (2014)

$$P_{out} = 1 - \exp\left\{-\xi(\theta_d, \alpha)\left(\rho_{bs}\lambda_{bs}d_1^2 + \frac{p_r\lambda_r}{N}d_2^2\right)\right\} \tag{4.8}$$

where α is path loss exponent in data link and θ_d is the SIR threshold for D2D mode transmission and $\xi(\theta_d, \alpha)$ is given as,

$$\xi(\theta, \alpha) = \frac{2\pi^2}{\alpha} csc\left(\frac{2\pi}{\alpha}\right)\theta^2/\alpha. \tag{4.9}$$

In the D2D mode transmission, the outage occurs when at least one of the two links (BS to R, and R to UER) does not achieve the target SIR θ_d. Consider that in the Fig. 4.1 the BS locates at (x_s, y_s), R locates at (x_r, y_r), and UER locates at (x_d, y_d), then it can have $d_1^2 = (x_r - x_s)^2 + (y_r - y_s)^2$ and $d_2^2 = (x_d - x_r)^2 + (y_d - y_r)^2$.

The outage probability in (4.8) can now be rewritten as

$$P_{out} \quad = \quad 1 - \exp\{-\rho_{bs}\lambda_{bs}\xi(\theta_d, \alpha) f(x_r, y_r)\} \tag{4.10}$$

where

$$\begin{aligned} f(x_r, y_r) &= \|(x_s - x_r)\|^2 + \|(y_s - y_r)\|^2 + \\ &\quad \Lambda\|(x_r - x_d)\|^2 + \Lambda\|(y_r - y_d)\|^2) \end{aligned} \tag{4.11}$$

and Λ is given as

$$\Lambda = \frac{p_r \lambda_r}{N \rho_{bs} \lambda_{bs}}. \tag{4.12}$$

The optimal location of R that minimizes P_{out} is obtained by

$$\begin{aligned} (x_r^o, y_r^o) &= \arg \min_{\{x_r, y_r\}} P_{out} \\ &= \arg \min_{\{x_r, y_r\}} f(x_r, y_r). \end{aligned} \tag{4.13}$$

By taking partial differentiation of $f(x_r, y_r)$ with respect to x_r and y_r separately and equate it to zero, It can achieve the optimal location of R as follows

$$(x_r^o, y_r^o) = \big(\frac{x_s + \Lambda x_d}{1 + \Lambda}, \frac{y_s + \Lambda y_d}{1 + \Lambda}\big). \tag{4.14}$$

Now, using the optimal location of R, the outage probability can be represented as

$$P_{out}(x, d_o) = 1 - exp\Big\{ - \rho_{bs}\lambda_{bs}\xi(\theta_d, \alpha)\big(\frac{\Lambda x^2}{1 + \Lambda} + (1 + \Lambda)d_o^2\big)\Big\} \tag{4.15}$$

where x is the distance between a source and the UER, and the d_o is the distance between the optimal R location (x_o, y_o) and the actual R location. From (4.15) and (4.17), here, R is a circle centered at (x_o, y_o). The radius of this circle can be used to determine whether the outage probability is satisfactory. If it is then we can conclude that the UER is in the D2D selection mode and will use the nearest R from the optimal R location for its further communication.

This transmission mode selection can be useful to exploit the D2D energy harvesting network (EHN) communication efficiency. Therefore, it is useful to study the outage probability of the D2D-EHN by considering the transmission mode selection and the energy harvesting as follows Yang et al. (2014)

$$\begin{aligned} P_{out} &= \frac{\rho_{bs}\lambda_{bs}\xi(\theta_d,\alpha)(1+\Lambda)}{\lambda_r\pi+\rho_{bs}\lambda_{bs}\xi(\theta_d,\alpha)(1+\Lambda)} \\ &\quad\times\frac{\lambda_r\kappa^2\pi+\rho_{bs}\lambda_{bs}\varphi(\theta_b,\alpha)}{\lambda_{bs}\pi+\lambda_r\kappa^2\pi+\rho_b\lambda_{bs}\varphi(\theta_b,\alpha)} \\ &\quad+\frac{\lambda_r\pi}{\lambda_r\pi+\rho_{bs}\lambda_{bs}\xi(\theta_d,\alpha)(1+\Lambda)} \\ &\quad\times\frac{\xi(\theta_d,\alpha)\rho_{bs}\lambda_{bs}\Lambda}{\lambda_{bs}\pi(1+\Lambda)+\xi(\theta_d,\alpha)\rho_{bs}\lambda_{bs}\Lambda}. \end{aligned} \tag{4.16}$$

where

$$\kappa=\sqrt{\left(\frac{\varphi(\theta_b,\alpha)}{\xi(\theta_d,\alpha)}-\frac{\Lambda}{1+\Lambda}\right)\frac{\Lambda}{1+\Lambda}} \tag{4.17}$$

and

$$\begin{aligned} \lambda_r &= \lambda_{ue}p_a(1-p_{rc}) \\ &= \frac{\lambda_{ue}p_r^{-1}(1-p_{rc})\left(1-e^{-\pi\lambda_{bs}R_h^2}\right)}{1-e^{-\pi\lambda_{bs}R_h^2}+N} \end{aligned} \tag{4.18}$$

and

$$\begin{aligned} \varphi(\theta,\alpha) &= \frac{2\pi\theta^{2/\alpha}}{\alpha}\mathbb{E}\left[h^{2/\alpha}\left(\Gamma\left(-\frac{2}{\alpha},\theta h\right)-\Gamma\left(-\frac{2}{\alpha}\right)\right)\right]-\pi \\ &= \frac{2\pi{}_2F_1\left(1,1+\frac{2}{\alpha},2+\frac{2}{\alpha},-\frac{1}{\theta}\right)}{(2+\alpha)^{\theta}}-\frac{2\pi^2\theta^{2/\alpha}}{\alpha}csc\left(\frac{2\pi}{\alpha}\right)-\pi. \end{aligned}$$

Here, h is the channel gain which experiences Rayleigh fading, ${}_2F_1(a,b;\ c,x)$ is the hypergeometric function. We assess the performance of the system and prove that D2D is the favorable option for communication in disaster situations.

As shown in Fig. 4.2, It is observed that an optimal efficiency value exists and shifts towards zero as P_{bs} becomes larger. For D2D EHN with $P_{bs}=3$W, P_{out} reduces exponentially as the EH efficiency increases, but with $P_{bs}=5$W,

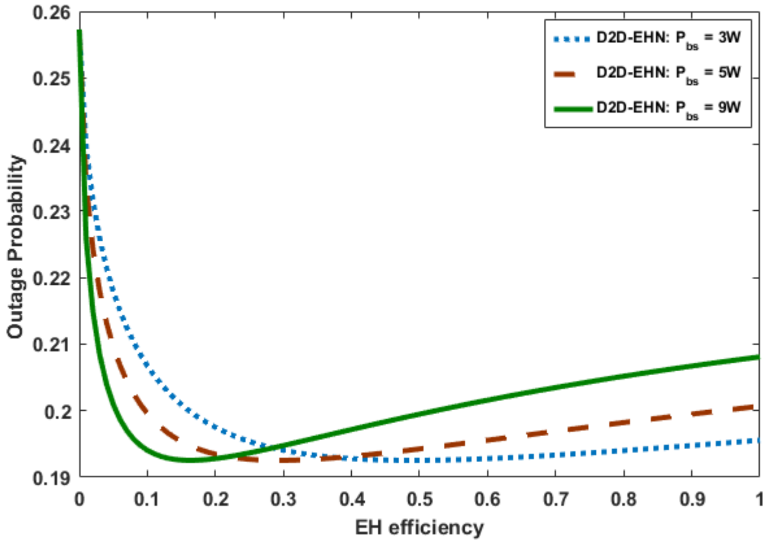


Figure 4.2: Outage probability as a function of energy efficiency for different values of BS power(P_{bs}).

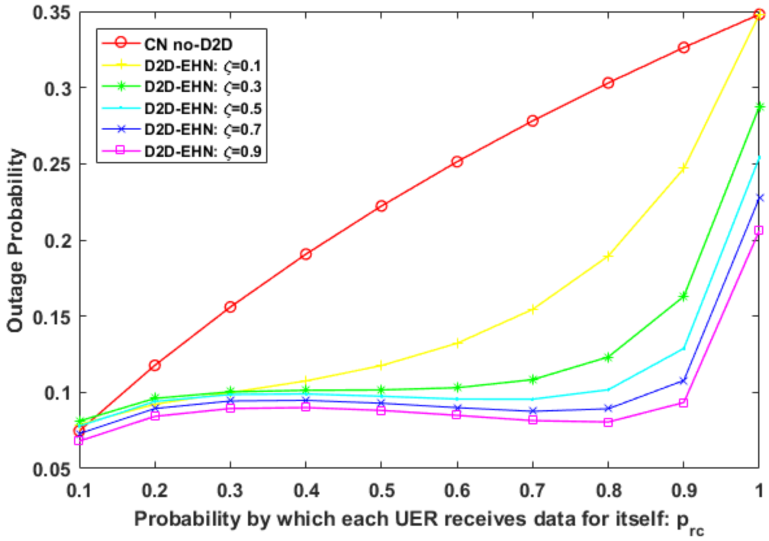


Figure 4.3: Outage probability as a function of p_{rc} for different values of ζ.

P_{out} reduces exponentially till that EH efficiency is equal to 0.5. After that, P_{out} increases steadily. Moreover, with $P_{bs} = 9$W P_{out} decreases dramatically till the EH efficiency value of 0.2 and then increases linearly subsequently. As a result, there are more chances to adopt UEs to select D2D mode for the purpose to

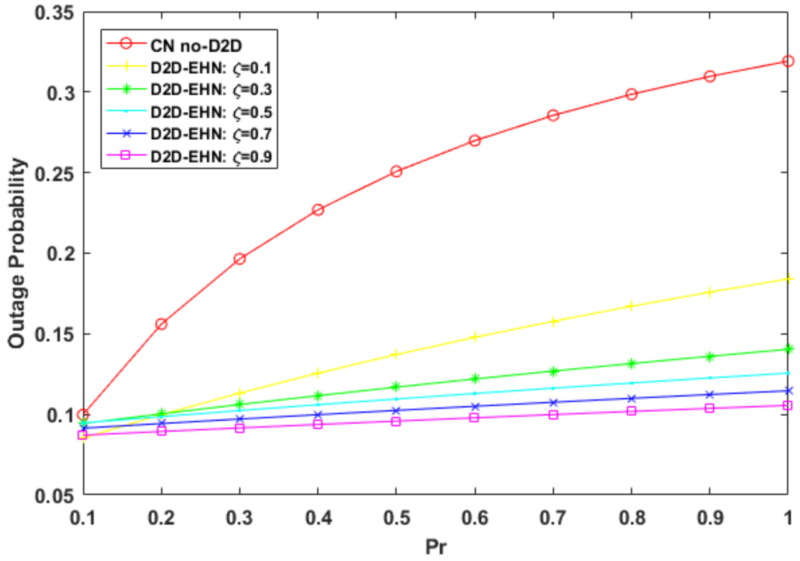


Figure 4.4: Outage probability as a function of p_r for different values of ζ.

reduce the outage probability. For larger P_{bs}, we observe that the UER density increases dramatically with ζ, which means that it leads to increasing the number of UERs and each UE has a high chance to communicate in D2D mode.

Figure 4.3 shows the outage probability (P_{out}) as a function of p_{rc} (i.e. probability by which an UER receives data for itself). When a UER is receiving its own data from the R, it is incapable of serving as an UER. It is observed that P_{out} is increasing when p_{rc} increases. Moreover, using D2D communications reduces P_{out}, especially with high EH efficiency. Higher values of EH efficiency factor reduce p_{rc} which increases the effect on P_{out}, and it stabilizes around the value of 0.07. As shown in Fig. 4.4, outage probability as a function of P_r (i.e. probability that a UE can support other UEs as a UER) for different values of EH efficiency. Outage probability increases as P_r increases but in different manners: exponentially in absence of D2D communications and linearly when D2D communications apply. This makes the prediction of the D2D outage probability possible. When a UER has harvested sufficient energy and served as a UER, it can then be solicited by other UEs to relay their data and connection.

4.3 Power Transfer Using Relaying And Clustering In D2D Mode

4.3.1 Our Approach

In the previous section, the aim was to send signals from the functional area to the non-functional area with the help of a network relay. The energy harvesting technique is also implemented so that, the relay could be active in the field and further passes the energy and information into the disaster area as per requirement of the system. Now, in this section, a novel approach by using clustering techniques in D2D relay mode to facilitate communication of multiple users that are affected within the disaster area is presented. From the technical perspective, exploiting the nature of proximity may provide multiple benefits in disaster situations like:

- D2D may utilize a high data rate and low end-to-end delays.
- Compared to normal cellular communication, direct communication saves energy and improves the utilization ratio.

Since network assisted D2D communications to take advantage of the cellular infrastructure presences, it is proposed to build on the D2D underlay concept, but extend it in such a way that allows infrastructure/infrastructure-less operation. According to the presented scenario, high-end capability UE can take over some of the radio access network (RAN) functionalities when one or more BS becomes dysfunctional. Such functionalities including providing synchronization signals and acting as a UER or cluster head (CH). We will use in this chapter the concept and functionality of User Equipment Relay and Cluster Head (UERCH). It is observed that the capability of nodes to become a UERCH must be taken into account (e.g. available transmit power, support spectrum or synchronization or radio resource management capability). However, network coverage distinguishes two types of UEs:

Category 1 (Cat-1): The UEs are capable of becoming UERCH, directing the D2D links and managing the resource usage among a group of D2D devices (UEs) associated with them.

Category 2 (Cat-2): The UEs are devices that can only act as a cluster member and according to disaster situation they are out of network coverage area and controlled by appropriate Category-1 UEs.

The UERCH selection has already been discussed in our previous work Ali et al. (2016a) where complete flowchart is presented to differentiate between nodes of Cat-1 and Cat-2 category. Furthermore, UERCH depends on the outage probability derived in Section 4.2.4. UERCH node proposed in our architecture depends on nodes broadcasting so-called beacon signal on peer discovery resource (PDR). The authors of Zhe (2013) evaluated the impact of network assistance on the performance of D2D discovery algorithms in terms of discovery probability, discover time and consumed energy. The grouping strategies, selection of PDRs, beacon signaling and the setting of beacon transmission probability in each time slot with beacon transmission power were discussed. The authors also highlighted the energy, spectral efficiency, and the capability of dynamically reconfiguring the network due to mobility, changing radio conditions and nodes joining/leaving the network.

The key of our approach is to select which user device should act as UERCH because it has established a communication link via network relay, so the following points must be considered in reality to select the UERCH:

- *Capacity*: UERCH must have certain functions like dual mode function, which means that they can work in both low and high power mode.
- *Network Coverage*: If the device is able to achieve network coverage, other devices are capable to connect to the network through it. Besides, the network can assist D2D communication and make the system more efficient.
- *Mobility*: If the user moves fast, it can easily move out of the current cluster and the stable situation is changed and a UERCH reselection is needed which costs computation and time. Thus, slowly moving or static devices are more suitable to be a UERCH.

4.3.2 Performance Evaluation of D2D in Clustering

In order to cope with disaster situations, a novel cooperative disaster D2D clustering is implemented. For better performance, power transfer relay and D2D clustering methods are adapted to provide novel, robust and stable solution at the time of critical situation. The scenario is considered, in which link successfully establish from the functional area's BS to non-functional area's devices with the help of a network relay. A number of devices can then form a cluster (i.e, coalition) with one device acting as a UERCH and the rest of the devices in the cluster are called cluster members (CM). Moreover, within each cluster, D2D communications are adopted to perform content distribution. Data content is sent from BS via R using the long-range link, as shown in Fig. 4.5, to the UERCH and then each UERCH send the content to its particular CM via the short-range link. All the devices operate in D2D mode. At the time of communication, each CM

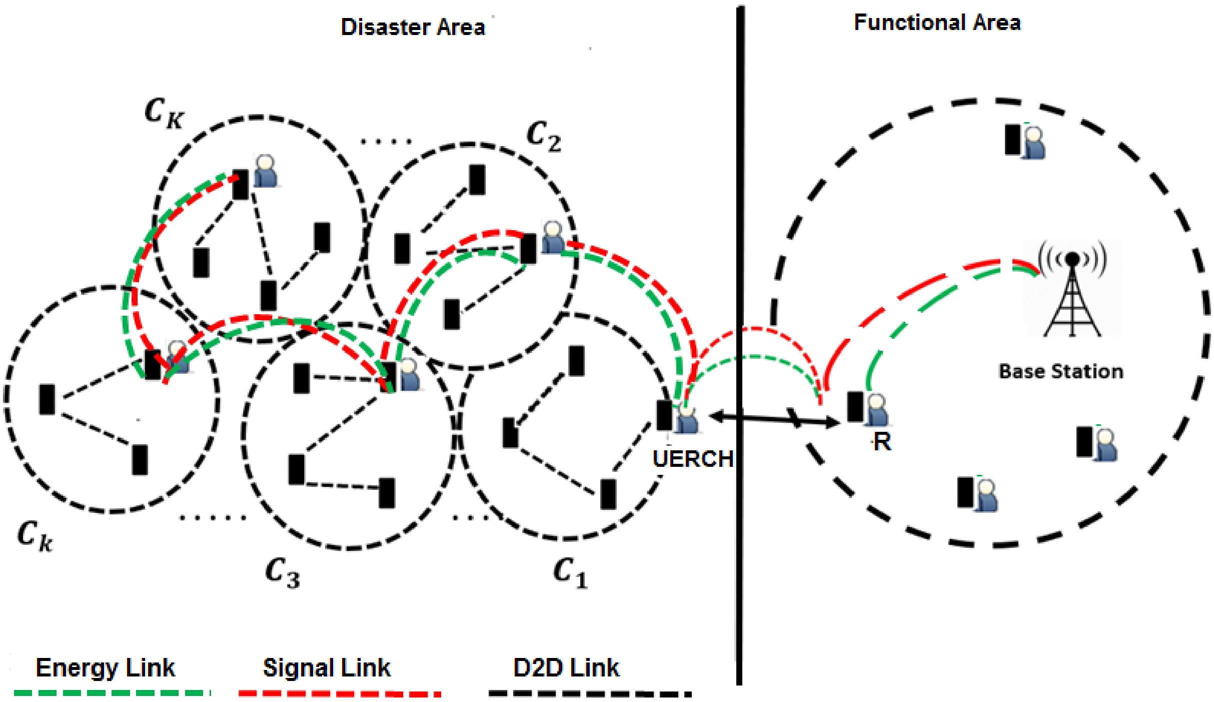


Figure 4.5: Combined System Model
Framework for disaster recovery communication using D2D, Clustering and EH.

receives the content from a single source UERCH. All the nodes can form a coalition (see Algorithm 1) where the energy consumption in the coalition is lower than the sum of the individual energy consumptions of the coalition members Yaacoub and Kubbar (2012). Meanwhile, the UERCH also communicates with the relay on behalf of all cluster members. Assume that there are K clusters to be formed, C_1, C_2, $\cdots, C_K$, as shown in Fig. 4.5. Within each cluster C_k ($k = 1, 2, \cdots, K$), there are $I_k + 1$ nodes: one UERCH node $n_{k,0}$, and I_k other CM nodes n_{k,i_k}, $i_k = 1, 2, \cdots, I_k$.

Energy Calculation: Consider a communication link between two node $n_{k,u}$ and $n_{k,v}$ ($u, v = 1, 2, \cdots, i_k$ and $u \neq v$) with cluster C_k. The time needed to transmit a data content of size S_T bits on this link having an achievable rate R_{uv} bps is given by S_T/R_{uv}. Denoting the power drained from the battery of node $n_{k,v}$ to receive the data from node $n_{k,u}$ by $P_{\mathrm{Rx},uv}$, then the energy consumed by $n_{k,v}$ to receive the data from $n_{k,u}$ is given by $S_T P_{\mathrm{Rx},uv}/R_{uv}$. Likewise, representing by $P_{\mathrm{Tx},uv}$ the power drained from the battery of node $n_{k,u}$ to transmit the data to $n_{k,v}$, then the energy consumed by $n_{k,u}$ to transmit the content to $n_{k,v}$ is given by $S_T P_{\mathrm{Tx},uv}/R_{uv}$, where $P_{\mathrm{Tx},uv}$ can be expressed as

$$P_{\mathrm{Tx},uv} = P_{\mathrm{Tx}_{ref},uv} + P_{t,uv}, \tag{4.19}$$

where, $P_{t,uv}$ is transmitted power over the air interface on the link between nodes and $P_{\mathrm{Tx}_{ref},uv}$ is the power consumed by the circuitry of nodes during transmission. Denote E_{C_k} as the total energy consumed by cluster C_k, which can be expressed as

$$E_{C_k} = S_T \sum_{u \neq v, u,v=1,2,\cdots,I_k} \left(\frac{\Gamma_k P_{\mathrm{Tx},uv} + P_{\mathrm{Rx},uv}}{R_{uv}} + \frac{P_{R\mathbf{x},u}}{R_u} \right), \tag{4.20}$$

where the first term links to the energy consumed by node $n_{k,u}$ to receive the data from R on the large link called cellular link; the second term corresponds to energy consumed by the node $n_{k,u}$ to transmit the data to the other nodes in its cluster on the short link via D2D communication and the last term corresponds to the energy consumed by the nodes to receive their data from node $n_{k,u}$ on the SR. The variable Γ_k is used to differentiate between unicasting and multicasting. In fact, in the uplink process, each node has different data to transmit. Hence, only unicasting is used but on the other hand, the same data is transmitted to the member of each cluster in the downlink case.

Considering a single cluster only, the harvested energy (in (4.1)) should not be smaller than the energy consumption ((4.20)), leading to:

$$E \geq E_{C_k} \tag{4.21}$$

$$\begin{aligned} \alpha_1 T \rho \sum_{n=1}^{N} p_n^{S,1} \mid h_n^{SR} \mid^2 &\geq E_{C_k} \\ \sum_{n=1}^{N} p_n^{S,1} \mid h_n^{SR} \mid^2 &\geq \frac{E_{C_k}}{\alpha_1 T \rho}. \end{aligned} \tag{4.22}$$

Assuming power of each subcarrier is the same, (i.e $p_1^{S,1} = p_2^{S,1} = p_N^{S,1} = p^{S,1}$) we should have

$$p \geq \frac{E_{C_k}}{\alpha_1 T \rho \sum_{n=1}^{N} \mid h_n^{SR} \mid^2}. \tag{4.23}$$

Here, $p^{S,1}$ represents the power of single sub-carrier required for energy recovery as a function of number of devices. This power refers to the necessary single sub-carrier power in such a way that harvested energy from the source in the relay is greater or equal to consumed energy to transmit the signal from relay to destination.

Now, lets consider multiple clusters to be formed. Each cluster will transfer energy and communicate with the next cluster in a serial multihop manner, as shown in Fig. 4.6. In addition to the energy consumption E_{C_k}, there will be energy loss when transferring between one cluster to the next, denoted by $E_{L_{(k-1),k}}$.

Therefore, propose a coalition formation algorithm (see Algorithm 2) to form the clusters in the most energy-efficient way. In particular, the proposed algorithm is to form the clusters among all the UEs in a way to reduce the average energy consumption. As soon as a UE decides to enter/form a cluster, it enters a binding agreement with the other users within the coalition and then considers the benefit of the coalition above their individual benefit. Because all the UEs are cooperative and individually rational with this assumption in place, the UEs that

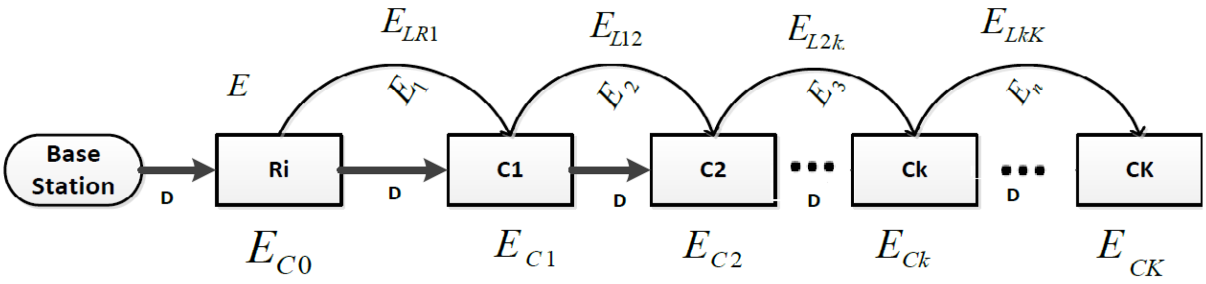


Figure 4.6: Energy loss during transfer of energy.

are in proximity to one another can form coalitions to provide connectivity and data sharing with each other. It is assumed that there is an arbitrator/coordinator who makes decisions with respect to the coalition structures, based on the energy profiles of all participating users. The simulation results show that utilization of this coalition clustering algorithm obtains energy efficiency and potential to be highly efficient in disaster situations as verified in our simulation results.

4.4 Results and Discussion

The LTE coverage area with uniform UE distribution is considered where a BS in coverage area transmitting at full power with 10 MHz of bandwidth which is subdivided into 50 RBs of 12 sub-carriers each. Channel and energy consumption parameters for simulation are taken from Yaacoub and Kubbar (2012), shown in Table 4.1.

Table 4.1: Simluation Parameters

Parameters	**Values**	**Parameters**	**Values**
B (Bandwidth)	10 MHz	ν	3.76
N_{RB}	50	T	1
S_T (Content size)	1Mbits	Rayleigh parameter	$E[a^2] = 1$
$P_{Tx,SR}$	1.425 Joules/s	Max. $UE_{TXpower}$	0.125W
$P_{Rx,SR}$	0.925 Joules/s	$P_{Rx,LR}$	1.8 Joules/s

The Matlab is used to analyse the impact of UE device variations, energy consumption of UEs, the number of UEs and the number of clusters in the field.

Algorithm 1 Coalition formation phases

```
Initialization
Cluster is formed with its proximity devices
One device act as UERCH $C_k = \{n_k\}$ and $| C_k |= 1$
All clusters are in search space $S = \{k;\ C_k \neq \emptyset\}$.

    Phase 1 – Cluster and Coalition Candidate Search

Clusters are searched, based on its energy consumption per node. Find the highest energy consumption: $k = \arg\max_{i \in s} E_{C_i} / | C_i |$
Finding cluster $C_j$ which when merged with $C_k$ will consume lowest energy $j = \arg\min_{i \neq k} E_{C_j \cup C_k}$.

    Phase 2 – Coalition formation

do
    if $E_{C_j \cup C_k} \leq E_{C_j} + E_{C_k}$ then
        Form a coalition between the members of clusters $C_j$ and $C_k$
    else
        Work independently
    end if
    if Merger condition is satisfied then
        Set $\acute{C}_j = C_j \cup C_k$ .
        $n_j$ is the lowest energy consumption cluster head of the new coalition cluster.
    end if
    if Merger condition is not satisfied then
        keep cluster $C_j$ and $C_k$ separate
    end if
    Update the clusters, $C_j = \acute{C}_j$ and $C_k = \emptyset$.
while search space $S \neq \emptyset$
```

A coalition efficiency method was used to carry out simulation which leads to significant energy saving as shown in the results. The scenario investigated in Fig. 4.5 is based on one BS in the functional area transmitting at full power, while in a disaster area the BS(s) are non-functional. In emergency conditions, users located in the non-functional area can take advantage of the D2D UE proximity services. Additionally, D2D relay enhances the data throughput of edge-user (s) that can be used to link far away UEs with cellular coverage to the BS which extends the cellular coverage. We use a clustering approach to reduce energy consumption and extend coverage area. A number of UEs form a cluster with one node acting as a UERCH and the rest of the UEs in the cluster are called CMs.

We also investigated that the impact of a different number of UEs per cluster. Fig. 4.7 is only for the D2D scenario with cooperative clustering method by showing the variation in the power of each cluster and the average number of UEs in D2D network by implementing coalition cluster formation algorithm. The average number of clusters is increasing linearly, which means that it is easy to predict the number of clusters by the number of devices. When a UERCH transmits signals to its CM at high power, there are number of clusters in the network, which means that each UERCH could have less UEs around and this could also save energy and time to transmit data within clusters. Furthermore in Fig. 4.8, box-plot provides a visualization of summary statistics for sample data. In our plot, we set the outlier as a value that is more than 1.5 times the interquartile range away from the top or bottom of the box. The number of samples used to plot Fig. 4.8 is 100 UE placements × 100 Rayleigh fading realizations. This is equivalent to 10^4 sample points. From the result, it is observed that the energy gain (in percentage) increases with the increase in the number of UE devices. Its is also notice that the variation of energy value decreases with the increase in UE devices (i.e., smaller blue box).

The power of single sub-carrier required for energy recovery as a function of a number of devices for various EH efficiency values is shown in Fig. 4.9. This power refers to the necessary single sub-carrier power in such a way that harvested energy from the source is greater than or equal to the consumed energy required to transmit the signal from the source to destination ($E \geq E_{C_k}$). This implies

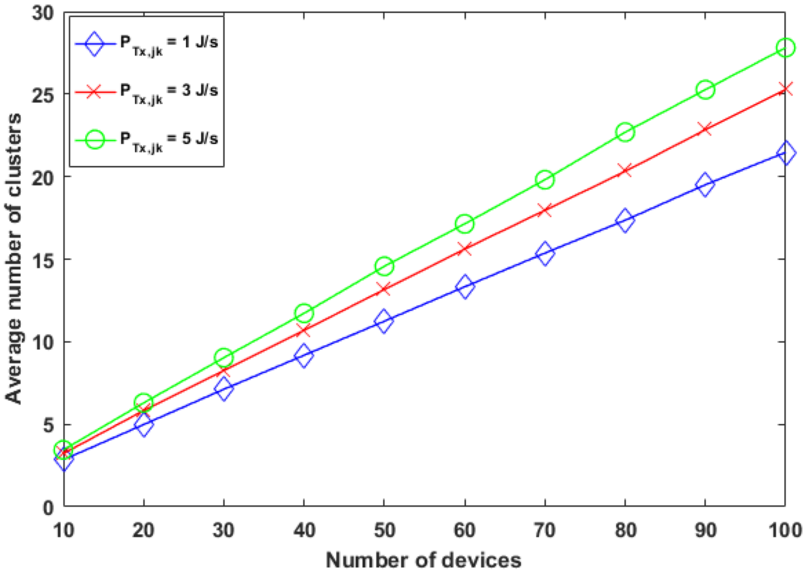


Figure 4.7: Average number of clusters

that the power of single sub-carrier $p_n^{S,1}$ should be greater than or equal to a threshold. In fact, the represented curve corresponds to this threshold: values of $p_n^{S,1}$ greater than or equal to the curve satisfy the energy recovery equation (4.21), values of $p_n^{S,1}$ lower than the curve do not satisfy the energy recovery equation, and hence harvested energy is not sufficient to transmit the signal from the source to the destination. It is also notice that as the EH efficiency is getting larger, the represented threshold of single sub-carrier power becomes smaller for the same number of devices. This means that when the energy is efficiently harvested, the power threshold is lowered and as a result, the system requires less energy for the sub-carriers and important energy savings would be made.

In results, the cumulative distribution function (CDF) for clusters is evaluated. In Fig. 4.10 shows the CDF of the number of clusters for 100 UE devices. The cluster formation algorithm applied on 100 UEs devices results in less than 25 clusters for 90 percent of the time. It can be seen that less than 22 clusters are obtained only for 30 percent of the time during small power (1 J/s). As we are able to increase the level of power to be received, the formation of clusters will take less time, which accordingly reflects the efficiency of the proposed system. It means that communications in the disaster area can be initiated by using this ap-

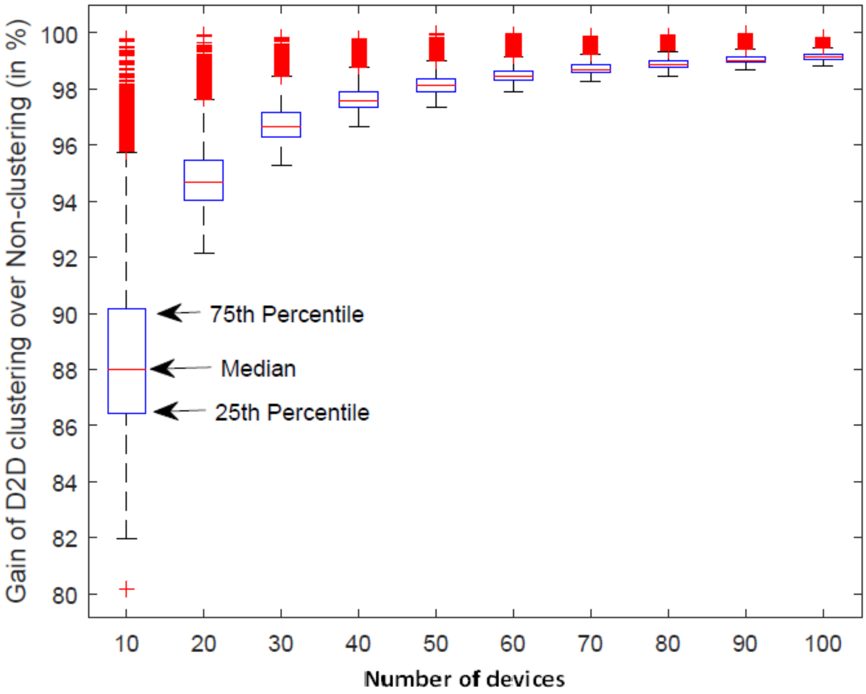


Figure 4.8: Gain of D2D Clustering vs. Non-Clustering
Box-plot of Energy gain (in percent) of UE devices in D2D Clustering based over Non-clustering communication for varying number of UE devices.

proach for rapidly recovery. The link between the relay and the UER is therefore of great significance, especially in our proposed PS networks model. Furthermore, deploying clustering and EH techniques to keep the nodes alive and passing information further in the non-functional area is a robust physical network design for survivable networks. The Fig. 4.11 represents the average number of clusters in D2D communications and power used for transmission (power drained from the battery of node n_k to transmit data to node n_j) for different sizes of transmitted data contents. The number of clusters increases as $P_{T\mathbf{x},jk}$ increases. This means that when a node n_k uses more power to transmit data, it is more likely that the number of formed clusters increases. Moreover, clusters are formed to reduce energy consumption which confirms the results found in Fig. 4.7 and 4.8.

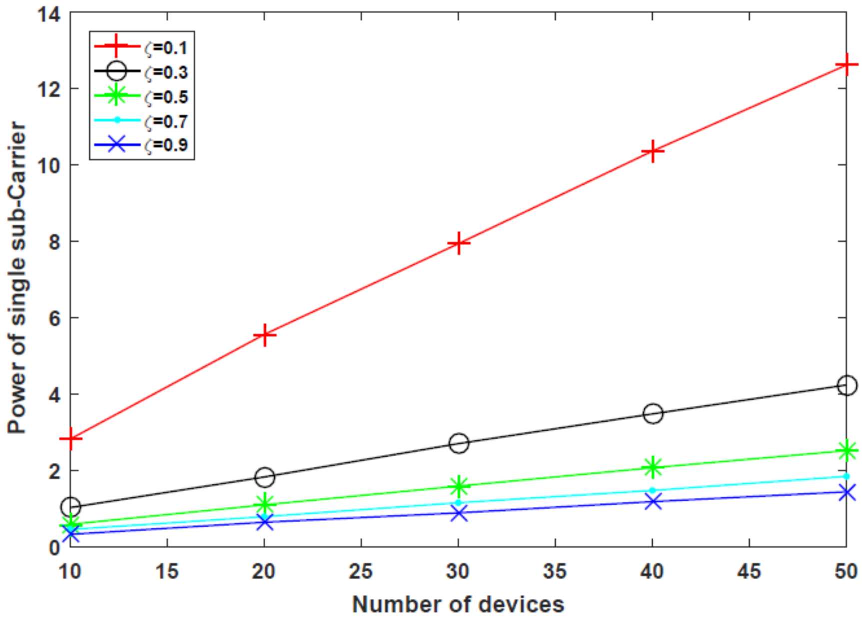


Figure 4.9: Power of single sub-carrier

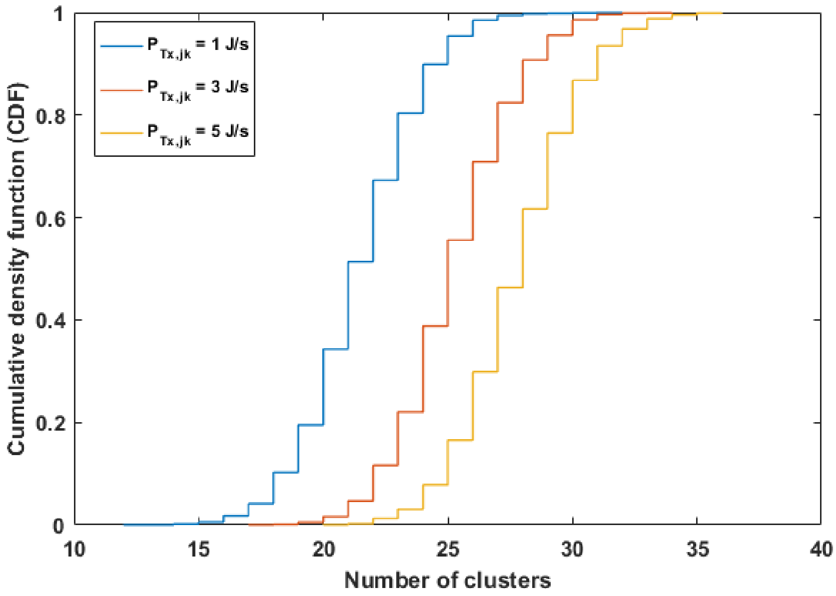


Figure 4.10: CDF for 100 UEs devices

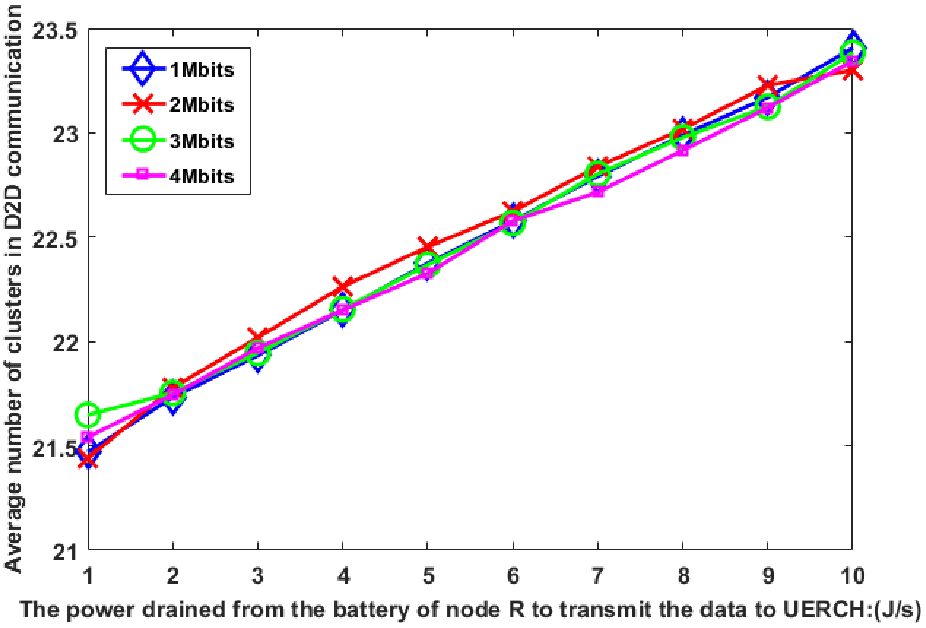


Figure 4.11: The power drained from the battery
The power drained from the battery of relay to transmit the data to UERCH.

4.4.1 Summary

This chapter focusses on PS network and D2D communication. The RF-based EH framework is proposed for emergency situations which minimize the end-to-end disconnection and enables the connectivity from functional area to non-functional area. The framework adds a new step to the provisioning phase for a network survivability against network failure and can be executed in an incremental fashion. It can also be combined with other protection and restoration systems to enhance network robustness in a post-disaster situation to provide a better link connection. The major requirement for the end-user in a disaster situation is connectivity, storage, and reliable power within a very short period of time. Looking at such requirements without deploying and operationalising hardware, the unmanned aerial vehicles based network is proposed to cope with such a situation. The traditional design of disaster communication architecture lacks many features as mentioned in chapters 1 and 2. Therefore, emerging technologies towards getting real-time services for disaster communication system are proposed to make communication not only reliable but resilient and robust as well. Hence, the next chapter proposes the use of unmanned aerial vehicles (UAV) and small cells to increase the accuracy and bandwidth during a disaster.

Chapter 5

Drone Based Small Cells for Public Safety Communication System

In the event of a natural disaster, communications infrastructure plays an important role in organizing effective rescue services. However, the infrastructure-based communications are often affected during severe disaster events such as earthquakes, landslides, floods, and storm surges. In this chapter a novel drone based cellular infrastructure to revive necessary communications for out-of-coverage user equipment who is in the disaster area. In particular, a matching game algorithm is proposed using one-to-many approach wherein several drone small cells are deployed to match different UEs to reach a stable connection with optimal throughput. In addition, a medium access control framework is then developed to optimize emergency and high priority communications initiated from the rescue workers and vulnerable individuals.

5.1 Introduction

The ad-hoc wireless networks can play an important role. As the Federal Communications Commission (FCC) posits, the public safety communications can make use of the cutting edge broadband technologies "to allow first responders to send and receive critical voice, video, and data to save lives, reduce injuries and prevent acts of crime and terror" FCC (Mar. 2010). Hence, the on-demand deployment of wireless networks will not only reduce the network recovery time but will also provide necessary communications support for the first responders to effectively execute help and rescue services. Furthermore, the network efficiency, cost reduction, flexibility, self-sustainability, reach, and robustness are some of the added benefits of ad-hoc wireless networks to assist first responders and rescue teams in a disaster zone.

The communications in emergency networks can be classified into a number of precedence levels where alerting messages, wellbeing messages, control messages, distress calls, data collection, relevant and irrelevant communications can be characterized separately to optimize communications. Therefore, a suitable mechanism is needed to associate priority levels with these calls, messages and schedule them accordingly Raza et al. (2018a). The study and appropriate improvements in approaches for infrastructure-less communications for emergency networks can also support in disaster communications, device to device (D2D), machine to machine (M2M) communications, Internet of Things (IoT), smart networks, largescale sensor networks, and Unmanned Aerial Vehicles (UAVs) communications Raza et al. (2018a).

Recent developments in microelectromechanical systems (MEMS) technology and very-large-scale-integration (VLSI) have been very influential in transforming large base station system (BSS) to minute structures, which enables the adaptation of small-sized drones (UAVs). The drones, with the ability to move autonomously and to hover over the affected area, can function as a small cell to establish communications with the UE active in the designated emergency coverage area. The ability of the Drone Small Cells (DSCs) to reposition itself and respond to the UE by reducing distance extends coverage, decreases outage probability of the UE in coverage zones, improves bandwidth efficiency and optimizes system throughput. Research in DSC is still in its infancy and many practitioners and academics are keen to pursue their research in this scholarly area Fotouhi et al. (2017b).

Notable research advances in wireless technology have provided the necessary platform for future developments. The recent growth in 5G and developments on Ultra Reliable and Low Latency Communications (URLLC) offer a suitable solution for reliable communications in ad-hoc wireless networks. The preliminary developments in URLLC offer great potential to address the communication issues in emergency and time-critical communications Hu et al. (2018). Further developments in this domain will not only introduce reliable means to interconnect people but will also permit connectivity of a large number of smart devices to form smart automated environments López et al. (2018). URLLC is desirable in applications with strict time and reliability requirements She et al. (2017). The need for critical, time-sensitive and emergency communications in the infrastructure-less network is evident in emergency and safety applications. Post-disaster rescue activities, highly sensitive process control, feedback systems, necessary M2M communications and emergency and safety systems are some of the examples of time critical and reliability sensitive applications. To offer improved reliability and optimized network communications, MAC layer plays an important role. It handles access to the physical channel, generation of beacons, time slotted access, device security, reliability and link assurance between the MAC entities. Due to the added features and access to critical processes, improvements in MAC can be very influential in achieving URLLC. The existing work in MAC layer optimization targets various aspects of communication optimization. The authors of Raza et al. (2018a),Huang et al. (2013) classified MAC protocols in several categories including periodic, slotted, random, synchronous, asynchronous, hybrid, multi-channel and priority enabled schemes. Each of these classifications offers certain benefits including network lifetime enhancement, reliability, data-rate improvements etc. Out of various MAC classifications, to ensure effective communication in emergency networks, priority-based communications plays an important role.

In the post-disaster rescue activities, the efficient communication establishment has great significance. Wireless ad-hoc networks are most suited for disaster relief operations, in the event of failure of the cellular infrastructure. However, for larger communications outage area, the information routing, channel congestion, multi-hop delay, and poor link quality can limit the scope of deployment of such networks. Therefore, drones are considered, both in the context of cellular link and data delivery. Use of drones allows formulating a two-layer communications hierarchy where the information is communicated from UE to drone and from drone to the core network. This limits the maximum delay in such networks. As developments in drones based communications networks are in initial stages, the existing work is relatively scarce. However, few attempts have been made to produce a workable infrastructure for drone-based communications. In Rohde and Wietfeld (2012) authors have highlighted the placement technique that uses drones as relays for cell overloading and outage compensation. However, only an analytical model was created for system performance evaluation. The paper was also lacking details of drone base station coverage and deployment methods. In Mozaffari et al. (2015), the authors analysed the altitude of a drone base station that minimizes transmission power requirements while covering the desired area. The interference of adjacent drone cells was also analysed. In Mozaffari et al. (2015)-Sharma et al. (2016), authors studied optimal drone position for the drone while serving the target zone. Similarly, the authors of Al-Hourani et al. (2014) provided an analytical model to discover an optimal altitude for a drone to offer maximum coverage area. A service edge was defined as maximum allowable path loss. In Mozaffari et al. (2016), authors discussed the problem of finding the optimal cell boundaries and deployment location for multiple non-interfering unmanned aerial vehicles. Their aim was to minimize the transmission power of the UAVs.

Some research was also conducted to address further challenges in . Ali et al. (2016b) and Ali et al. (2017) examined how the in-coverage UE deliver the elementary network services to out-of-coverage UE by relaying their data to eNB. The study investigated the selection of an in-coverage UE in public safety network (PSN). The findings suggested that there is no centralized entity in PSN to assist the discovery and synchronization of UE and should separately be addressed which results in high energy consumption and delay. In addition, Ali et al. (2018) highlighted that UE selection process was also highly critical because of both in and out-of-coverage UE had very limited energy and processing capability. There was limited reliability in terms of availability, throughput, and traffic handling capabilities of UE and cannot concurrently handle PSN demands. Therefore, the use of DSCs are well suited for PSNs. The suitability of DSCs in PSNs is primarily attributed to self-organization, mobility and delay minimization abilities

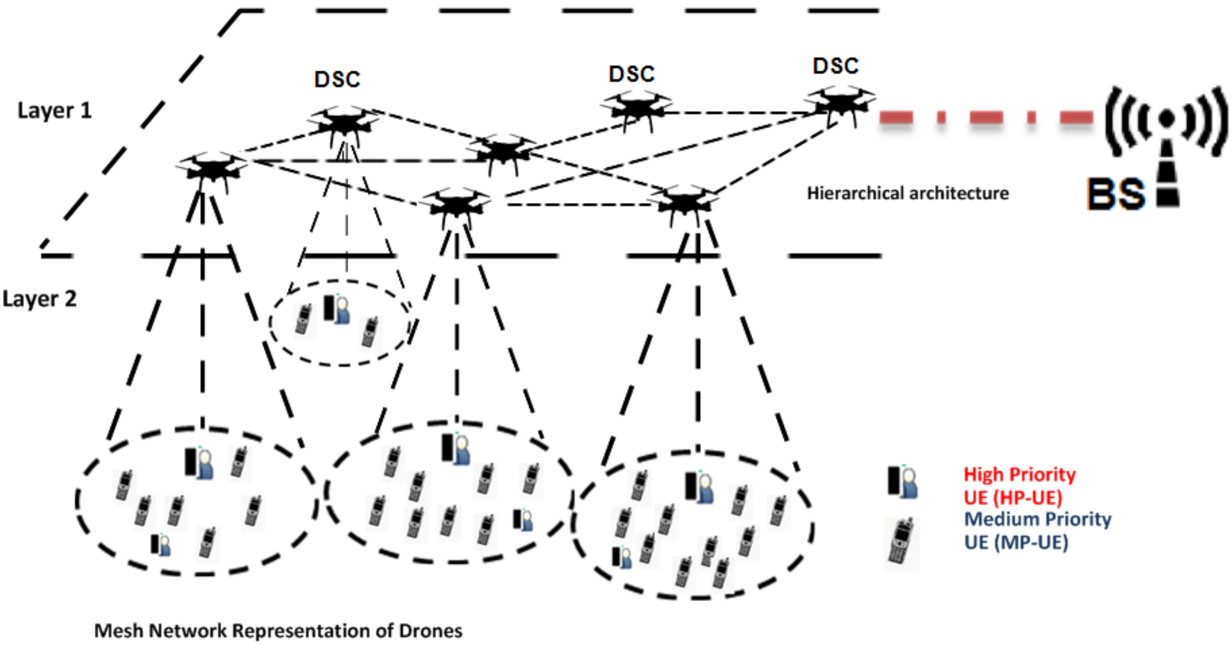


Figure 5.1: Disaster Scenario and System Model

of DSCs. In D2D network architecture resource allocation is very challenging task Chu et al. (2017a). Fortunately, game theory suggests a set of mathematical tools to study complex interactions between rational players and to adapt their choices of strategies. Therefore, game theory is an appropriate tool to model and analyse the resource allocation problems for D2D networks.

This chapter advocate the following reasons of DSC deployment in a PSN: 1) drones can hover at higher altitude to provide suitable height gain; 2) drones are suitable for PSN while hovering which allow energy sustainability; 3) while hovering, drones improve connection reliability, offer better connectivity and efficiency for UE and itself; 4) the usage of DSCs can allow efficient use of bandwidth and improve frequency reusability, and 5) the use of DSCs will result in rapid deployment of communication network in disaster-affected areas.

5.2 System Model

A total of K UE are considered in the communications outage area, previously affiliated to BSS as shown in layer 2 of Fig. 5.1. Based on the logs of the currently non-functional BSS and the communications outage area, the core network decides as to how many drones are needed to cover the outage area effectively. A total of N drones are considered to serve the UE in the disaster-affected area. Each DSC is connected to the core network via a wireless backhaul (see Fig. 5.1). In this scenario, Time Division Multiple Access (TDMA) based channel access scheme is used and a hierarchical access to the core network is ensured with maximum two hop delay from UE to the BSS. TDMA is used to allow several drones to share the same backhaul and further frequency channel by dividing the signals into different time slots for UEs. As communication between the drones and the relevant UE use both requests oriented and on-demand communication in the given scenario. Furthermore, multi-channel access between the drone and BSS is ensured to establish multiple data streams. The UE association is carried out prior to communication and each UE in the affected area is affiliated to the most appropriate DSC based on the resource unit.

In every DSC, drone acts as a base station for UE and will replicate the necessary functionalities of BSS. The mobility of UE is facilitated using the control channel and the moving UE can request affiliation to new DSC based on the link quality. A resource sharing mechanism is also introduced for the effective management of nonlinear density of the UE in the drone coverage area.

5.2.1 Channel model

This paper considers, both Line-of-Sight (LoS) and Non-Light-of-Sight (NLoS) transmissions. More practically, the path loss model is expressed as probabilistic portions of LoS and NLoS transmissions. As in real scenario, the channel between the UE and DSC depends on the elevation angle of the transmission link due to which the latter impacts the probability of LoS or NLoS transmissions. According to Al-Hourani et al. (2014) and Fotouhi et al. (2017a), the loss probability functions for LoS and NLoS transmission from the kth UE (denoted by UE_k, $k \in \mathcal{K} = \{1, 2, \cdots, K\}$) connected to the nth DSC (denoted by DSC_n,

$n \in \mathcal{N} = \{1, 2, \cdots, N\}$) are expressed as

$$P_{LoS}(h, d_{kn}) = \frac{1}{1 + \alpha \exp(-\beta[\theta - \alpha])}, \tag{5.1}$$

$$P_{NLoS}(h, d_{kn}) = 1 - P_{LoS}(h, d_{kn}), \tag{5.2}$$

respectively, where α and β are environment-dependent constants, $\theta = \arcsin(h/d_{kn})$ Al-Hourani et al. (2014). Here, h and d_{kn} denote the drone height (assuming it is the same for all drones) and the distance from the drone DSC_n to the UE_k.

For simplicity, let *path* denote either LoS or NLoS. The signal to interference plus noise ratio (SINR) of UE_k connected to DSC_n via the *path* (either LoS or NLoS) is expressed as:

$$\gamma_{kn}^{path} = \frac{S_{path}(h, d_{kn})}{I_k + N_k}, \tag{5.3}$$

where $S_{path}(h, d_{kn})$ is the received power by the UE_k via the *path*, I_k is the interference signal from neighbouring cells received at the UE_k and N_k is the total noise power including the thermal noise. The achievable rate in UE_k from DSC_n is expressed as follows:

$$\begin{aligned} r_{kn} = \quad & RB\Big(P_{LoS}(h, d_{kn}) \times \log_2(1 + \gamma_{kn}^{LoS}) \quad + \\ & P_{NLoS}(h, d_{kn}) \times \log_2(1 + \gamma_{kn}^{NLoS})\Big) \end{aligned} \tag{5.4}$$

where RB is the available bandwidth from the DSC_n to each UE, then the total number of available resource allocations to the UEs by DSC_n is

$$q_n = \frac{\omega_n}{RB}.$$

Here, ω_n is the available resource (i.e., bandwidth) from DSC_n. Finally, the accumulative throughput of all UEs, denoted by R_{total}, can be written

$$R_{total} = \sum_{k \in K} \sum_{n \in N} \eta_{kn} r_{kn} \tag{5.5}$$

where η_{kn} is a binary variable with value of 1 if UE_k is allocated to DSC_n, and

0 otherwise.

5.3 Proposed DSC-based Public Safety System

Firstly, a matching game approach is considered to maximize the overall throughput for the drone-based public safety network. Once the connections between the drones and the ground users are established, the access and control mechanism is optimised in the MAC layer for the priority of emergency and rescue services.

5.3.1 Matching Game Approach

It is aimed to maximise the throughput of all UEs by formulating the following optimization problem:

$$\max R_{total} \tag{5.6}$$

subject to:

$$\begin{aligned} r_{kn} &\leq C_o, \quad \forall n \in \mathcal{N} && (5.7)\\ \sum_{n \in N} \eta_{kn} &\leq 1, \quad \forall k \in \mathcal{K} && (5.8)\\ \sum_{k \in K} \eta_{kn} &\leq q_n, \quad \forall n \in \mathcal{N} && (5.9)\\ \eta_{kn} &\in \{0,1\}, \quad \forall k \in \mathcal{K}, \forall n \in \mathcal{N} && (5.10) \end{aligned}$$

- The objective function in (5.6) represents the overall throughput of all present UEs in the disaster area.
- The constraint in (5.7) implies that the rate for each user should not exceed the Shannon capacity limit C_o of the channel.
- The constraint in (5.8) implies that each UE_k may be allocated to maximum one DSC or not allocated to any DSC at all.
- The constraint in (5.9) suggests that the maximum number of allocated UE to DSC_n cannot exceed its capacity (i.e. the maximum number of servable UE).

- The constraint in (5.10) defines the binary nature of η_{kn} variable.

The above optimization can be solved using matching approach. The DSCs have designated resources available to assign to the UEs and each UE needs to be assigned to a DSC to have access to the network. This is a mixed integer optimization problem which is hard to solve with classical optimisation approaches Hassine et al. (11 pages, 2017). Therefore, a matching algorithm is proposed to address this two-sided nature of the system (DSC-to-UE) in a disaster situation.

A matching approach is a two-sided assignment problem. Each side represents a separate set of entities seeking for their best match among the entities. Here, each UE identifies its possible match among the available DSCs and then initiates communication for a selection procedure as shown in Fig. 5.1. This choice of procedure is based on a preference relationship defined for each side In the chosen context, a two-sided one-to-many matching game is presented, where all the DSCs are ready to provide their available backhaul capacity to the UEs and can be described as follows:

Definition: A matching approach μ is a function defined as $\mathcal{K} :\rightarrow \mathcal{N}$, where

(1) $\forall n \in \mathcal{N}, \mu(n) \subseteq \mathcal{K}$
   i.e., for each DSC_n, its matching UE set is a subset of $\mathcal{K}$

(2) $\forall k \in \mathcal{K}, \mu(k) \in \mathcal{N}$
   i.e., for each UE_k, its matching is in the set $\mathcal{N}$

(3) $\mu(k) = n$ if and only if $k \in \mu(n)$
   i.e., the matching of UE_k is the DSC_n if and only if UE_k is in the matching set of DSC_n.

Let V_{kn} and U_{nk} are the utility functions of the members of the sets $\mathcal{K}$ and $\mathcal{N}$, respectively. However, S_k to be the set of available DSCs, each UE will be looking for the most suitable DSC. So, the UE utility function V_{kn} of the UE_k to the DSC_n, based on achievable rate, can be expressed as

$$\begin{aligned} V_{kn}(\gamma_{kn}^{LoS}, \gamma_{kn}^{NLoS}) = RB\Big(& P_{LoS}(h, d_{kn}) \log_2(1 + \gamma_{kn}^{LoS}) \\ & + P_{NLoS}(h, d_{kn}) \log_2(1 + \gamma_{kn}^{NLoS})\Big). \end{aligned} \tag{5.11}$$

The DSC utility function U_{nk} for the opposite direction is similarly obtained with SINR pair of γ_{nk}^{NLoS} and γ_{nk}^{LoS} as both parties need to agree on the same benefit.

The matching algorithm, to ensure optimal system performance while considering the system constraints is presented in Algorithm 1.

Algorithm 2 UE Matching Algorithm

```
Data $\mathcal{K}$, $\mathcal{N}$, $q_n$
Result Optimal matching $\mu^*$
Initialization
$S_k$: the total available DSCs for a given $UE_k$ that are within a distance $\kappa$
$q_n$: the total number of available resource allocations (i.e., resource blocks) in $DSC_n$
    Phase 1 – UEs Applications
UEs rank all DSCs based on $V_{kn}$
Every $UE_k$ applies for the $DSC^*$ from $S_k$ with the highest $V_{kn}$, and removes $DSC^*$ from $S_k$
    Phase 2 –  DSCs Selections
i) DSCs rank applicant UE using $U_{nk}$ (i.e. $V_{kn}$)
ii) Among all the applicant UE, the $DSC_n$ accepts each $UE^*$ with the highest $U_{nk}$ while not exceeding its capacity limit $q_n$ and rejects the other UE that don't respect these conditions.
    IF $UE_k$ is accepted by $DSC_n$, then:
    Phase 3 – Repetition
Repeat Stage 1 and Stage 2 for every $UE_k \in K$ until:
```

Further details on throughput analysis and suitability of the matching approach, in comparison to state of the art techniques, are presented in results Section.

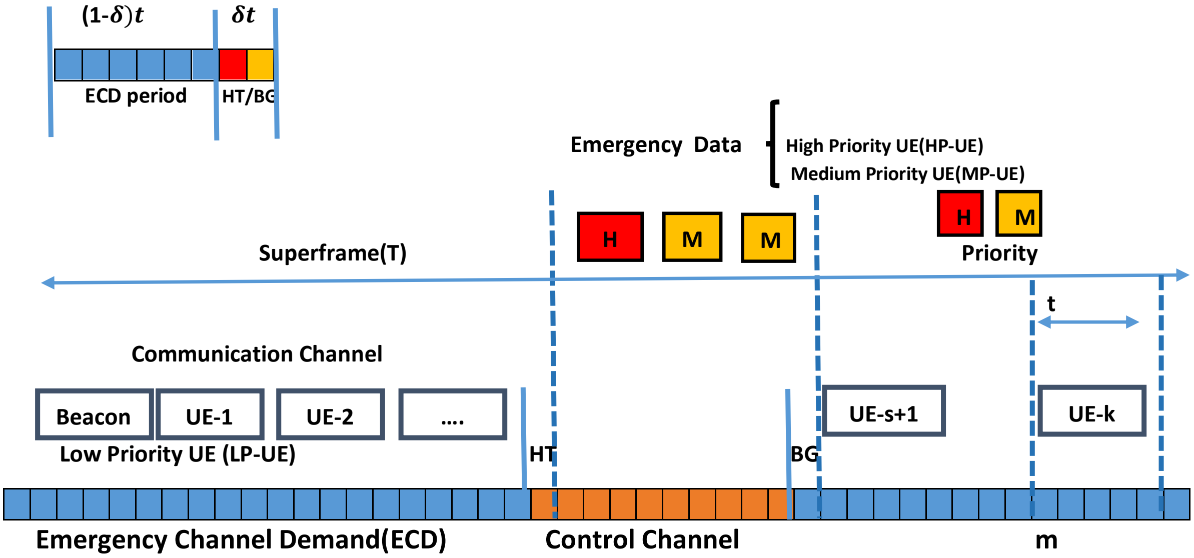


Figure 5.2: Priority MAC (P-MAC) Operation

5.3.2 MAC Design: Prioritized Access and Control Channel

The varying circumstances of users within the emergency networks urge the implementation of prioritized access for critical users such as the first responders or any users in highly vulnerable regions (e.g. survivors trapped in a building). To further assist the communications optimization, a three-level priority mechanism is proposed to offer an early channel access for the critical users. The proposed superframe structure along with segmented control channel slots are presented in Fig. 5.2. Each superframe is divided in n timeslots each of duration t. In the control channel each time slot is divided in emergency channel demand (ECD) and halt/begin (HT/BG) period. The control channel is used to communicate urgent requests to the servicing drones which communicates critical information on priority basis Raza et al. (2018b). The proposed scheme permits UE with emergency data to request channel access and the λ is emergency channel requests originated per second. The hybrid scheme is introduced because of asynchronous nature of emergency communication requests. Within the network, to ensure prioritized access, a control channel based slotted request mechanism is proposed. In case of an emergency channel request, low priority communications can be stopped to initiate emergency communications. In case, numerous emergency requests are received simultaneously, a queuing function is introduced to sequentially assign resources. For such cases the communication of regular TDMA requests can be stopped for multiple timeslots. However, to ensure the collision free transition, halt (HT) and begin (BG) sequences are defined, which stop and reinitiate communication. Different types of UE located in the DSC are designated with high, medium and low (H/M/L-UE) priorities and communication takes place according to the predefined UE priority. As represented in the Fig. 5.2, TDMA based channel access scheme is implemented with beacons to synchronize communication of affiliated UE. The default low priority channel assignment is represented in original superframe whereas in case of an emergency request, the high priority communications are provided optimized channel access.

The mathematical representation of average access delay d Raza et al. (2017), between channel requests to transmission for both Long-Term Evolution (LTE) and proposed scheme Priority MAC (P-MAC) is presented below

$$\begin{aligned} d_{LTE} &= \frac{1}{2}T_{LTE}, && (5.12) \\ d_{P-MAC} &= \sum_{x=1}^{m}\left[\left(\delta t + \frac{1}{2}t + (x-1)\times t + \left(\frac{x}{n}\times \right.\right.\right. \\ &\qquad (PL - delay))) \times P_X(x)] && (5.13) \end{aligned}$$

where, m is the number of emergency UEs, x is emergency occurrences in ECD, t is the duration of time slot, $PL-delay$ is payload transmission time respectively. A detailed discussion on delay optimization using P-MAC is presented in results section.

According to the proposed approach, DSCs are willing to cede their available capacity to the UE on a competitive basis amongst them. All the K UEs will compete to obtain the resources from N to DSCs each having a total available bandwidth of ω_n. More practically, each UE will compete to access the DSC that will provide the best connection. On the other hand, each DSC has a limited bandwidth as a result limited number of UE will be served by this Small Cell.

5.4 Results

The overall system performance of the proposed strategy for drone based communication restoration is thoroughly investigated through simulations and analytical analysis. The parameters are set according to Table 5.1.

Table 5.1: Parameter values in our simulation

Definition	**Symbols**	**Value(s)**
Set of User Equipment (UE)	K	-
Set of Drone Small Cells (DSC)	N	16
Available resource in DSC_n	ω_n	10,15,20 MHz
Signal-to-noise-plus-interference ratio	γ_{kn}	2.09/3.75
Drone height	h	15m,20m
DSC Transmission power	P_{tx}	24 dBm
Interference distance	κ	200m
UE noise figure	I_k	9 dB
Environment-dependent constants	α, β	9.61,0.16
Binary variable	η_{kn}	0,1
Emergency channel requests / second	λ	1,5,10,25, 100,500
Payload transmission time	$PL - delay$	3.84 ms
Communication window duration	$(1-\delta) \times t$	-
Acknowledgement window duration	$\delta \times t$	-

In the proposed P-MAC, average channel access delay for high priority UE is evaluated in comparison to the traditional access delay in LTE. The overall system throughput is also evaluated to analyse the throughput optimization using the matching algorithm. Both aspects of analysis are discussed in detail along with the setup establishment and preliminary setup phase operation. Furthermore, the suitability of drone-based public safety networks is also evaluated. The ability of drones to move in any incident location provides a suitable optimization mechanism towards achieving improved system throughput and reliable network formation. To illustrate possible improvements different aspects of drone deployment were considered to improve the network throughput for the given scenario in Fig.5.1

The Fig. 5.3 represents the distribution of UE in disaster affected areas where initially drones are uniformly distributed. At first, none of the UE is allocated to any DSC. The proposed allocation method ensures the suitability of the UE-drone pair for optimal performance. In Fig. 3 the allocated UE to the relevant DSCs are represented with a distinct colour code. Note that for allocation of UE to suitable DSC, two techniques are used, namely, matching game algorithm and minimum distance allocation.

In Fig. 5.4 (a) matching algorithm based UE association is established where as Fig. 5.4(b) uses minimal distance allocation (also referred as 'k' nearest neighbour (kNN)). In Fig.5.4, the affiliated UE is represented by a star of the same colour of the diamond, representing a drone. The black stars signify the UE that are not affiliated with any DSC.

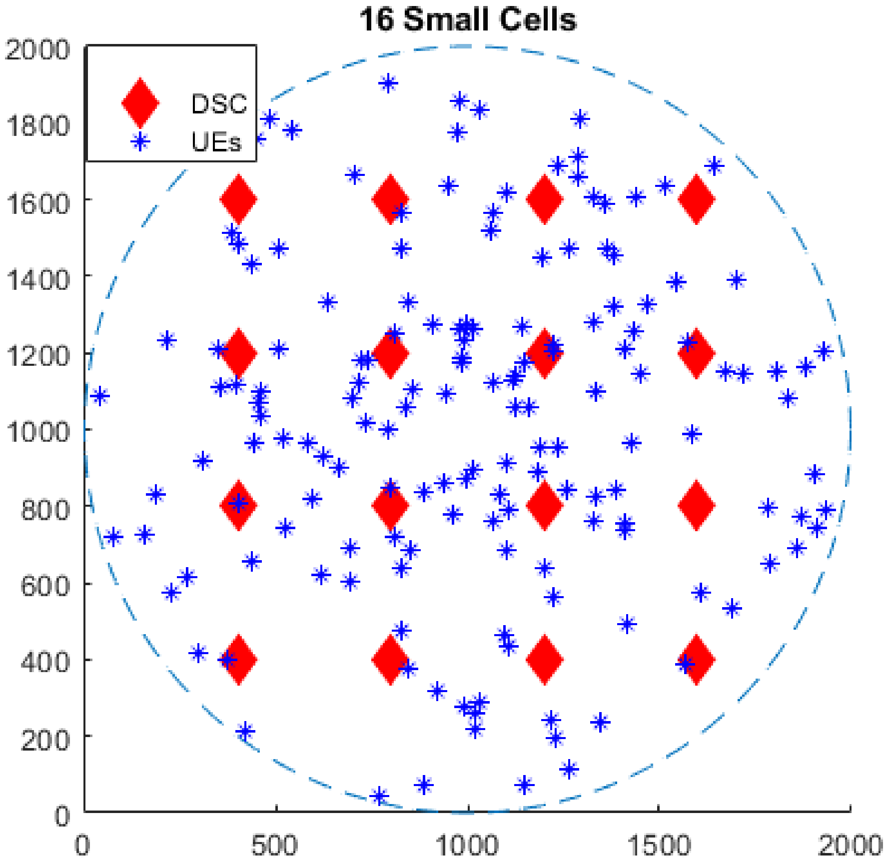


Figure 5.3:
Initial scenario before UE allocation to DSC

Once the UE are affiliated to the DSC, a relevant priority level is defined

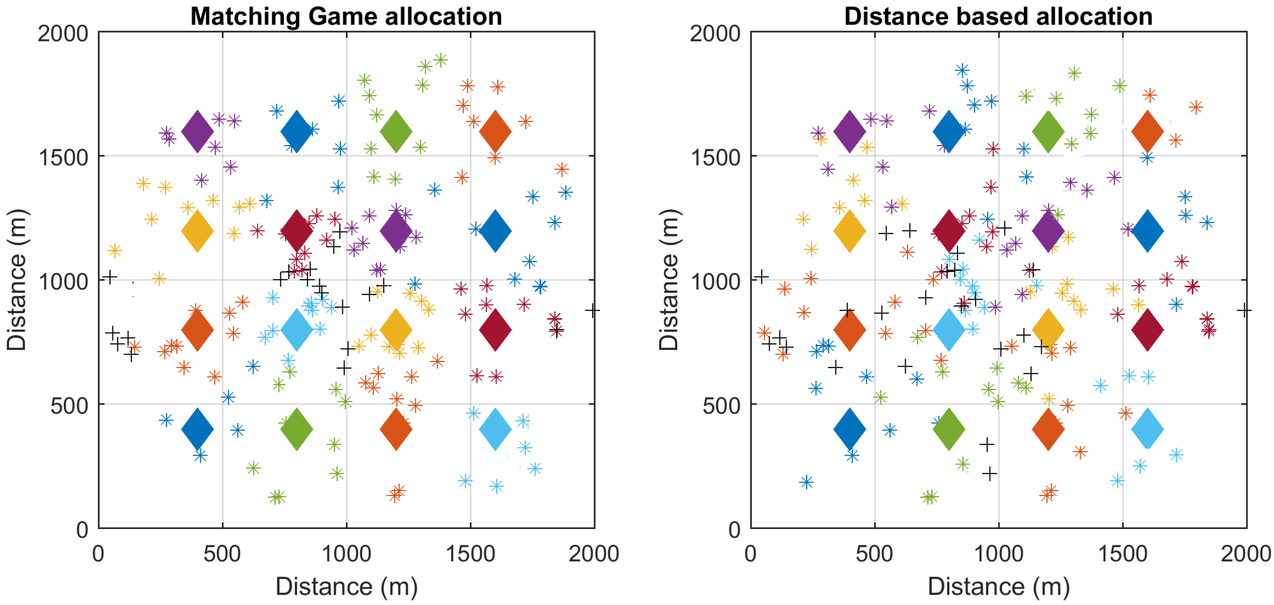


Figure 5.4: UE Allocation using: a) Matching Game Algorithm (left), and b) Minimum Distance Allocation (right)

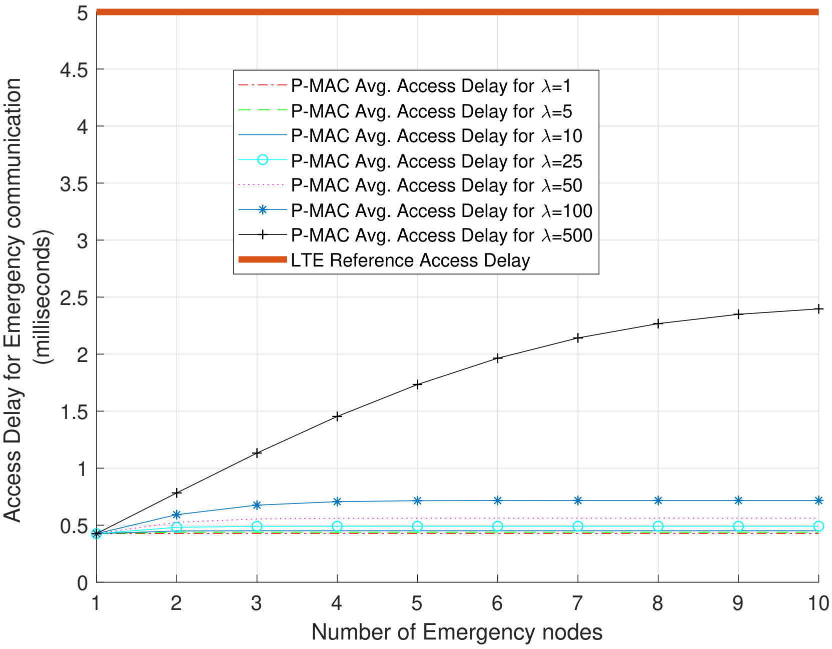


Figure 5.5: Average channel access delay (P-MAC)

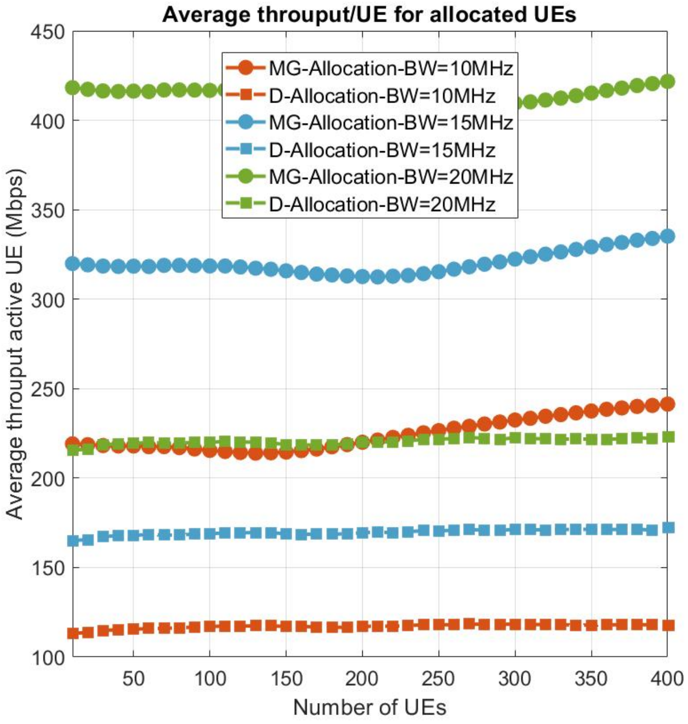


Figure 5.6: Average throughput per UE as a function of number of UEs

for each of the affiliated UE. Based on the priority level, the UE will access the channel resources accordingly. The use of the prioritized access allows the reduction in delay of highly critical communications. In Fig. 5.5, the average channel access delay of highly critical information is represented. It can be seen that access delay is evaluated for various number of channel requests, λ, originated per second. The simulation results show that the average access delay in critical UE is reduced notably in comparison to LTE. This ensures low level latency in communications from the critical users.

The use of matching algorithm also gives a notable improvement in the individual (UE) as well as collective throughput of the system. In Fig. 5.6, the average achievable data rate per UE is presented in both allocation methods (matching approach and kNN). It was observed that the average throughput obtained using matching allocation was better than the one obtained with minimal distance allocation (kNN). The average achievable rate almost doubled with matching al-

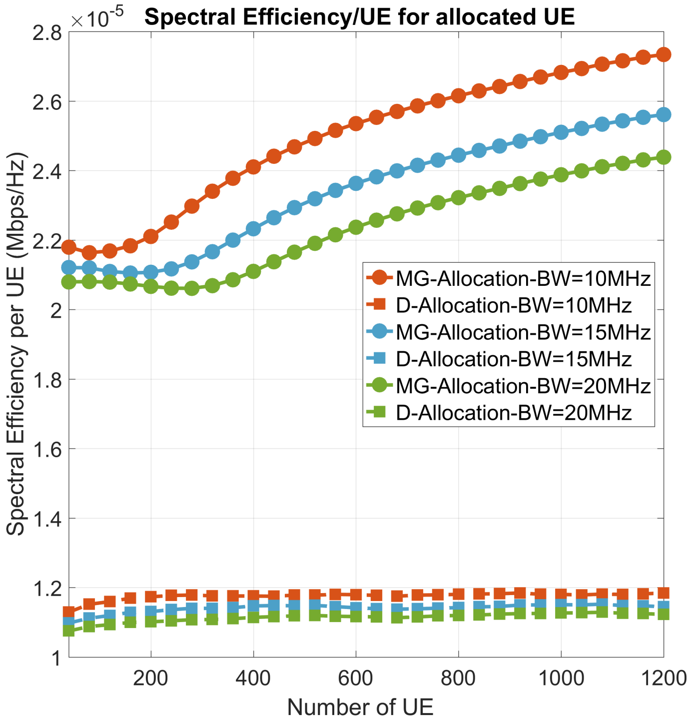


Figure 5.7: Spectral efficiency per-UE as a function of number of UE

gorithm. The overall spectrum efficiency improved as well. In Fig. 5.7 spectral efficiency for an active UE in disaster area is represented. The proposed matching based algorithm provides better spectral efficiency than the traditional minimal distance based efficiency. The results presented in Fig. 5.6 and Fig. 5.7 show notable improvements in comparison to traditional schemes.

Figure 5.7 represents the spectral efficiency for an active UE in disaster area as a function of number of UE. Again we notice that our proposed matching game based algorithm provides better spectral efficiency than the traditional minimal distance based one. This confirms how efficiently the bandwidth resources are used by UE in disaster area where resources are keenly observed before allocation. Figure 5.8 represents the system throughput obtained from allocated UEs single throughputs for both matching game and distance based allocation mechanisms. The first observation we can make is that system throughput increases as the number of present UEs increases for wider bandwidth systems and reaches a

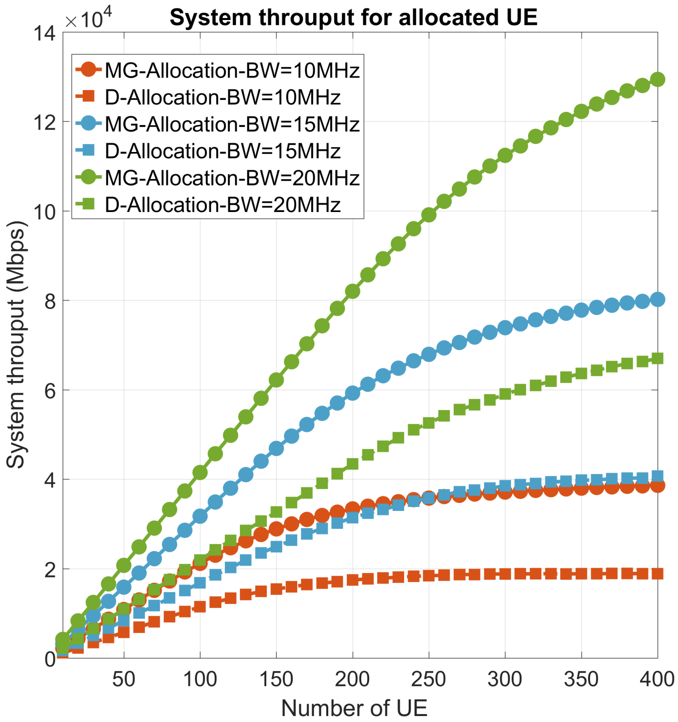


Figure 5.8: System Throughput for allocated UE

saturation level for shorter bandwidth systems. This is due to resource limitations dictated by system bandwidth. Secondly, the plots show that matching game algorithm provides better system throughput than distance based technique. This proves how the matching game performs better in enhancing both UE and system throughputs.

To further investigate the ability to match approach and kNN, the maximum number of manageable UE are investigated for a variety of UE densities in the coverage area. In Fig.5.9, the results for both, kNN and the proposed scheme are represented. The figure shows that the number of affiliated UE within the DSCs (in both schemes) show similar performance. However the matching approach still offers slightly better performance out of the two by examining it more closely. In case of increasing bandwidth from 10 MHz to 15 MHz and 20 MHz, a linear increase in allocation ability of UE is observed.

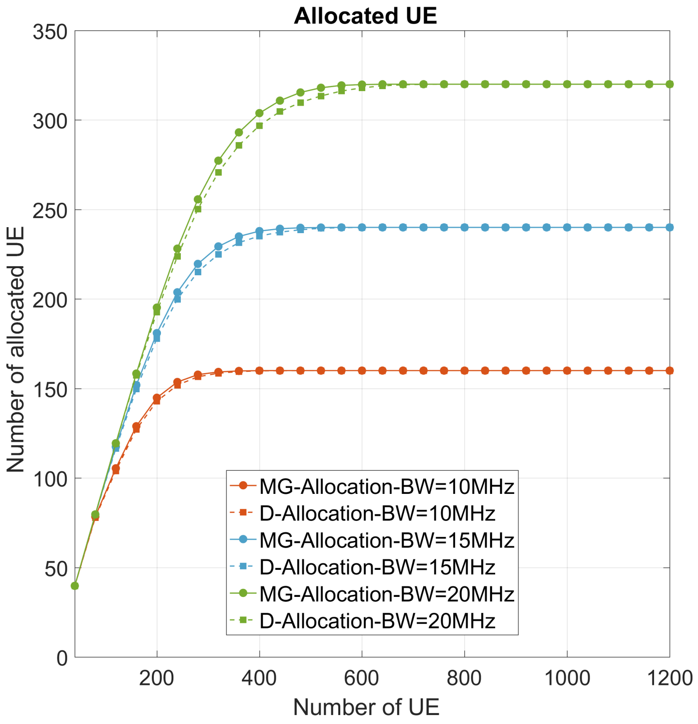


Figure 5.9: Number of allocated UE as a function of number of UE

5.4.1 Summary

Public safety communications can benefit from deploying drones to facilitate interrupted communications in the event of natural catastrophes. The establishment of DSCs is highly beneficial in re-establishing communication links to the first responders, rescue workers, and trapped survivors by conducting coordinated rescue activities. The proposed drone-based resilient communication architecture, presented in this chapter not only enables effective communication in disaster-affected out of coverage areas but also ensures communication optimization in individual DSCs. A novel drone based cellular infrastructure is proposed to revive communication by proposing a matching algorithm with the one-to-many approach, wherein several DSCs can be matched to UE to reach an optimal and stable solution. Furthermore, a dynamic priority scheme is also proposed which classifies various types of communication which take place within disaster situations to improve channel access delay. This classification helps in prioritizing the communication of critical UE (Rescue workers and vulnerable survivors).

Chapter 6

Conclusion and Future Work

The actual deployed technologies for public safety networks are not able to face the issues that arise in the aftermath of a natural or human disaster. In fact, the lack of communication infrastructures or the damage that these latter experience during the disaster, make the first recovery operations difficult to be fulfilled by the rescue teams.

6.1 Conclusion

The need for communication in drastic events is paramount wherein infrastructure makes services unavailable due to disasters. The existing infrastructures do not cope with such calamities. They neither render help to those affected nor to the rescue teams. The existing infrastructure cannot undertake the required availability, reliability, repairability, recoverability and robustness of ICT. Similarly, present disaster communication systems rely on an existing network infrastructure and fail to provide services because of physical destruction of network equipment. PSNs failed to cope in such disaster situations and are not designed to support higher bandwidth applications. However, the evolution in LTE mobile radio technology, 3GPP which introduces the support to D2D in LTE enabling P2P transmissions between devices in proximity, laid the foundation for enhanced PSN communication system. Therefore, the need for more efficient, reliable and resilient disaster communication architecture design is needed on such foundation of LTE to cope with the disaster situation and provide connectivity amongst devices in the areas affected by calamities.

Hence, this research aimed to address the above gap to design a disaster resilient network architecture system using D2D technology that is able to cope with the hazardous conditions and emergency disaster situation where communication infrastructure is not sufficient to support the rescue teams and victims. The aim was to design self-organising autonomous systems to re-establish the network connectivity and enable end-user devices to create spontaneous communication networks that facilitates the cooperation during the rescue operations. The ultimate goal was to design a disaster resilient network architecture which includes the integration of modern computing technologies and also offer effective provision in regards to disaster communication and management system. To achieve the above aim the following objectives were set.

First objective was to examine the challenges and constraints within traditional ICT disaster architecture and this research found that the existing network technologies are limited to specific applications and are not suitable to create large-scale emergency networks due to their limitations in terms of coverage, bandwidth, and interoperability with defined devices. In addition, the existing networks have limited self-organising and self-healing capabilities, spectrum efficiency, power, energy, reliability, robustness, resources, and limited network density.

The second objective was to analyse the next generation of wireless technologies suitable for disaster communication system and it highlighted the well-known technologies for example, ad hoc networks, 3GPP-LTE with device to device communication approach, movable base stations with aerial unmanned vehicles (drones), clustering of nodes and energy harvesting ability along with proposed algorithms for better connectivity and communication. It utilised major technologies that are integral part of the PS framework.

The third objective was to examine the applicability of D2D technology to tackle safety and emergency concerns where conventional methods of communication were not be available. It was found that D2D to technology was providing in coverage, partial coverage, out-of-coverage and D2D-based relay which means that they enabled UEs to communicate directly with each other using with and without the access network. It was also found that the vital functions of D2D communication was proximity services (ProSe). Based on the above propositions different frameworks were designed to enhance the capability of D2D technologies and its integration with other technologies.

The fourth objective was to utilise relay communication (single or Multi-hop) to extend coverage area for information sharing during a disaster and it was found that D2D multi-hop relay technology connected and provided communication links from source to destination with intrusion of other UEs acting as wireless relay. The findings in this research justified 3GPP release 13 major points of D2D relay communication which effectively enhanced power efficiency while increasing the number of relay hops. Such proposed relay architecture in this research assisted in power saving and distance especially when D2D users are far away from each other in a disaster situation.

The fifth objective was to examine mode selection strategy for D2D communication suitability and this research developed a framework whereby it applied Time Switching protocol at relay to provide energy harvesting and information to further strengthen the life of relay based network during disasters. It also adopted mode selection strategy to gauge the suitability of D2D communication and the employment of the UER during disaster to harvest energy from relay via BS so that the energy is sustained for D2D communication in disaster situation. In addition, this research found that a novel cooperative D2D energy harvesting clustering network for disaster management is developed to enhance performance, reliability and energy efficiency.

The sixth objective was to examine and enhance disaster communication framework using unmanned aerial vehicles communication in the context of 5G and this research proposed a UAV based framework to establish emergency communication within the disaster affected and communications outage areas which offered optimised on-demand communications with enhanced throughput to support highly resilient networks within critical and emergency scenarios. It proposed Ad-hoc on-demand formation of small cells to re-establish communications within disaster affected and communications outage areas. In addition, the proposed framework not only enhanced the number of users to be served by the UAV but also prioritised the communications of the rescue workers and first responders.

Finally, this research presented a ray of innovative thematic taxonomy for disaster management. The taxonomy identifies and categorizes key attributes essential for the development of disaster communication architecture. The taxonomy is categorized into two attributes pre-disaster and post-disaster phases which offers basic preparation concept and opportunities for disaster communication system development. They are classified with numerous related attributes for critical communication to develop robust and a sustainable system.

6.2 Future Work

Deployment agility and Time constraint: The deployment speed and the adaptivity of the deployed system is of fundamental importance. The first hours of the operations during a disaster are crucial. Due to huge data volumes, it is quite difficult to extract quality information in a limited time for emergency response decision-making. The data processing is time-consuming, as it involves multi-sourced data harvesting, filtering, and categorizing; that can take a lot of time even with advanced big data analytical tools. It is an important challenge for the existing techniques and tools to pre-process data and generate the required results in a specified amount of time to provide quick emergency response and save lives Mohammadi et al. (2018). To cope with such situation and provide better connectivity and data accuracy, machine learning techniques, the use of D2D, mobile relay, clustering, energy harvesting and UAVs are the main promising techniques which this research has unearthed Alnoman and Anpalagan (2017). However the ability of these kind of technologies in facilitating a communication network is still an open issue.

System lifetime and Real-time Processing: After the deployment of the proposed frameworks in different critical occasions, the system must supply the rescue team for the duration of the rescue operations. Faster recharge mechanisms in term of power and efficiency must be developed in order to cope with this issue. Because due to the dynamic and demanding nature of disasters, real-time processing is the key requirement in any disaster management environment. Connectivity among various data sources results in massive data generation at high speed that can create hurdles in performing real-time processing. The fog communications can play an important role Mao et al. (2017). Fog devices offer two basic functionalities in the event of natural disaster: 1) the information received at the fog can be filtered and redundant information can be discarded, thus reducing the load on the multi-hop D2D communication links and core networks, 2) A data-hub and emergency response server creation, where the fog devices can accumulate responses to redundant local queries, resulting in time efficient and timely response to the queries Shi et al. (2016). Further to this, fog serves suitably in improving situational awareness between the rescuers response centres and the individuals in the disaster affected areas.

Standardization of the communication technologies: Different public safety workers use different communication technologies over different wireless communication frequencies. A standardization operation must be started in order to allow fast communication amongst the different organizations that operate in the emergency area. Standards can promote system efficiency, foster technological changes and provide recognized guidelines for policy, governance and future research. As disaster management requires various systematic solutions, it can be difficult to develop standards initially. However, standards such as communication protocols, network protocols, data aggregation standards and security standards are the core activities that need to be formalized to increase the value of data and services.

In conclusion, the work presented in this thesis aims to use enhanced technologies during emergency scenario in order to save the highest number of lives, reducing the rescue operation time, effort and anguish by helping the rescue teams in their crucial rescue operation.

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