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LTE-based Public Safety Networks: A Survey

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***Abstract*—Public safety networks (PSNs) are very crucial for Public Protection and Disaster Relief (PPDR). Land Mobile Radio (LMR) technologies have been used extensively in the deployment of PSNs so far. LMR networks support sophisticated voice applications that can, to some extent, deal with the mission-critical nature of PPDR services. However, LMR networks lack technological advancements to support broadband applications. Due to this limitation, the attention is drawn to the Long-Term Evolution (LTE) technology for Public Safety (PS) deployment as it has the potential to support various narrowband and broadband applications and services. LTE-based PSNs should have strict requirements in terms of scalability, robustness, and resilience. In this survey, we will highlight the history of PSNs, including LMR and LTE-based PSNs, discuss the requirements that have to be inherited in PSNs, and examine the spectrum allocated for PS use. Moreover, we will study the architecture of LTE-based PSNs and provide deployment and migration solutions. Furthermore, voice delivery over LTE and LTE standardized solutions tailored to support PS services are discussed. Finally, rapid emergency deployment, spectrum management, priority management, and radio resource management schemes in LTE-based PSNs are discussed as well. At the end of the survey, we present PSNs simulation environment using Network Simulator (NS-3) and provide the results of multiple disaster scenarios.**

***Index Terms*—Public Safety, Public Protection and Disaster Relief, LTE, TETRA, P25, VoLTE, ProSe, GCSE, MCPTT.**

I. Introduction

THE Public Protection and Disaster Relief (PPDR) agencies are responsible for creating safe and stable environments, and for executing mission-critical operations such as a response for possible disastrous situations that are caused by nature or by human activities. The PPDR services include law enforcement, police operations, fire fighting, emergency medical response, border security, and disaster recovery [1]. One of the key elements for successful PPDR operations is to have efficient ways for wireless communication and data exchange between the units operating in the field and with a central dispatcher. Wireless telecommunication networks used for PPDR operations are usually referred to as Public Safety Networks (PSNs). In legacy PSNs, the traffic exchanged between Public Safety (PS) entities is mainly voice traffic and majority of PSNs around the world are voice-oriented networks.

The current PSNs are designed based on the professional mobile radio technology; known as Land Mobile Radio (LMR) in North America and Private Mobile Radio (PMR) in Europe. We will use PMR and LMR interchangeably throughout the paper. LMR systems consist of portable user equipment, base stations, and a dispatcher. LMR networks provide rich voice-centric applications, nevertheless, they have low data rates and their technologies lag far behind the advancements that have been made in the wireless commercial domains. Terrestrial Trunked Radio (TETRA), Digital Mobile Radio (DMR), and Project 25 (P25) are well-known examples of LMR systems for PSNs. TETRA and DMR are standardized by the European Telecommunications Standards Institute (ETSI). On the other hand, P25 is standardized by the U.S. Telecommunications Industry Association (TIA).

Communication technologies can be classified, based on their supported data rates, into three categories; Narrowband (NB), Wideband (WB), and Broadband (BB). NB technologies have data rates around few tens of Kbps, and they are suitable for voice-centric applications. TETRA and P25 are classified within this category. WB technologies support applications with data rates around several hundreds of Kbps. The evolutionary TETRA system, TETRA Enhanced Data Service (TEDS), is an example of WB technologies. Finally, BB technologies can run services with data rates beyond 1 Mbps. These data rates can be used for applications such as multimedia sharing, High-Definition (HD) video transmission, live-video streaming, database access, file sharing, and a lot more sophisticated applications.

Unlike ordinary voice communications that may have some laxity, PSNs support voice communications in very efficient ways with tight constraints. However, the demand for broadband communications in PSNs, such as multimedia sharing, video calls, and live-video streaming, is rising as it would play a major role in having more operations completed successfully. For instance, sending live video-streaming to the central control unit will enable them to assess the situation accurately which will allow them to dispatch enough first responders to handle the disaster efficiently and reduce any possible fatalities.

Due to the current massive advancement in Long-Term Evolution (LTE) technologies, it is considered as a very promising candidate to serve the striving, tightly-constrained needs of PSNs [2]. LTE systems are capable of supporting PS and mission-critical communications [3]. Mission-critical communication represents situations where communication is critical and must be carried with high success probability. PSNs must be able to carry both mission-critical (during emergency situations) and non-mission-critical (during regular situations) communications. LTE provides a flat all-IP (Internet Protocol) system architecture with low air interface latency which will enhance system performance. Moreover, LTE systems work

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TABLE I: Types of services that should be supported by PSNs.

Service Type	Interactivity	Examples	
Voice Services	Interactive: voices messages and calls exchanged between multiple entities interactively	Full-Duplex Calls	Calls between two entities where voices data is exchanged in both directions simultaneously
		Half-Duplex PTT	Calls between two entities where voices data is exchanged in one direction at a time
		Group Calls	Full- or half-duplex calls that include more than two entities
		Emergency Calls	Urgent calls that require high reliability and priority
	Non-Interactive: informative voice messages from one entity to others without an immediate reply being required	Ambient Listening	Listening to broadcast voice channels of nearby entities
		Alert Voice Messages	Exchanging voice notifications and alerts
		Caller ID	Identification of call members during one-to-one or group calls
Data Services	Interactive: queries about specific pieces of data are made and an immediate response is needed	RTLS Systems	Identify and track the location of PS practitioners in limited disaster areas such as buildings
		Accessing PS Servers	Ability to access PS databases
		Map Access	Global localization, maps reading, and exchanging positioning information
		Biometrics ID	Identifying people based on their biometrics which needs interactive communications with PS servers
	Non-Interactive: data sharing without requiring any response	Text messaging	Sending and receiving text messages among two or more entities
		WSNs Data Monitoring	Ability to collect Information from WSNs deployed at disaster areas
		Vital Signs Monitoring	Monitoring vital signs from PS practitioners using body WSNs
Multimedia Services	Interactive: queries about multimedia-type information are made and an immediate response is needed	Facial Recognition	Identifying people based on their facial images
		Video Calls	One-to-one or group video calls
	Non-Interactive: accessing and sharing multimedia and real-time streaming	Surveillance	Recording and accessing video from surveillance systems
		Image Sharing	Sharing images with other PS practitioners
		Video Streaming	Real-time access to live video streaming

at different carrier frequencies which reflects their regional flexibility and their potential interoperability. Interoperability is important to facilitate multi-vendor support of LTE equipment and to improve the ability to access foreign networks as a visiting entity. Also, LTE systems are highly scalable and are able to support large number of users. Furthermore, LTE systems are flexible in terms of network deployment and cell size covering small or large geographical areas.

In this paper, we focus specifically on LTE-based emergency networks since LTE is regarded as the main technology on which modern PSNs are going to be based. The contribution of this work is highlighted in three points as follows. First, a complete overview of LTE-based PSNs, including their requirements, history, spectrum allocation, and architecture, is provided. This part is helpful for governmental bodies and researchers seeking guidelines to upgrade/redesign their respective PSNs. Second, challenges and future development areas are discussed, which constitutes a guideline for further improvement of LTE-based PSNs. Another contribution is adding all the up-to-date works to address the studied future development areas in a comprehensive way. Some of these aspects were not addressed by other LTE-based PSNs surveys. Finally, a simulation environment is developed using NS-3 to enable realistic evaluation of future LTE-based PSNs. The performance of LTE networks in relief and disaster scenarios is evaluated in terms of connectivity, throughput, spectral efficiency, and delay. What makes this work different than other surveys, such as [1], [2], is the development and discussion of this software environment. Simulations are important due to the high cost and time of running tests on LTE networks for preliminary evaluations, especially for the research community. Many organizations are looking for solutions that provide extensive simulations for PSNs planning. Also, it enables governmental bodies to assess the behavior of the provisioned PSNs during disasters since it is easier to simulate disaster scenarios than actually running them in real life.

This paper is arranged as follows. Section II starts by describing the basic requirements for PSNs that have to be considered during the system design. In section III, the history of PSNs and the motivation behind the migration towards LTE BB technology will be illustrated. The spectrum allocated for PS and its implications will be summarized. The architecture of LTE systems will be illustrated and different solutions for LTE-based PSNs will be studied in section III-C. Various kinds of resources sharing between PSNs and commercial networks are also discussed. Furthermore, section IV-C studies LTE-based technologies and architectures that are being standardized by the 3GPP to support PS applications such as Proximity Services (ProSe), Group Communication System Enabler (GCSE), and Mission-Critical Push-To-Talk (MCPTT). The study also includes the use of access wireless local area networks and backhauling architecture. Future

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TABLE II: PS communication technical requirements as defined by 3GPP's bearer characteristics [4].

	Latency (ms)	Packet loss	Guaranteed Bit Rate (GBR)	Call-setup time (ms)	Priority
Mission-critical voice	75	10^{-2}	GBR	300	0.7
Non-mission-critical voice	100	10^{-2}	GBR	300	2
Conversational video	150	10^{-3}	GBR	1000	4
Non-conversational video	300	10^{-6}	GBR	—	5
Mission-critical data	200	10^{-6}	Non-GBR	—	5.5
Mission-critical delay sensitive signaling	60	10^{-6}	Non-GBR	—	0.5

challenges and open research areas in LTE-based PSNs are discussed in section VI, which include rapid emergency deployment, spectrum management, priority management, and radio resource management. Finally, a simulation environment for LTE-based PSNs is built using Network Simulator NS-3 in section VII. Building such framework enables testing and evaluating any designed architectures and protocols. Scenarios and simulation results of disaster relief using mobile base stations are presented. Finally, section VIII concludes our paper.

II. Requirements of Public Safety Networks

PSNs are utilized by first responders agencies such as military, police, firefighters, and paramedics. They are used to provide PPDR services which include law enforcement, police operations, firefighting, emergency medical response, border security, and disaster recovery [1]. Also, they can be used to establish mission-critical communication in transportation, construction, factories, forest operations, mining operations, and remote areas [5]. Due to the critical aspect of such applications, the essential requirements and needs that must be considered while designing PSNs must be highlighted. In this section, the applications and services that have to be supported by PSNs and their technical requirements will be discussed.

A. Communication Services for PSNs

As shown in Table I, the services provided by PSNs can be categorized into voice, data, and multimedia [6]. PS voice services include full-duplex high quality calls, half-duplex Push-To-Talk (PTT), group calls, one-to-one calls, one-to-many calls, emergency calls, and ambient listening. PS data services include messaging, Wireless Sensor Networks (WSN), map reading, Real-Time Localizing Systems (RTLS), tracking services, web surfing, accessing PS servers, and biometrics reading. Furthermore, services like image sharing, video sharing, video streaming, live video feeds streaming, and facial recognition are examples of multimedia services. A description of each service is provided in Table I. The communication between different PS units can be categorized into interactive and non-interactive communication. Interactive voice or data communication happens when messages transmitted from one unit to other units require an immediate response, like group calls. On the other hand, non-interactive communications do not need a rapid response, like voice or data messages broadcast by the dispatcher, database access, and field monitoring. Figure I shows different types of services that should be supported by PSNs.

B. Technical Requirements of PS services

The performance and capabilities of PS services are tightly-constrained in terms of their technical requirements for delivery and quality. In [7], the Office for Interoperability and Compatibility (OIC), established by the U.S. Department of Homeland Security (DHS), studied the minimum requirements for the PS mission-critical voice, video, and data applications. Regarding PS voice applications, the background sound carries useful information and is usually desirable. Hence, the usual voice coders (vocoders) with background noise cancellation are not suitable for PS applications. Moreover, the use of Voice Activity Detectors (VAD) in some PS voice applications may not be appropriate because they reduce the chance of having accurate representation of the acoustic environment. Moreover, for mission-critical voice, the call-setup time should be lower than 300 ms, the end-to-end delay should be less than 150 ms, and the packet loss ratio should be less than 2% for packets with a duration of 40 ms or less in order to satisfy 80% of PS practitioners. For PS video applications, parameters regarding video acquisition, transmission, storage, and display must be addressed. For example, based on [7], the end-to-end video delay should be less than 1000 ms, and the frame rate should be more than 10 frame/s.

The technical requirement of voice, video, and data in PSNs is illustrated in Table II. The requirement are presented in terms of end-to-end latency, packet loss, call-setup time, priority, and whether a minimum bit rate is guaranteed or not. The values in this table is standardized by the 3GPP (Third Generation Partnership Project) in the Technical Specification TS-23.203 [4]. It is highlighted that higher priority traffic gets lower priority values, i.e. mission-critical delay sensitive signaling has the highest priority with respect to other types of traffic. More details regarding the priority and LTE bearer type (GBR or non-GBR) will be studied in section VI-C.

Resilient availability and reliability of communication provision in PSNs represent a critical demand. All networks are vulnerable to different kinds of failures such as node and link failures. In [8], it is concluded that 70% of failures are single-failures. Also, node failures are usually ten times more often than link failures. Therefore, it is essential that PSNs overcome such failures even at disaster scenarios where more

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TABLE III: Legacy public safety networks specifications.

	TETRAPOL	TETRA Release 1	TEDS	P25 phase 1	P25 phase 2
Release date	1980s	1995	2005	1995	2010
Developing organization	Airbus Defence and Space	ETSI	ETSI	TIA	TIA
Vendor support	Single	Multiple	Multiple	Multiple	Multiple
Modulation	GMSK	π/4-DQPSK	4/16/64-QAM	C4FM	C4FM
Access method	FDMA	TDMA (4 slots)	TDMA (4 slots)	FDMA	TDMA (2 slots)
Frequency bands (MHz)	VHF, UHF, or 800	VHF, UHF, or 800	VHF, UHF, or 800	VHF, UHF, 700, 800, or 900	VHF, UHF, 700, 800, or 900
Channel bandwidth (KHz)	12.5	25	25, 50, 100, or 150	12.5	6.25
Peak data rate (Kbps)	8	28.8	473	9.6	9.6
Driven applications	Voice and NB data services	Voice and NB data services	Voice and WB data services	Voice and NB data services	Voice and NB data services
Professional use	only PS	PS and other professional uses	PS and other professional uses	only PS	only PS

failures are expected to occur. The resilience of PSNs depends on the adopted redundancy mechanism which can be done in software and/or hardware. Bayesian Networks (BNs) can be used in order to perform risk assessment [9]. BNs are effective in representing dependencies between network components and their impact on the reliability. It is critical to use such techniques while planning and designing resilient LTE-based PSNs.

Network coverage, reconfigurability, capacity, service availability, service continuity, priority management, resources management, spectrum management, interconnection, and interoperability must be inherent with strict specifications in PSNs. Security is also required through all communication layers including the physical layer [10]. In legacy PSNs, most of these requirements are adopted but with limitations due to the reliance on old technologies. In this paper, we will address some of these requirements in the scope of PSNs.

III. History of Public Safety Networks

A. Legacy PSNs

LMR systems are the heart of the currently deployed PSNs [11]. In the evolution road of LMR networks, two distinct paths are followed; TETRA in Europe and P25 in North America. As mentioned earlier, while TETRA is developed by ETSI, P25 is standardized by TIA. Both of them were conceived around 1995 and have been evolving since then. Also, TETRAPOL, which is not related to the TETRA systems, was developed by a French company called MATRA in the 1980s and is currently controlled by the French Airbus Defense and Space. These technologies are designed to provide efficient voice communication which is a must for mission-critical nature of PS applications. Until these days, they are widely used for PSNs in more than 130 countries around the world.

TETRA systems are not only used to provide PS services, but also for other private professional applications in Europe and North America. For example, they may be used to equip private security teams around a soccer field. On the other hand, P25 systems are exclusively dedicated to serve PSNs in North America. Table III shows the technical specifications of legacy LMR systems. The table provides some details about frequency bands, channel bandwidth, access method, modulation technique, peak data rates, and supported applications.

LMR PSNs provide voice communication, NB data, and WB data services [2]. However, they do not support BB applications, which no longer satisfies PS stakeholders. In this regard, LTE technology is selected by many, including the U.S. Federal Communications Commission (FCC), for deployment in the broadband portion of the PS allocated spectrum [12]. However, there are challenges regarding the use of LTE for mission-critical applications. These challenges must be addressed in order to fully adopt this technology. In this context, standards are currently being developed by the Third Generation Partnership Project (3GPP) organization in order to improve the capabilities of LTE technology and make it more appropriate for the mission-critical nature of PS applications [13].

In fact, some LTE-based PSNs are currently being deployed and maintained around the world. The First Responder Network Authority (FirstNet) of the Uninted States, also known as Nationwide Public Safety Broadband Network (NPSBN), is an example of that [14]. FirstNet is designed to provide broadband data capabilities to PS users. However, it is not intented to replcae the legacy LMR systems because it is not capable of providing dependability and mission-critical characteristics of voice communication. It is worth mentioning that, in 2017, AT&T was contracted to manage the FirstNet for the next 25 years.

B. LTE as a technology enabler for PSNs

The use of LTE technology in PSNs offers lots of advantages over PMR technologies. To begin with, LTE technology is capable of running BB emergency services that demand sharing photos, files, and videos [15]. Adopting LTE for PSNs will open the door for new applications such as live video streaming, video conferencing, field sensing, tracking, and many more services that are not achievable by the current

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LMR PSNs. Furthermore, LTE technology offers a huge economical advantage in terms of infrastructure costs (CAPEX) and running costs (OPEX). The huge market of LTE, in comparison with other markets of LMR systems with few suppliers, and the multiple vendor and carrier support of LTE technology makes it possible to reduce the cost of effective deployment. Moreover, there are more than three hundred LTE networks that are currently deployed across the globe. Hence, it is easy to build interoperable PSNs in many countries using LTE systems. In PMR systems, interoperability is an issue since TETRA equipment do not work in P25 networks, and vice versa.

Also, the security domain of LTE networks is very active [16]. In terms of security, LTE systems are exposed to many threats like identity theft, privacy exposure, IP tracking threat that leads to location exposure, broadcast/multicast of false information threat, Denial-of-Service (DoS) attacks, physical attacks on base stations, and protocol attacks on radio access network. However, many experts are working on strengthening all security aspects, closing the backdoors, and stopping all possible breaches. Besides, LTE security protocols are updated regularly to maintain their immunity against existing and new attacks.

Moreover, infrastructure and spectrum sharing between LTE-based PS and LTE commercial networks will provide effective and reliable emergency management systems [17]. This will impact the number of PS practitioners that can be rapidly deployed in tight duration. An economically optimal solution for BB services provisioning in PSNs is to use hybrid PS systems where the services are provided via dedicated and commercial networks [18].

Furthermore, LTE systems are highly scalable since a large number of distributed users can communicate efficiently. They are, also, flexible in terms of cell size; macrocells, microcells, picocells, and femtocells. Moreover, Quality of Service (QoS) concept and priority management inherent in LTE systems are beneficial in PSNs domain as discussed in [19]. As a conclusion, QoS mechanisms applied in the LTE systems are found to be suitable for mission-critical data transfer in PSNs especially during critical operations and congestion times. There is a variety of PPDR services that can be facilitated via LTE systems, including the ones that require IP connectivity between clients and servers which can be efficiently handled by the basic IP connectivity provided by LTE networks. Moreover, many PPDR services can be run over the existing commercial LTE service enablers. For example, Open Mobile Alliance (OMA) push-to-talk (PTT) over cellular (PoC) service provides similar functionality to the one used in PSNs [20].

However, there are a few barriers facing the deployment of LTE-based PSNs. First, LTE systems are not optimized for voice communication as the existing PMR systems. Second, LTE is not reliable and cannot be trusted in mission-critical operations compared to PMR systems [21]. In this regard, 3GPP has been working to enhance LTE services for the PS use. As a result, two main areas are addressed in releases 12, 13, and 14 by 3GPP; Proximity Services (ProSe) and Group Communication System Enabler (GCSE). These services are tailored for PS mission-critical aspect, and will be discussed later in this paper.

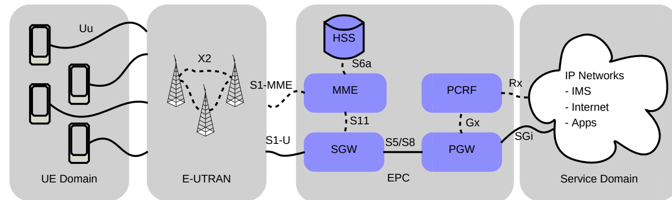

Fig. 1: LTE network architecture.

C. Spectrum Allocation for LTE-Based PSNs

Countries have regulatory bodies that are responsible for allocating available spectrum for commercial and governmental systems including PS systems, such as, FCC in the U.S., ISED in Canada, and OFCOM in UK. Some countries decided to designate spectrum for PS broadband use. The U.S. and Canada designated 20 MHz in the 700 MHz spectrum (also called Band class 14) for public safety broadband use in order to deploy a national interoperable PSN [22], [23]. 10 MHz is allocated for uplink transmissions and the other 10 MHz for downlink communications. South Korea has also allocated 20 MHz in 700 MHz (Band class 28) for its PS LTE Network. However, the rules in North American countries allow commercial traffic to share the PS spectrum on condition that the PS traffic keeps priority and preemption rights.

It is also important to realize that the 700 MHz band has beach-front characteristics [24]. In other words, it has superior propagation characteristics that enable broad coverage with fewer base stations which reduces the cost of deployment. It also ensures a better performance for in-building communications due to its good penetration characteristics.

IV. Toward LTE-Based Public Safety Networks

A. LTE System Architecture

As specified by the 3GPP, an LTE network comprises two major parts; Evolved UMTS (Universal Mobile Telecommunications Service) Terrestrial Radio Access Network (E-UTRAN) and Evolved Packet Core (EPC) [25]. E-UTRAN, the radio access network part, consists of base stations only, each of which is know as evolved NodeB (eNB). This part is responsible of a reliable Radio Frequency (RF) transmission between the LTE network and the User Equipment (UEs). At the data plane, eNBs are responsible for reliable delivery over the RF links, radio interface data encryption, header compression, and integrity protection through the radio protocol stack. At the control plane, eNBs are responsible for the Radio Resource Management (RRM) including admission control, radio bearer control, and scheduling through the Radio Resource Control (RRC) protocol stack.

On the other hand, EPC, the core network part, consists of Serving Gateway (S-GW), Packet Data Network (PDN) gateway (P-GW), Mobile Management Entity (MME), Home Subscriber Server (HSS), and Policy and Charging Rules Function (PCRF) software node. S-GW, the main part of

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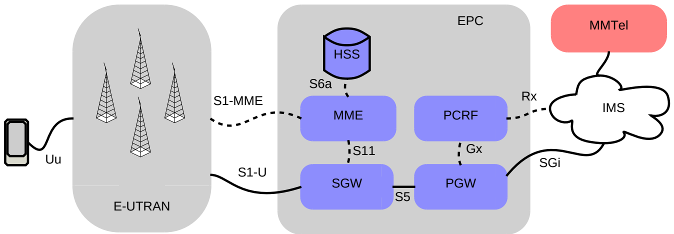

Fig. 2: Voice over LTE (VoLTE) using IP multimedia subsystem telephony service (IMS MMTel).

the EPC, is the anchor point between the E-UTRAN and the EPC. Moreover, it assists interworking with other 3GPP technologies, e.g., GPRS (General Packet Radio Service) or UMTS (Universal Mobile Telecommunications Service) systems. MME is the controlling node that processes signaling between the UE and the EPC. It is also responsible for the session and mobility management at the control plane. P-GW is responsible for providing IP connectivity to the UEs, IP address assignment, connecting the LTE network with other PDNs, and QoS provisioning insurance via the PCRF. Moreover, it assists interworking with non-3GPP technologies like CDMA2000 systems. HSS is responsible for holding users' information including subscriptions, holding information about the PDNs, carrying authentication functions, and assisting mobility management. Figure 1 shows the architecture of LTE networks. In general, an LTE network comprises four domains; service domain, core network (EPC) domain, access network (E-UTRAN) domain, and user equipment (UE) domain.

B. Voice over LTE

In previous generations, such as GSM (Global System for Mobile communication) and UMTS networks, voice is delivered using voice bearers via a circuit-switched (C-S) domain. However, data, like SMS and multimedia, is delivered via a Packet-Switched (P-S) domain using P-S data bearers. On the other hand, LTE networks are completely P-S networks and they have an all-IP flat architecture. Hence, all services, like voice, SMS, data, and video, are carried via P-S bearers. This IP architecture of LTE networks enables the access to different IP multimedia services. As an integration, 3GPP has defined the IP Multimedia Subsystem (IMS), as per 3GPP's TS 23.228 [26], which is an architecture framework to provide IP multimedia services to the mobile users [27]. Voice communication delivery over LTE networks is referred to as Voice over LTE (VoLTE). Three main types for VoLTE implementation are defined [28]; IMS Multimedia Telephony service (MMTel), Circuit-Switched Fallback (CSFB), and VoLTE via Generic Access (VoLGA).

The IMS ensures multimedia service delivery, including voice, with specified end-to-end QoS. Unlike Voice over IP (VoIP) solutions, IMS enables voice delivery with a quality similar to or higher than the C-S voice delivery. This solution is known as IMS VoIP or IMS MMTel. Interestingly, it enables running a few services in parallel with voice delivery. For example, one can add pictures, video clips, real-time video, text messages, or a file transfer to the call. As agreed by many, voice delivery over IMS is the ultimate solution for LTE networks. A simplified architecture of LTE networks supporting IMS MMTel is shown by Figure 2 [29]. In this regard, multiple initiatives, named as "One Voice Initiative" and "GSMA VoLTE Initiative", were launched by 3GPP and GSM Association (GSMA), respectively, and have led to the creation of VoLTE profile in order to set the minimum requirements to unify specifications at all layers and to have an interoperable and continuous service provisioning system through different types of cellular networks.

IMS MMTel service is developed in a way to be accessed from legacy 2G/3G C-S networks. By doing so, interoperability is achieved and service continuity is ensured when an in-call UE move to a legacy 2G/3G location. Depending on the legacy cell, this can be done in two ways: through IMS Centralized Service (ICS) or through Single Radio Voice Call Continuity (SRVCC). In ICS, an LTE based UE that supports IMS MMTel can access the IMS services through the legacy network using C-S bearer when it has no LTE coverage. In SRVCC, when a UE starts a call in an LTE network domain, it connects to the IMS MMTel application server. After that, if that UE moves to a C-S network, the call and the IMS session will be handed to the new C-S network through an interface between the MME in the LTE network and the Mobile switching Center (MSC) server, that supports SRVCC, that controls the host cell. In the single simple approach, IMS MMTel solutions are not sufficient due to the roaming failures (e.g. handovers to cells that do not support LTE nor IMS services) or due to the existence of legacy mobile devices that do not support IMS services and can work only in legacy cellular environments. In this regard, solutions that do not rely on IMS service have emerged like CSFB (Circuit-Switched Fallback) and VoLGA (VoLTE via Generic Access) to provide a seamless VoLTE [30].

CSFB mechanism was, initially, developed in order to connect GSM and UMTS systems with Enhanced Data for Global Evolution (EDGE) and High Speed Packet Access (HSPA) systems, respectively. Keeping in mind that EDGE, HSPA, and LTE cellular Systems are exclusively P-S networks, CSFB was standardized to be used in LTE systems too. In CSFB, when a UE receives or requests a call through an LTE network, the location of the UE is checked. If the UE is covered by a 2G/3G network at that location, a handover request is initiated to hand the UE from the LTE network to the 2G/3G side. And then, the call is carried through a 2G/3G C-S domain. One disadvantage of this method is that the call setup time usually encounters longer delays, 1.5 seconds at least, due to the handover process.

In VoLGA, the P-GW of an LTE network is connected to the existing 2G/3G MSCs through a gateway [31]. The gateway is called VoLGA Access Network Controller (VANC). From the LTE network point of view, the VANC looks like an IP based network or gateway. Also, the P-GW transmits the voice IP packets to the VANC. From the 2G/3G network side, the VANC looks like a UMTS Radio Network Controller (RNC) to a UMTS MSC or like a Base Station Controller (BSC) to a GSM MSC. The main advantage of the VoLGA is that the call setup time is lower than that for the CSFB case and it

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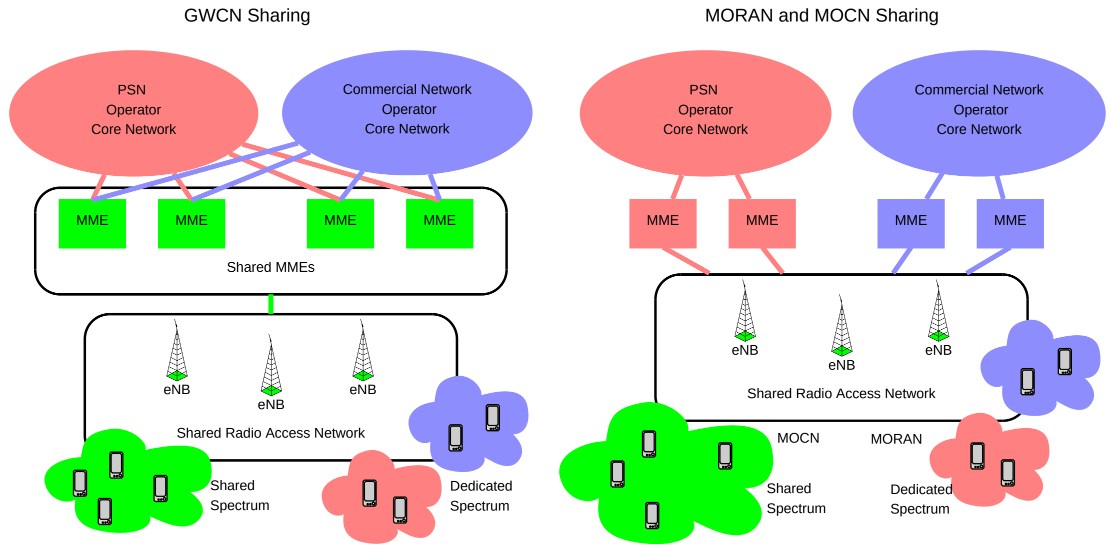

Fig. 3: LTE infrastructure sharing.

is similar to GSM and UMTS networks. Moreover, it enables the C-S services without additional components at the cellular networks side.

C. Evolutionary Approach for LTE-Based PSNs

It is expensive and impractical to switch PSNs to LTE in one step. Instead, an evolutionary approach has to take place. Therefore, many LTE-based PSNs deployment solutions have been considered [17]. The first step is to provide PPDR services through the commercial LTE networks. In this solution, PS operator domain is deployed at the service domain of LTE commercial networks, i.e., as a Mobile Virtual Network Operator (MVNO) [32]. Hence, PS practitioners may access many non-critical BB PPDR services via existing commercial LTE networks. Although this method seems appealing due to the short-time and low-cost deployment, it has many drawbacks. First, QoS capabilities do not meet PS requirements since mission-critical communications mandate more severe QoS (call-setup time, latency, reliability, etc.) with respect to commercial communications [17]. Second, system is vulnerable in terms of security because the network is exposed to unknown devices. Third, not all PS applications can be applied without installing dedicated network functionalities, like direct or group communication. Fourth, commercial networks resources (especially in terms of spectrum) are limited, therefore, they are not reliable to some extent.

The ultimate goal is to have dedicated LTE-based PSNs to provide BB PPDR services. In this case, LTE network infrastructure is owned by the PS operator in all of its parts, i.e. service, core network, and access network domains. This solution is perfectly suitable for PS as the LTE network may be designed accordingly. One of the essential PSNs characteristics is to have the service available nearly everywhere. Hence, a huge number of dedicated eNBs need to be deployed to achieve such goal. However, it requires a lot of time, CAPEX, and OPEX to be deployed with a suitable coverage [33].

As a middle stage, hybrid solutions combining the previous two solutions are suggested for LTE-based PSN deployment. This is accomplished by sharing infrastructure and resources with other Mobile Network Operators (MNOs). There are two ways for infrastructure sharing; passive and active. In passive sharing, radio equipment such as cell sites, power supplies, batteries, and radio steel towers can be shared. In active sharing, the shared entities include radio antennas, wired transport media, controlling entities, and spectrum resources.

In 3GPP specifications, there are three types of LTE radio access network (RAN) active sharing; the Multi-Operator Core Network sharing (MOCN), the Multi-Operator Radio Access Network sharing (MORAN), and the Gateway Core Network sharing (GWCN) [34], [35]. A PSN, in these cases, shares a number of eNBs with the commercial networks, i.e. a part LTE RAN is shared. In MOCN, the radio spectrum is shared, or pooled, between the PS operator and the commercial network operator. However, in MORAN, each operator uses its own dedicated radio frequencies. In GWCN, a part of LTE RAN and several MMEs are shared between the two operators. The radio spectrum in GWCN can be dedicated (as in MORAN) or shared (as in MOCN) between the operators. However, the implementation of GWCN in PSNs is difficult because of the risk of sharing the MMEs which are responsible for UEs authentication and authorization. It is more preferable for PSNs to have their own MMEs. Figure 3 shows the different kinds of sharing between commercial and PS domains.

Infrastructure sharing enables PSNs to be deployed faster than having a dedicated networks with lower costs. Moreover, flexible spectrum and resources sharing is possible depending on the situation. For example, during relief times, when no PS services are needed, more resources may be allocated to the public use. On the other hand, during emergency times, most of the resources can be given to the PS domain. Moreover, this sharing may give PS domain the ability to install dedicated base stations in places that are not covered by the commercial LTE networks, such as borders or uninhabited areas. In order to share infrastructure, very strict policies are needed to be put on place with the commercial operators.

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The transition between different deployment solutions may be smooth. The expected evolutionary approach goes as follows. First, basic BB PPDR services can be delivered without a mission-critical manner by relying completely on the commercial networks (as in MVNO). The second step, is to have LTE RAN and MMEs sharing with the commercial networks (as in GWCN). After that, PSNs shall migrate to share only a part of LTE RAN with the commercial operators (as in MORAN or MOCN). Ideally, the ultimate step would be the separation of PS domain by building dedicated LTE-based PSNs to fully support strict PS requirements and the mission-critical nature of operation. However, very high CAPEX and OPEX are needed to achieve this ideal solution.

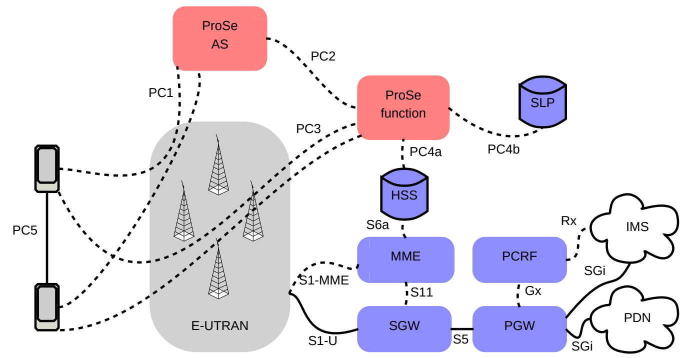

Fig. 4: LTE architecture for proximity services provisioning.

V. Essential Architectures of LTE-Based Public Safety Networks

3GPP has been working on enhancing LTE services for PS usage starting from Release 12. Their end-goal is to build a solid architecture in order to satisfy PSNs demands in terms of communication services, strict quality of communication, resilience and reliability, among others conditions, which were discussed in section II. To do that, they have established a cooperation with organizations, such as TETRA and Critical Communications Association (TCCA), ETSI Technical Committee (TC) TETRA, and US National Institute of Standards and Technology (NIST). In this section, the essential architectures that has to be added to the LTE technology, in order to fit PS demands, are discussed.

A. *LTE Proximity Services (ProSe)*

Proximity Services (ProSe), also known as device-to-device (D2D) communication, is a mechanism by which an LTE UE discovers and communicates with other UEs through a direct communication path, i.e., the user data traffic is not routed through the LTE network [36]. This saves network resources, saves radio resources, and reduces communication latency. Also, it makes the communication possible in out-of-coverage areas.

Since the direct communication between two UEs can be accomplished using a Wireless Local Area Network (WLAN) technology, ProSe role is to establish connections and to ensure service continuity. The direct communication can take place either in licensed (in-band) or unlicensed (out-of-band) spectrum [37]. On the other hand, the LTE mobile network is responsible for resource control and authorization processes.

ProSe services offer many immediate advantages. First, the spectral efficiency is improved since some of cellular frequency channels would be replaced by direct links. Moreover, D2D communication will provide higher data rate transfer with lower end-to-end delays. It also saves energy and enhances radio resource utilization. Moreover, the UEs may not rely on the E-UTRAN coverage to set up calls and can communicate with each other during network outages or when located in out-of-coverage areas.

ProSe framework supports many functions such as direct communication in or out of network coverage, direct discovery, EPC-level discovery, ProSe UE-to-Network relaying, and ProSe UE-to-UE relaying. In direct discovery, the ProSe-enabled UE has the ability to collect information of the surrounding UEs and to communicate with them. In EPC-level discovery, a UE rely on the LTE network to discover its neighbors. In ProSe relaying, a UE can act as a relay between another out-of-coverage UE and the E-UTRAN or between two other UEs. Moreover, ProSe services can be used to support one-to-many type of communication.

The architecture of D2D communication is shown in Figure 4 as defined by [38]. To enable ProSe in an LTE network, a new functional entity, known as the ProSe Function, must be added to the LTE architecture. It provides network services related to the ProSe such as authentication, authorization, and data management. Moreover, a ProSe Application Server (AS) is introduced to manage the connection at the application layer. To support EPC-level discovery, where a UE can discover its neighbors through the EPC, a Secure User Plane (SUP) Location Platform (SLP) is connected with the ProSe function. Also, a new set of interfaces (the PC's in Figure 4) is introduced.

Over PorSe, a UE communicates with another one via PC5 reference point. Two types of discovery are defined over PC5; network-assisted discovery and network-independent discovery. In network-assisted discovery, the EPC is used in order to authorize and generate a UE ProSe identification (ID) for each participating UE. In network-independent discovery, no network assistance is needed to generate UE ProSe IDs. In this case, UEs use predefined IDs.

For instance, WiFi Direct technology can be used at the direct communication links between UEs to create groups in LTE-based PS environments [39]. The LTE network can discover nearby ProSe-enabled UEs and then a WiFi Direct connection can be established between them, without exchanging setup information, using WiFi technology. The LTE network is responsible for group establishment, authentication, authorization, and controlling relevant parameters such as UE ProSe IDs and encryption keys. The signaling framework for communication setup is discussed for both in-coverage and out-of-coverage scenarios. During the in-coverage communication, LTE network will establish and control the communication. If the connection to the network is lost, predefined groups will be established and preconfigured settings will be used to initiate WiFi-Direct communication links.

Also, Software Defined Network (SDN) controllers can be leveraged at the ProSe AS (Application Server) in order

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to enhance group formulation, resource allocation, routing mechanism, and other features of SDN. In [40]. Using ProSe, nearby devices can establish connections among each other using out-of-band technology, like WiFi. After that, a mobile cloud (cloud head) is assigned for each group and is registered at the SDN controller. Each cloud head has a direct connection to the E-UTRAN. Finally, the global SDN controller will have the full picture of the network which enables it to manage the cloud heads and end UEs efficiently. The hierarchical architecture of having cloud heads offers scalability. Also, it enhances the resource utilization by decreasing the communication load with a central SDN controller.

A comprehensive survey of the recent research in D2D communications in LTE-Advanced environment is provided in [41]. ProSe service is a promising technology for making LTE technology extremely useful for PPDR. However, this adds more concerns in terms of security and authorization especially when involved UEs are outside network coverage [42], [43].

B. Access WLANs and Backhaul Connections

In order to take the most advantage of the ProSe in LTE networks, access WLANs (aWLANs) can be used to provide access links for end UEs and to facilitate D2D communication. These aWLANs are connected to the corresponding LTE-based PSN through backhaul links. This architecture enables engineers to combine advancements of WLAN (e.g. ad hoc) and centralized communication systems [41]. Relying on aWLANs and backhaul connections is extremely beneficial for PSNs because aWLANs can be designed to act as isolated networks, i.e. facilitate out-of-coverage communication, whenever backhaul connections are lost due to disasters or to perform operations in remote areas. It also improves communications in terms of latency, throughput, spectral efficiency, and physical network resources. Research is currently active to improve and optimize the architecture and technology of the intended aWLANs.

By leverging aWLANs technologies, relaying in LTE can also be used to establish a robust connection between UEs and the EPC [44]. Therefore, it offers advantages to PSNs in terms of improved coverage and connectivity. For instance, relay nodes can apply a decode-and-forward relaying between UEs and eNBs which are referred to as Donor eNBs (DeNBs). A relay node has two physical network interfaces which establish a backhaul link with a DeNBs and many access links with system UEs. In-band or out-of-band frequencies can be used for the backhaul and access links.

Wireless mesh networking can be utilized to build aWLANs with backhaul connection to eNBs of an LTE system during disaster scenarios [45]. The wireless mesh network can be composed of multiple access points (APs) which provide connectivity to end UEs. In this case, the APs are considered as a backbone for the aWLAN. However, the capacity of the links between the APs is insufficient to handle heavy traffic from end UEs during disasters. Therefore, cooperative communication can be used to improve backbone links capacity where end UEs are able to function as relays between APs.

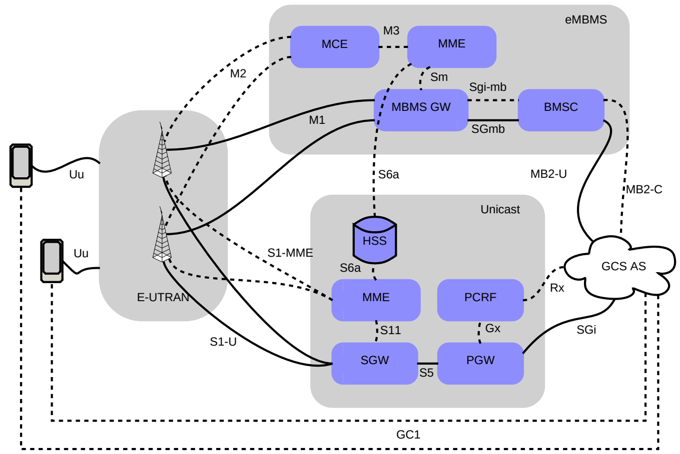

Fig. 5: GCSE architecture: evolved Multimedia Broadcast/Multicast Service (eMBMS) and unicast delivery modes.

WLANs are based on commercial technologies, therefore, they may lack the required resilience and reliability to support PS services. To improve the resilience of aWLANs in PSNs, redundancy should be added either in hardware or software. For instance, [46] studies resilience improvement through data redundancy in aWLANs. They discuss using SDN technology in order to create multipath transmission for PS practitioners during disasters.

It is worth mentioning that the architecture of using aWLANs and backhaul connections is a key enabler for rapid deployment of emergency networks in disastrous scenarios. Various rapid emergency deployment solutions and architectures are studied in section VI-A.

C. Group Communication over LTE

Group Communication (GC) service offers an efficient way to share different types of data content between multiple users simultaneously. This type of communication is paramount for PPDR and must be accessible through PSNs because it is very important in a team work to share different kinds of information among specified groups of users. It is used extensively in LMR technologies such as P.25 and TETRA PSNs. In these networks, the primary use of GC is PTT applications where one group member can talk at a time while other units in the same group have the ability only to listen. When the talking member is finished, other group members can talk. 3GPP has been working to add and enhance GC service in LTE technology to meet the strict demands of PS mission-critical nature. GC service, when supported by LTE technology, opens the door of more complex applications than PTT because it is a broadband technology. 3GPP has defined two major areas to support this kind of service; group communication system enablers for LTE (GCSE) and Mission-Critical Push-To-Talk (MCPTT) over LTE. GCSE and MCPTT are being under development since 3GPP's releases 12 and 13, respectively.

1) Group Communication System Enabler: GCSE focuses on efficient delivery of voice, video, or data among a group of UEs at the same time while they are at RRC (Radio Resource Control) idle mode, so it is supposed to provide

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lower layer functions. Group management functions, such as parallel group communications management, priority and preemption mechanisms, and group creation, change, or deletion, are provided by the application layer residing in the UEs and by the group call system application server (GCS AS) at the LTE network side, as shown Figure 5 [47]. The GCS AS may be owned by parties not related to the network operator.

At the downlink, as defined by 3GPP TS 123.468, there are two mechanisms of delivering GCSE services: unicast delivery and evolved Multimedia Broadcast/Multicast Service (eMBMS) delivery. In unicast delivery, the usual Evolved Packet System (EPS) bearers are used to deliver contents to each UE individually, i.e., a unicast to each regarded UE. On the other hand, in eMBMS delivery, the data is delivered by using MBMS broadcast bearers as a Point-to-Many (P2M) transmission. Usually the eMBMS delivery is used at the downlink, however, unicast delivery is used to ensure service continuity. In other words, downlink may switch back and forth between the two mentioned delivery modes. At the uplink, usual EPS bearers are used in a unicast mode. The GCSE architecture of unicast and eMBMS delivery modes is shown in Figure 5.

To support eMBMS, some functional entities must be installed in the LTE system as shown Figure 5. The broadcast/multicast service center (BMSC) represents the interface between the EPC and the content provider GCS AS. It is responsible for eMBMS service scheduling and is used to initiate the eMBMS broadcast bearer services. The MBMS gateway (MBMS GW) delivers the data content to the intended part of the E-UTRAN; the defined zone where group members are located. Moreover, it provides session control via the MME and assigns multicast IP address. The multi-cell/multicast coordination entity (MCE) is responsible for eMBMS admission control and resource management.

In eMBMS framework, there are two defined mechanisms for content delivery through the E-UTRAN: single cell eMBMS (SC-eMBMS) and single frequency network eMBMs (SFN-eMBMS). In SC-eMBMS, the broadcast signals are transmitted by each regarded eNB independently. However, in SFN-eMBMS, the eNBs are synchronized to transmit the broadcast signals simultaneously, such that the signals received by a UE from multiple eNBs can be combined instead of being an interfering source.

In [48], the performance of the eMBMS delivery system is analyzed in terms of the spectral efficiency. They concluded that the eMBMS may be used efficiently in a metropolitan zone at 700 MHz radio band with a spectral efficiency around 1.5 bps/Hz which is suitable for many PS applications.

Two approaches are suggested to enhance eMBMS activation for PSNs use: static eMBMS activation and dynamic eMBMS activation [49]. In static eMBMS activation, the eMBMS delivery is activated whenever data contents need to be broadcast to a group. However, when a UE, that belongs to the group, suffers from bad channel conditions, a unicast bearer is activated towards that UE. In dynamic eMBMS activation, the eMBMS delivery is activated at an eNB only when the number of the group members at that cell is more than a threshold number. Otherwise, a unicast bearer is activated for each intended UEs in that cell. This mechanism adds more flexibility to the network and prevents inefficient eMBMS broadcast in some cells, hence, the spectral efficiency is enhanced.

In [50], the authors suggest techniques for privacy, group management, priority and preemption, and call set up time enhancement to improve eMBMS so that it can fulfill PPDR requirements. For example, it is suggested that an encryption should be done at the Multicast Control Channel (MCCH) for each eNB that concerns PSNs. This is because information about a PS dispatch in a location can be learned by monitoring this channel.

2) Mission-Critical Push-To-Talk: LTE networks can provide BB service accessibility to the PS practitioners. However, they cannot be used for mission-critical scenarios. Starting from Release 13, the development of MCPTT to meet strict PPDR requirements is being undertaken by 3GPP. In order to achieve interoperability between LTE-based PSNs and legacy PMR networks, MCPTT service must behave exactly like PMR PTT service, at least in the transition phase. This will eliminate any confusion for the PS practitioners.

MCPTT is relying on GCSE and ProSe services and on other techniques provided by the EPS such as priority and preemption. In other words, MCPTT combines many technologies to work under the same shell. For example, a broadcast message using eMBMS bearers may not reach group members outside the network coverage, and there comes the role of ProSe where a UE can act as a relay to deliver the data to nearby out-of-coverage UEs.

VI. Future Challenges and Open Research Areas

Lots of effort are needed to facilitate the migration towards having flexible LTE-based PSNs. Flexibility and dynamicity are very important in building PSNs that are capable of dealing with various disastrous situations. In this section, various aspects of LTE systems that need further customization to upgrade PSNs capabilities are illustrated.

A. Rapid Emergency Networks

In the case of emergency, a part of the E-UTRAN may be damaged and one or more eNBs are expected to malfunction. Moreover, some faults and shortages in the backbone network are expected. Also, a traffic congestion is expected to happen in the parts of the network near the incident. For instance, a major infrastructure and communication loss occurred during the Great East Japan Earthquake in 2011. It was a huge challenge to establish communication even after few days from the disaster [51]. An example of infrastructure loss on a smaller scale is simulated in section VII where simulations show the effect of losing one eNB on UEs' connectivity (in terms of latency, throughput, and packet loss) near the disaster area. Therefore, PSNs must have different solutions to quickly overcome such difficulties. One solution to overcome such difficulties is to have resilience in the network where redundant parts, eNBs, and connections are added. This solution is hectic and not feasible because of the cost, however, it is usually considered at some vital locations in the network. A more practical

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solution is to have rapid deployment to overcome shortages that happen whenever critical failures occur. Through which, movable and deployable resource units (MDRUs) are added to the network in order to restore connectivity and establish a reliable communication networks whenever needed [52]. Other proposed solutions include virtualization of some networks entities, such as EPCs, to reduce the dependency between networks components which promotes flexibility and magability during hardware failures [53]. A disaster relief scenario is also presented through simulations in section VII to show the significance of MDRUs on restoring communication.

Different rapid deployment solutions are discussed in the literature. Usually, new BSs are added to an LTE network in order to enhance the coverage or to increase the capacity of the network at the deployment locations. Due to the necessity of rapid deployment, the capabilities of the deployed BSs can be limited in terms of size, transmission power, lifetime, coverage, and backhaul connections. The deployed BSs are of different architectures, access, and backhauling technologies. In the literature, the following technologies are considered for rapid BSs deployment:

1) Heterogeneous Networks:
An LTE network is called a Heterogeneous network (HetNet) if it comprises different types of base stations (access points), e.g., macrocells, microscells, picocells, and femtocells base stations. This novel technology is based on having small cells by deploying low-power, short-range, and low-cost base stations under the macrocells coverage area. The HetNet aims to bring LTE access points closer to end users in order to enhance the performance in terms of capacity, coverage, and delays. For example, if network capacity enhancement is targeted, the coverage areas provided from small cells may overlap with a macrocell coverage or with the coverage of other small cells. Due to such enhancements, HetNets technology can be considered as a solution to backup or compensate any possible shortage at infrastructure domain [17]. Small cells can be deployed at disaster locations without previous planning to provide coverage or increase the capacity of the system. Also, they can be deployed using wireless backhaul links instead of higher capacity physical backhaul connections.

Emergency base stations should operate at the frequencies assigned to the PS, e.g. Band 14 in North America. However, they can also share a few frequency channels with the commercial macrocells deployed at the same location. To increase the efficiency of the network, different kinds of advanced technologies may be used at a deployed small cell. For example, beamforming technology can be used in order to spatially separate small and macrocells [54]. In the case of frequency sharing, inter-cell interference is the bottleneck of communications. Hence, it is important to use cognitive or network cooperative solutions, such as enhanced intercell interference coordination (eICIC), to overcome this type of interference in small cell deployment [55].

2) Mobile Personal Cells:
Another solution for rapid deployment is to use mobile Small Cells (mSCs), also known as mobile Personal Cells (mPCs) [56]. A group of mPCs can be connected to a macrocell eNB via wireless backhaul links, which results in forming a two-tier mobile HetNet as shown Figure 6. The mPC is a mobile access point that can move from one place to another while maintaining connectivity to a group of end users. They can be placed on trains, buses, or PS vehicles. Hence, mPCs must be connected to the EPC via high-speed wireless links. The deployment of the mPCs is becoming more practical due to the development of New Carrier Type (NCT) technologies, such as millimeter waves, to support the backhaul links. Also, it is possible to use a NCT technology at the access links. mPCs are expected to play a significant role in future PSNs deployment in order to extend coverage, substitute damaged eNBs, improve capacity, reduce delays, and enable reliable communication. They are also capable of coordinating and maintaining local connectivity between multiple end users without going through the core network (EPC). Moreover, more sophisticated mPCs can hold local databases to provide more reliable access to data. However, interference between different links in the HetNets and mobility are challenges that must be studied and dealt with. Hence, interference coordination schemes, mobility management schemes, and upper-layer protocols for dense and highly mobile HetNets must be developed to satisfy PSNs demands.

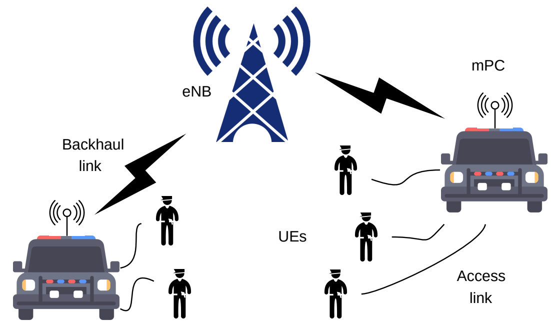

Fig. 6: Mobile personal cells (mPCs).

More complex architectures can be built using mPCs technology to cover more disastrous scenarios. For instance, relaying in mPCs is proposed to enable high capacity communications in out-of-coverage areas [57]. Isolated mPCs (ImPCs), which exist outside macrocells coverage, are connected through relay links to relay mPCs (RmPCs). The RmPCs are connected to eachother via sidehaul links and to macrocells through backhaul links. UEs are able to establish connections to macrocells, RmPCs, and ImPCs. Various frequency bands are used on different links; 2 GHz band at backhaul links, 700 MHz band at sidehaul and relay links, and 3.5 GHz band at UE-to-mPCs access links.

In [58], authors provide a scheme for priority-based user-to-mPC association in LTE-based PSNs. The proposed scheme offers improvement in call blocking probability by load-balancing based on the network load conditions and user priority. Moreover, it reduces the inter-cell interference by using an eICIC scheme. Since mPCs are mobile, the Conventional Static User Association (C-SUA) schemes, [59], cannot be used due to its limited capability for dynamic user-to-mPC association responding to varying load conditions and priority especially in PSNs.

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3) Temporary Cognitive Femtocell Networks:
Another solution is based on the concept of Temporary Cognitive Femtocell Network (TCFN) [60]. The role of TCFN is to support the main LTE network in case of emergencies. A TCFN can exist within, at the edge, or outside the LTE network coverage. Each TCFN contains a cluster head UE (CH-UE) and a group of cluster member UEs (CM-UEs). The CM-UEs can connect to the main LTE network only through the CH-UE. The CH-UE would be similar to any UE but with more computational capabilities and functionality. It manages the communication and is responsible for the local radio resource management. The communication between CM-UEs can happen using D2D links (ProSe). This type of deployment is suitable for PSNs because it enhances the coverage and enables D2D communication.

4) Satellite-Capable Deployables:
Geostationary (GEO) satellite systems can be effectively integrated with terrestrial LTE systems in order to provide global LTE coverage. One solution is to use the satellite systems to provide backhaul connection to Mobile Emergency Operations-control Center (MEOC) which provides LTE access to surrounding UEs [61]. The MEOC carries the EUTRAN and the EPC subsystems in order to provide IP connectivity to LTE-enabled UEs. The MEOC is able to support communications between the surrounding UEs and, if needed, it can route data through satellite connection to grant global IP connectivity. No terrestrial core network is required when few MEOCs are deployed. Furthermore, MEOCs can also be deployed at in-coverage areas in order to densify LTE access points which increases the capacity to accommodate more users and traffic.

Another form for this integration is called Satellite-LTE (S-LTE) [62]. In S-LTE, satellite systems are used to constitute the access links between system UEs and eNBs in out-of-coverage areas. There is no need to deploy MEOCs in this architecture, however, UEs should be satellite-enabled. Another challenge of using S-LTE technology in critical communication and PSNs is the long propagation delays in the satellite communication part [63].

Since terrestrial and satellite environments are different, it is challenging to design suitable communication protocols. For instance, a delay-tolerant TCP (Transmission Control Protocol) is developed in [62] to cope with large propagation delays in S-LTE systems. Also, robust spectrum resource, beam resource, and cross-layer power management schemes are needed to facilitate the integration between terrestrial LTE and satellite systems [64].

5) Aerial Base Stations:
Another promising mechanism for rapid emergency networks is to use aerial eNBs (AeNBs) [65]. Low amplitude platform such as drones (use batteries), aircrafts (use liqued fuel), airships (use light gases), and tethered Helikite (a helium ballon and a kite) could be used to provide network access. Helikites are the most popular due to their low cost, ability to fly in various weather conditions for long time, and low-complex regulations [66]. Helikites are composed of two segments; a terrestrial segment and an aerial segment. The terrestrial segment is installed onto a vehicle and it contains the baseband unit (BBU) of the eNB and an EPC. It also has a satellite system that enables backhauling to LTE networks. The aerial segment (i.e. Helikite) is connected to the terrestrial vehicle by a flying cord and an optical fiber cable. It carries the remote radio head (RRH) and an antenna, therefore, providing dynamic coverage. The European FP7 ABSOLUTE project proved that this architecture provides rapid deployment of low delay and high capacity LTE-based PSNs [67].

The deployed AeNBs can be of different types which are capable of flying at different altitudes. Therefore, they form cells with variable coverage radius. Similar to the concept of HetNets, this architecture is referred to as Aerial-Heterogeneous Networks (AeHetNets) [68]. The AeHetNets are able to satisfy variable and nonuniform user demand dynamically in terms of coverage and capacity. This is due to the fact that dynamic altitude control can potentially expand cell coverage to host UEs on larger ground areas. It also can shrink cell coverage to enable access-point densification in order to increase capacity.

There are many factors to be considered for designing AeNBs which includes air-to-ground channel models, optimal positioning and altitude, backhaul technologies, interference managment, and clustering techniques [66]. More research is needed to address these issues and optimize the deployment process and performance of AeNBs in disaster scenarios. For instance, optimized positioning of unmanned aerial vehicles (UAVs) is considered to improve throughput and coverage during disasters in [69], [70].

B. Spectrum Management in PSNs

Having a wide dedicated bandwidth for the PS is not an efficient solution due to the high fluctuation in the capacity demand from time to another. For example, system capacity needed at relief is much lower than that at disaster times. Therefore, efficient spectrum management schemes must be developed for the future LTE-based PSNs. In North America, 20 MHz of broadband spectrum is designated for PS, but can be shared with commercial traffic in relief time. In UK and Australia, there is no dedicated spectrum; PS traffic would share the same spectrum with commercial one. In both cases, the increasing demand of capacity mandates an efficient use of the spectrum. Spectrum sharing and cognitive solutions, if used effectively, can enhance the spectral efficiency and, therefore, network capacity significantly [71]. Moreover, a well-designed spectrum management scheme will provide a high flexibility to deal with any sudden demand of capacity.

As a complementary for the allocated PS spectrum at the 700 MHz band, FCC has allocated 150 MHz of bandwidth at the 3.5 GHz band under the CBRS (Citizens Broadband Radio Service) band, i.e. under 3550-3700 MHz [72], [73]. However, it is very difficult to perform feasibility studies because all of the currently available PS devices and network components do not operate at the 3.5 GHz band. A frequency-translating LTE repeaters can be used for that purpose [72]. Real experiments show how effective the frequency sharing at the 3.5 GHz can be even with the existence of primary users operating at this band. In their experiment, Motorola's LEX-700 and Rhode & Schwarz's CMW-500 are used as PS

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UEs and eNBs, respectively. Both of these devices have the capability to operate in the 700 MHz band. In order to test frequency sharing at the 3.5 GHz band, frequency-translating repeaters are used to move back and forth between 700 MHz and 3.5 GHz bands. Also, interfering devices are placed near the experiment location to act as primary users. The 150 MHz that is available for sharing is divided into several narrowband channels. Using frequency monitors, the primary user activity is observed. Based on the readings and using some dynamic spectrum access algorithm, the repeaters are tuned to work at an idle band. As a result, PS UEs were able to communicate bidirectionally with eNBs. Moreover, voice and video applications, such as Skype and Youtube, were able to run successfully over the testbed.

Many spectrum sharing models for PPDR have been discussed [74]. These models are put based on the characteristics of network operators that work at a disaster zone. The characteristics of a network operator is described by the type of frequency spectrum (PS or commercial spectrum), the existence of wireless coverage at the disaster zone (covered or not), and the rights-of-use of the spectrum partition. The possible sharing models can be divided into the following categories:

- Dynamic transfer of exclusive rights-of-use: in this model, the rights of spectrum are transferred between PS and commercial operators based on a temporary lease. For example, in a disaster situation, the rights-of-use of a commercial network spectrum are transferred to a PS operator. However, in relief situations, the rights-of-use of PS spectrum may be assigned to a commercial network.
- Coordinated secondary access sharing: unlicensed users (secondary users) are allowed to use the spectrum portions licensed to primary users such that the primary users are not affected by any interference. In this case, primary-secondary coordination schemes are used to manage the secondary usage of the spectrum. For example, a PS operator can make a part or all of his dedicated spectrum available for secondary users at relief times by keeping Quality of Service, priority, and preemption rights.
- Coexistence secondary access sharing: the primary operator has no control or management on the secondary usage of the spectrum. Simply, they coexist with each other using cognitive schemes to discover and exploit the unused spectrum.
- Coordinated collective use of spectrum: in this case, a number of users are allowed to use a shared spectrum that has no exclusive rights-of-use. The shared spectrum may be available for all operators or for authorized operators only. To reduce the interference, common coordination schemes can be used.
- Coexistence collective use of spectrum: similar to the coordinated collective use of spectrum but without using management protocols. Interference is reduced by forcing the devices to follow a regulator-imposed rules, i.e., spectrum etiquette.

Cognitive Radio (CR) technologies can also be leveraged in the PSNs' aWLANs which are discussed in section V-B. Integrating CR into the aWLANs enables the deployed PS entities to reconfigure their radio equipment in order to exploit available spectrum and avoid interference with other existing systems or other deployed aWLANs. It offers several advantages in terms of: 1) QoS support: radio reconfiguration to recover QoS drops, 2) rapid deployment: the plug-and-play nature of CR networks without preconfiguration, 3) robustness: ability to function well in various conditions and environments, and 4) regulation compliance: the ability to comply with spectrum regulation which varies across different countries [75].

Also, frequencies above 6 GHz, including millimeter wave (mmWave) bands, are interesting as they include a significantly more spectrum than current cellular allocation. However, it is very challenging to facilitate the use of such high frequencies in PSNs due to the high isotropic propagation path loss [76]. To overcome such high losses, it is advisable to use directional communication antennas which also represents a challenge in mobile PSNs. In this regard, many areas are open for research such as aerial channel modeling of mmWave communications [77], beam forming and alignment in vehicular networks [78], and low-latency communication [79].

C. Priority Management in PSNs

The standards of LTE technology adopt a priority management mechanism to enable different users or services to receive different levels of treatments [80]. This treatment is described in terms of access priority, resource allocation, and preemption capability. In PSNs, it is important to have a dynamic mechanism or scheme to assign different treatment for different PS practitioners. This is due to the fact that priority assignment should be flexible to vary between relief and disaster times. Also, during disaster scenarios, all PS UEs should not be assigned the same level of priority. For instance, the dispatched UEs and the ones near the disaster location should be getting higher priority. Moreover, having priority management is very important in case of infrastructure or spectrum sharing with commercial or other domains. Some resource allocation schemes are based on the priority assignment of system users similar to the one presented in [81] (which is called priority-based context-aware resource allocation scheme), therefore, it is critical to assign priorities correctly for other management schemes to function optimally.

In LTE, many types of EPS bearers are used to emphasize priority management. An EPS bearer represents the logical channel for the flow of data between the P-GW and a UE. There are two types of EPS bearers; default and dedicated bearers. A default bearer is established whenever a UE is attached to the EPC network. However, at any time, a UE can have zero, one, or several dedicated bearers assigned to it. Dedicated bearers are assigned to a UE when the data traffic between it and the LTE network have higher QoS requirements than that delivered by the default bearer.

A UE can run more than one service at a time, and different services may require same or different QoS. Data packets related to a service are assigned to a dedicated EPS bearer depending on the QoS supported by that bearer. This

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TABLE IV: QCI values and characteristics [4].

QCI	Bearer	Priority	Packet latency	Packet loss	Example
1	GBR	2	100 ms	10^{-2}	VoIP call
2	GBR	4	150 ms	10^{-3}	Video call
3	GBR	3	50 ms	10^{-3}	Online gaming
4	GBR	5	300 ms	10^{-6}	Video streaming
65	GBR	0.7	75 ms	10^{-2}	Mission-Critical PTT voice
66	GBR	2	100 ms	10^{-2}	Non-Mission-Critical PTT voice
5	Non-GBR	1	100 ms	10^{-6}	IMS signaling
6	Non-GBR	6	300 ms	10^{-6}	Video, TCP based services, web, email
7	Non-GBR	7	100 ms	10^{-3}	Voice, video, interactive gaming
8	Non-GBR	8	300 ms	10^{-6}	Video, TCP based services, web, email
9	Non-GBR	9	300 ms	10^{-6}	Video, TCP based services, web, email
69	Non-GBR	0.5	60 ms	10^{-6}	Mission-critical delay sensitive signaling
70	Non-GBR	5.5	200 ms	10^{-6}	Mission-critical data

assignment is done by giving a Traffic Flow Template (TFT) for each packet. In other words, TFTs are used to map data packets to different EPS bearers depending on both the QoS required by the application and the QoS provided by the bearer. If multiple services are running and they require the same QoS, the corresponding data packets will be given the same TFT and will be handled by the same bearer. However, if they have different QoS requirements, data packets will be given different TFTs.

The dedicated EPS bearers can be classified into two categories: Guaranteed Bit Rate (GBR) and non-Guaranteed Bit Rate (non-GBR) bearers. A minimum value of bit rate is guaranteed for the data flow rate through a GBR bearer once the bearer is established. In other words, at the network congestion, the data flow through a GBR bearer will not be lower than the minimum and can preempt other communication links. Also, the data flow bit rate can be limited to a specified Maximum Bit Rate (MBR). On the other hand, in the case of non-GBR bearers, no minimum bit rate is guaranteed, which means that during congestion, some packets may be dropped and that could result in packet loss. Also, the bit rate may be limited to a maximum value using Aggregate Maximum Bit Rate (AMBR). The AMBR can be set at the Access Point Name (APN-AMBR) or at the UE (UE-AMBR).

Whether to assign a GBR or a non-GBR bearer to a service depends on the service type. GBR bearers are usually assigned for services that demand having a stable connectivity once they are established, like video calls. Non-GBR bearers are assigned to services like web surfing and messaging because they do not require a minimum bit rate to be delivered. It must be clear that non-GBR bearers are not of less importance than GBR ones.

Each bearer is defined by two parameters that indicate the QoS it can provide: Allocation and Retention Priority (ARP) and QoS Class Identifier (QCI). The ARP priority level determines the priority for a bearer to be established over other bearers during network congestion when resources are limited. It also contains the bearer's preemption capability (the ability to preempt other bearers) and vulnerability (susceptibility to be preempted by other bearers). A scalar value is assigned for each bearer to hold its ARP priority, from 1 to 15 with 1 as the highest level of priority, and two flags, 0 or 1 each, are set for the preemption capability and vulnerability. Once the bearer is established, its ARP priority level does not play any role in traffic flow. At that point, the data flow (packet) via a bearer must be given a level of treatment, which can be done using the QCI. The QCI tells different entities (e.g. eNBs) in the LTE network how to treat packets, that belongs to different bearers, in terms of bearer type, priority, packet loss rate, and maximum packet delay. Table IV shows the different values and characteristics for the available QCIs. The QCI takes values from 0 to 9 for commercial use and values 65, 66, 69, and 70 for PS use. This table also shows that the QCI values represent various combinations of QoS (packet latency and loss) and priority levels.

In LTE-based PSNs, priority management differs from the one for usual commercial LTE networks. Many factors, such as application, location, time, and situation, play a significant role in determining how the priority management scheme should work. For some factors, static schemes may be used for priority management. For example, a voice or a video call should always be given a higher priority than web surfing or messaging. On the other hand, other factors, such as user type, time, or location, require a highly dynamic priority management schemes. For example, fire-fighters at the location of an incident should be given a higher priority than those located more than 5 Km away. Moreover, the future vision of PS priority management requires having a sophisticated context-awareness schemes. An abstraction of the data coming from many sensors deployed on the PS practitioners or at the field of operation must be provided in order to make such decisions in a proactive manner. To sum all up, a highly

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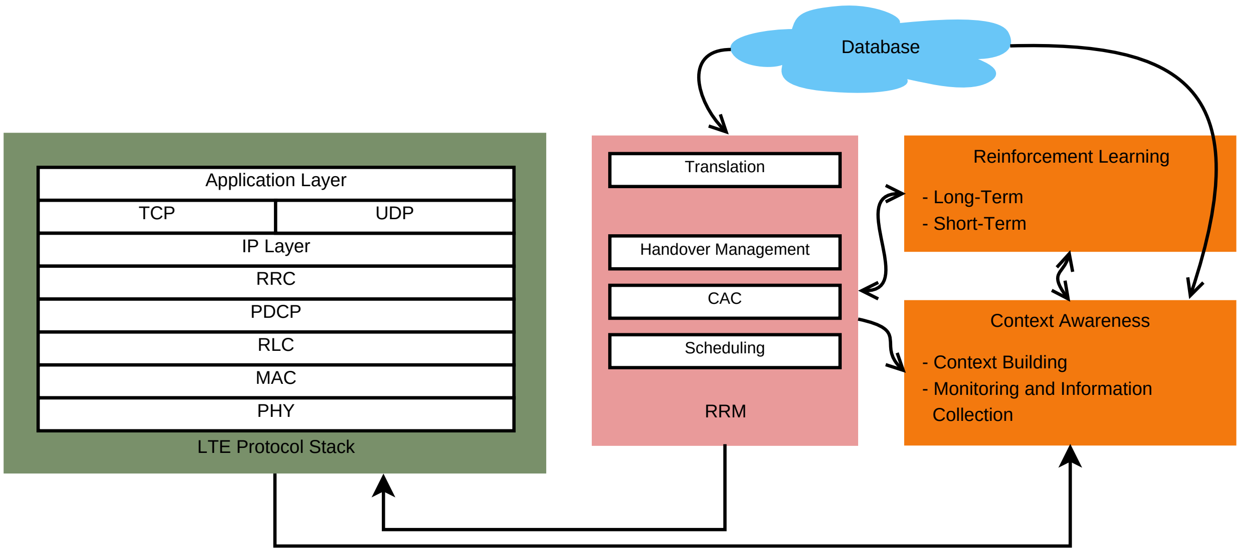

Fig. 7: Dynamic radio resource management (RRM) framework for LTE-based PSNs.

dynamic priority management mechanism must be considered for LTE-based PSNs which is still an open area for research.

The Software Defined Network (SDN) technology is suggested as a key enabler for dynamic priority management in PSNs [82]. In SDNs, network decisions are taken based on a flow basis, and implemented in form of rules. The flow of data is controlled based on policies and rules defined in an SDN controller. Hence, a priority management scheme can be effectively implemented using SDN technology.

D. Radio Resource Management in PSNs

Radio Resource Management (RRM) is important to utilize network resources efficiently. RRM is designed to improve multi-user and multi-cell system capacity and its goal is to maximize spectral efficiency most of the times. The framework of RRM includes bandwidth allocation, scheduling scheme, and call admission control (CAC). Also, it is related to the handover mechanism whether horizontal (to cells of the same network) or vertical (to cells of other networks). In PSNs, RRM must be aware of the context and able to take action intelligently in order to function better under different circumstances.

1) Dynamic RRM Framework:
A possible framework for dynamic RRM operation is suggested in [83]. The studied framework is shown in Figure 7. The framework shows how parameters in the LTE protocol stack are controlled based on some added level of intelligence that relies on context-awareness and reinforcement learning.

The LTE protocol stack includes Physical (PHY), Multiple Access Control (MAC), Radio Link Control (RLC), Packet Data Convergence Protocol (PDCP), Radio Resource Control (RRC), transport, and application layers. Each one of these layers is responsible for many tasks and its work depends on a set of parameters. For example, the value of the Channel Quality Indicator (CQI) parameter controls the modulation and coding scheme (MCS) that is being used at the PHY.

The RRM block includes the basic mechanisms that are used to manage resources between multiple users in the system. The translation block represents the part where the information, that is learned from the context or databases, is translated into useful network parameters that are usable by the RRM. The RRM includes functions related to handover, CAC, and scheduling schemes.

The context awareness block represents network monitoring and information collection. Also, it builds the context and delivers it to other entities in the framework. The context can be built based on the information gathered from the network, databases, and events. For example, in PSNs, the context may include the type of incident, its location, the type of responders needed, their number, and road conditions. It will also include network conditions such as lost infrastructure, expected congestion, and backhaul quality. This building block can be implemented at the E-UTRAN domain.

The reinforcement learning block represents the brain of the framework where the context is studied and actions are taken in order to improve the performance of the network. The long-term learning is used to study the history of the network such as location, usual routes, behavior, routine, and preferences of system users. In our case, system users are the PS first responders. This helps in predicting the traffic generated from PS responders at disaster locations. On the other hand, the short-term learning is concerned with the latest situation of the network such as the actual locations, speeds, and running applications. It may help with handovers or communication loss predictions. The long-term learning has to be implemented in a centralized manner because it studies events that happen across the network. However, short-term learning can be implemented at the E-UTRAN.

2) MAC scheduling scheme:
In commercial LTE network, schedulers are used to maximize throughput of the network or to provide fairness between users. Scheduling algorithms usually are build upon the knowledge of radio and traffic conditions in the network. Best Channel

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Quality Indicator (BCQI) scheduler, Round Robin (RR) scheduler, Proportional Fairness (PF) scheduler, Resource Fairness (RF) scheduler, and Maximum Minimum (MM) scheduler are examples of scheduler implemented in LTE commercial networks. In BCQI scheduler, Resource Blocks (RBs) are assigned to the UEs with the best channel conditions. This scheduler aims to maximize the throughput of the network regardless of fairness. In RR scheduler, the RBs are assigned to active UEs in turns, which improve the fairness without taking throughput into account. As a compromise between the previous two, PF and RF schedulers are being used. PF schedulers work based on utility functions that take CQIs and number of assigned RBs into account. On the other hand, RF schedulers targets the problem of maximizing the sum rate of all UEs while taking the number of assigned RBs into account. MM scheduler, tries to maximize the minimum value of a user throughput, which maximize the fairness between users. Because the goals of PSNs are different from that for commercial ones, these schedulers are expected to fail most of the time if applied to the PS domain.

In [84], a novel scheduling mechanism suitable for PSNs is discussed. The proposed scheme is studied for the case where some UEs have good channel conditions while other UEs suffer from bad channel conditions. This scheme schedules the UEs with weaker channel conditions first. The results show that the proposed scheme offers a better trade-off between throughput and fairness. Also, it has low complexity which is important to have a faster adjustment in PSNs. Finally, the proposed scheme can be efficiently combined with the PF scheduling scheme to serve PS and commercial UEs within the same network.

A dynamic resource management scheme for LTE-based PSNs is discussed in [85]. The scheme considers grouping of BSs into Base Station Groups (BSGs) where each of group contains more than one BS. When a disaster occurs, sudden increase in the demand is expected which, in turn, leads to degradation in performance at the infected locations. By switching off BSGs at areas far away from disaster location and allocating their resources to nearby BSGs, performance degradation in the system can be avoided. In general, more resources can be reallocated to nearby BSGs by switching off more BSGs. If groups comprise many base stations, fewer BSGs can be switched off since some BSGs cannot be switched off. On the other hand, if low number of BSs are grouped, there would be too many BSGs that can be switched off. Based on the results of [85], in the typical disaster situation, having BSGs with a size of 2 base stations performed higher than those with a size of 3 base stations.

3GPP described two mechanisms for resource allocation to be used in D2D communications [86]: scheduled resource allocation and autonomous resource selection. In scheduled resource allocation scheme, an eNB allocates RBs to D2D communicating UEs in the cell coverage range similar to uplink resource allocation schemes. In autonomous resource selection scheme, a pool of RBs is allocated for the uplink band. Communicating UEs autonomously select RBs from that pool. This mechanism can be used by in-coverage and out-of-coverage UEs since no resource allocation is taking place by a cell's eNB. In [87], the autonomous resource selection scheme is analyzed. The studied case assumes that the uplink frequency band is separated between network links (links connecting UEs and the network) and sides links (D2D communications links). Also, it assumes that a UE uses all the available RBs to communicate regardless of the interference. Using this simple spectrum management scheme, simulations show a 3.8 increment in the throughput than the case where no D2D communications were used.

VII. PSNs Simulation Environment

Due to the high cost of running real experiments, especially in cellular networks, research community finds it nearly impossible to run tests over them. Simulation tools are very important to get valid predictions about the performance of deployment scenarios. Moreover, LTE networks are very complicated and one cannot consider all network parameters in mathematical models that are developed as a research work. Simulation and emulation tools offer a chance of testing new designed algorithms in this complex system [88]. For example, a new designed scheduling algorithm can be tested and compared to other algorithms based on mathematical analysis. However, that is not enough because other sides of the whole system may affect scheduling process. Hence, simulation tools are important to validate mathematical analysis of system performance.

Regarding PSNs, some PS disastrous scenarios are very hard and costly to test using hardware LTE equipment. PSNs must perform well in scenarios that are tailored for PS. Many of them are dictated by unusual events and facts such as having a highly irregular distribution of UEs and eNBs, mobile eNBs, high spectrum use, and high data rate demand on both uplink and downlink. To validate the use of LTE technology to support PSNs, we need a simulation environment to evaluate how LTE networks perform in PS scenarios. Therefore, in this section, a simulation environment for LTE-based PSNs will be studied.

The LTE-based PSNs simulation environment was developed using Network Simulator (NS-3) [89], particularly NS-3 LTE-EPC Network Simulator (LENA) module [90]. In the simulation, almost all features of LENA module were exploited and put as end-user inputs through a Python source code. After setting up a simulation environment, the network performance metrics are exported to text files and plotted in PDF files. The next subsections describe the simulation setup and the type of results that one can obtain. The simulation platform has been built in collaboration with the Canadian *Communication Research Centre* and funded by the *Canadian Department of National Defence*. As we are not the only copyright holders, we are unable to release the source code at this point.

A. Simulation Environment Components

1) Physical Topology: In the simulation, users have two options for setting up the topology. The first one is based on the usual hexagonal topology. After setting up the number of eNBs and UEs and defining the distance between neighboring

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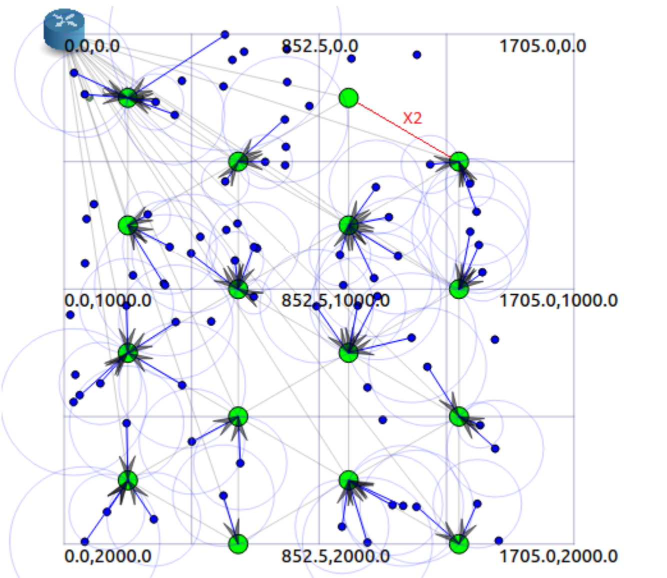

Fig. 8: An LTE network displayed using NetAnim. The Network consists of nine eNBs with 500 m spacing and twenty UEs, where the EPC core network is represented by the blue switch, the eNBs are represented by the green big circles, and the UEs are represented by the blue small circles.

eNBs, a hexagonal cellular network is created where UEs are, initially, distributed on a defined area based on Poisson distribution. In the second option, the number, location, antenna radio pattern, and mobility pattern of eNBs and UEs can be defined. This option can be used to simulate a very detailed scenario. Figure 8 shows an example of an LTE network built using the LENA module and displayed using the Network Animator (NetAnim) software package.

2) Mobility Model: Gauss-Markov mobility model (GMMM) is used here to characterize UEs trajectory. GMMM is a simple memory-based model that is based on tuning parameters that determine the amount of memory and randomness in the movement of a node [91]. For more realistic deployment scenarios, UEs trajectory can be tied to real maps using Simulation of Urban Mobility (SUMO) software package. SUMO is a free, open-source software used to generate, handle, and simulate traffic in roads of real world maps [92]. The mobility trace files generated by SUMO can be imported into NS-3 mobility models.

3) System Bandwidth: Different carrier frequencies can be considered in the simulation environment. The allocated spectrum determines the number of RBs in the system, therefore, it affects scheduling delays, transmission rates, and aggregate throughput for the whole system. In LTE networks, each RB is defined as a 200 KHz of spectrum; 180 KHz for use plus 20 KHz as a guardband. In our example of PSNs, band class 14, that is allocated for PS use in North America, is considered. 10 MHz for the uplink and another for the downlink are allocated, in other words, there are 50 RBs for each direction. In the simulation environment, the user can assign the bandwidth of each link separately.

4) Modulation and Coding Scheme: Adaptive modulation and coding (AMC) is used in LENA module. AMC causes the channel capacity to vary based on its quality. In AMC, the channel quality is measured in terms of a channel quality indicator (CQI). The CQI is mapped to a proper modulation and coding scheme (MCS). If the channel is good, a higher MCS is chosen which results in a higher channel spectral efficiency. CQI is also a very important factor in scheduling schemes. The AMC model that is used in the simulation is discussed in [93]. The mapping table from CQI to MCS is also provided there.

5) Path Loss model: The path loss model used in the simulation environment is based on the Three Log Distance Propagation Loss Model [94]. In this model, three regions for path loss calculation are defined. Moreover, log-normal shadowing is taken into account where shadowing is modeled as a log-normal distribution. In the simulation environment, we used the following as a default setup. The three regions extend from the transmitter to 400 m, from 400 m to 900 m, and from 900 m to infinity. Path loss exponents of 2, 3, and 4 are considered through these regions, respectively. To consider the shadowing effect, a zero mean Gaussian random variable is added to the deterministic path loss model (in decibels). The standard deviation of this random variable is assumed to be 8 dB in the simulation.

6) Small-Scale Fading: In the simulation, Rayleigh fading channels are considered. Fading traces are generated using a Matlab script (fading_trace_generator.m) that comes with NS-3 LENA module. Many parameters describing the environment, such as frequency band, number of multipath components, and mobility speed, are passed to the generator.

7) Transmission Mode: Depending on the number and functionality of antennas that each UE has, three NS-3's transmission modes (TMs) are considered here. TM_1 represents the single-input-single-output (SISO) case. In TM_2 and TM_3, a 2×2 multiple-input-multiple-output (MIMO) is used. In TM_2, MIMO is used as an open-loop transmit diversity, where in TM_3, it is used as an open-loop spatial multiplexing [95].

8) Handover Algorithm: The handover process mandates the existence of X2 interfaces between eNBs. This interface carries a handover request, procedure, and acknowledgment. In the simulation, X2 interfaces are created between each eNB and its neighbors as shown by Figure 8 in red. Control messages are transmitted over this interface whenever a handover is needed or some control messages are needed to be exchanged. There are many handover algorithms that can be used in cellular systems. Usually, handover algorithms are based on the Reference Signal Received Quality (RSRQ) [96]. Two handover schemes can be used in LENA module; A2-A4-RSRQ or A3-RSRQ.

9) MAC scheduler: According to the information available from radio channel conditions, RLC layer, and QoS policies, the implemented MAC scheduler assigns bandwidth resources (or RBs) to active UEs. Generally, scheduling schemes are meant to optimize the performance of the network in a sense, e.g., to maximize fairness. Moreover, scheduling procedure is carried periodically in order to adapt to the continuous variation in the network environment. In the simulation, the user can

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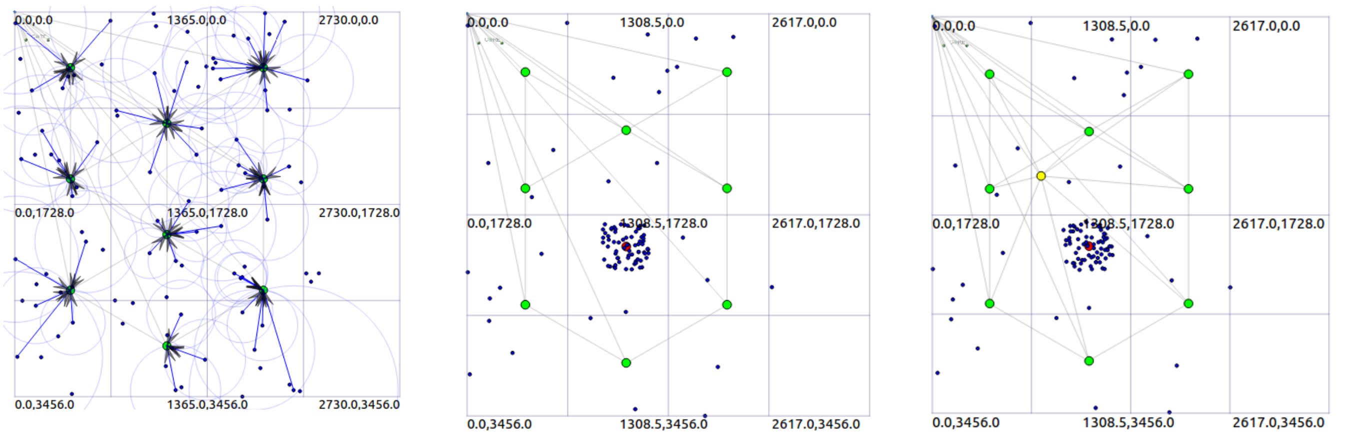

(a) Relief scenario. (b) Disaster scenario. (c) Disaster relief scenario.

Fig. 9: Studied Cases; eNBs, mobile eNBs, Lost eNBs, and UEs are represented by green, yellow, red, and blue dots, respectively. In (a), users are uniformly distributed and all eNBs are active. In (b), one eNB is lost and the majority of users are placed near it. In (c), a mobile eNB is approaching to replace the lost eNB in the middle of a disaster.

choose a MAC scheduler from the following set: Proportional Fair (PF), Round Robin (RR), Frequency Domain Maximum Throughput (FDMT), Time Domain Maximum Throughput (TDMT), Throughput to Average (TTA), FD-Blind Average Throughput (FDBAT), TD-Blind Average Throughput (TD-BAT), FD-Token Bank Fair Queue (FDTBFQ), TD-Token Bank Fair Queue (TDTBFQ), Priority Set Schedule (PSS), and Channel and QoS Aware Schedule (CQA) MAC schedulers [97]–[100].

10) Frequency Reuse Algorithm: In order to handle the Inter-Cell Interference (ICI), RBs reuse must be organized through a frequency reuse scheme. Many fractional frequency reuse algorithms are suggested to reduce the ICI [101]. In the proposed simulation, the default is to use a frequency reuse factor of one such that all RBs are used in each cell. However, the user can choose another reuse schemes. LENA module supports a frequency reuse factor of three alongside with one of the following frequency reuse schemes: Hard Frequency Reuse, Strict Frequency Reuse, Soft Frequency Reuse, Soft Fractional Frequency Reuse, Enhanced Fractional Frequency Reuse (EFFR), and Distributed Fractional Frequency Reuse [101]–[103].

11) Application Setup and Flow Monitor: In the simulation environment, communication takes place bidirectionally between a remote host that is connected directly to the P-GW and all UEs in the network simultaneously. To activate the uplinks and downlinks, EPS bearers must be defined for each data flow. All the flows in the simulated network are carried on the same type of EPS bearers as a default setup, however, different bearers can be considered. In other words, all traffic flows from and to all the UEs have the same QoS and priority. The user can choose between two types of applications; User Datagram Protocol (UDP) and Transmission Control Protocol (TCP) applications. Flow Monitor, a network monitoring framework for NS-3, is also used to obtain statistics about each data flow in the network [104].

12) Tracing: The performance of the LTE network and each UE in the system can be realized by enabling PHY, MAC, RLC, PDCP traces. During the simulation, trace files are generated from NS-3. These files contain information about Protocol Data Unit (PDU) delays, Signal-to-Noise Ratio (SNR), number of transmitted bytes, number of received bytes, etc. During the simulation, these files are used to print out the throughput for each UE, aggregate network throughput, and spectral efficiency at both uplink and downlink. At the end of simulation, the average and maximum throughput and delay for each UE is calculated, viewed, and saved to new text files.

B. Results

In this section, the performance of LTE-based PSNs in some disaster scenarios will be evaluated. First, we describe the topology of the tested network with all parameters settings of the network. Second, we describe the tested scenarios. Finally, we show how the performance of the network may change at disaster times.

1) Network Setup:

The studied PSN topology contains 9 eNBs arranged in a hexagonal grid, where the distance between any two neighboring eNBs is 1 Km. Isotropic antennas with a height of 3 m are used in the simulation. eNBs transmit their signals with a power of 30 dBm. The carrier frequency is located at class 14 band. 10 MHz of bandwidth is available for uplink and another one for downlink. Path loss and small-scale fading models are setup as discussed in sections VII-A5 and VII-A6. Finally, the PS server is connected with the P-GW directly through a high performance point-to-point link.

2) UEs Setup:

The tested scenarios contain 100 UEs. The distribution of these UEs vary depending on the scenario. For example, in a relief scenario, UEs would be uniformly distributed over the network coverage. But, in case of a disaster scenario, most of UEs (70%) would be located around the same area (presumably a 400×400 m^2). Regarding the mobility, UEs

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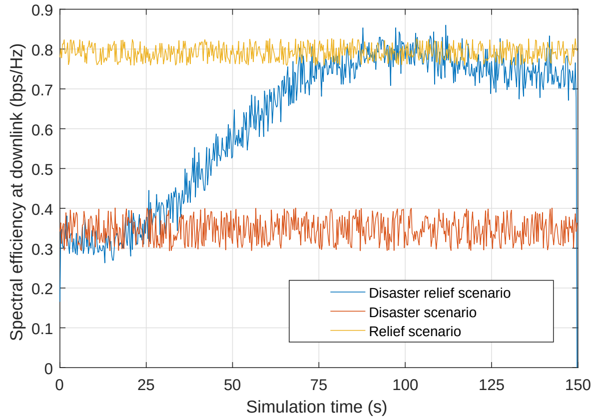

Fig. 10: Downlink spectral efficiency change through simulation time.

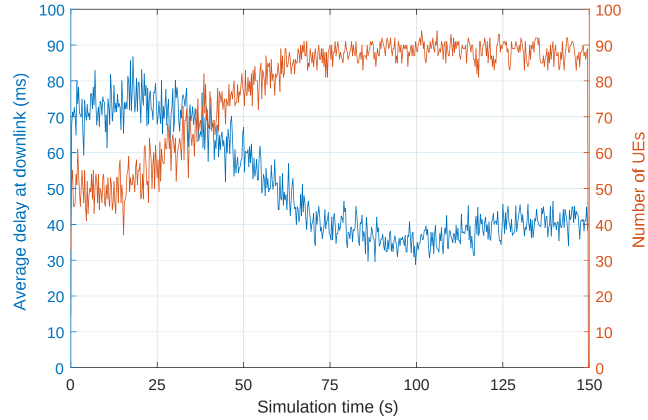

Fig. 11: Number of UEs that communicate successfully at the downlink and average delay through simulation time of the disaster relief scenario.

are set with a speed of 40 Kmph as discussed in VII-A2. Moreover, we assume that all UEs use TM_3 to communicate with eNBs. Lastly, closed-loop power control is used on the uplink.

3) Application Setup:

In the studied scenario, UDP uplink and downlink applications are installed at each UE to communicate with the PS server at the EPC side. We assume that each application generates 100 Kbps to be transferred over the network. We also assume that the generated traffic is carried over the same type of radio bearer. The results in this section are presented only for the downlink, however, a similar trend can be observed at the uplink.

To show how the network performance will be affected at disaster scenarios, we run the simulation for three cases. Scenarios correspond to NPSTC use cases Incident 1 and 2 []. In the first case (relief scenario), the 9 eNBs are functioning well and all UEs are uniformly distributed over the network grid. In the second case (disaster scenario), we assume that one eNB is lost during the disaster and 70% of the UEs are located within an area of 400×400 m^2 around the lost eNB. In the third case (disaster relief scenario), we assume that a mobile eNB moves to relief the disastrous situation. Figure 9 shows the three studied scenarios.

The studied scenarios are compared in terms of spectral efficiency, number of UEs with connectivity, and delay. Figure 10 shows how the spectral efficiency changes through the simulation time for different scenarios. This figure shows how a disaster could affect the network performance. It is also shown that the performance is significantly enhanced as the mobile eNB approaches the disaster location. The spectral efficiency has low values even at the relief case because the number of UEs and the application bit rate (100 kbps) is not high enough to utilize the available spectrum completely. The average spectral efficiency reaches 6 bps/Hz when the network is fully utilized. Figure 11 shows the downlink average delay and number of UEs that can successfully communicate with the remote host at the downlink through the simulation time for the disaster relief scenario described in Figure 9c. As the mobile eNB approaches the disaster location, more UEs can successfully communicate with lower delays.

Another studied scenario is to combine all events (relief, disaster, and disaster relief) in one simulation environment. At start, all UEs are randomly distributed on the area of the network. After 1 minute, a disaster happens and one eNB is lost as in Figure 9b. Also 70% of PS users start moving to that location with a speed of 80 Kmph, while running a downlink application of 1 Mbps. At minute 5 of simulation, a disaster relief is started and a mobile eNB is sent to replace the lost eNB similar to 9c. The network setup is the same as discussed earlier, but in this scenario, the distance between adjacent eNBs is increased to 2 Km, so that better visualization can be obtained. Figure 12 shows the results obtained from running this scenario. At the beginning, the spectral efficiency is high, all UEs are connected, and the delay is low. When the eNB is lost and 70 UEs start moving toward the lost eNB, UEs start losing connectivity, the spectral efficiency goes down, and delay gets higher. When the 70 UEs arrive at the disaster zone, they all lose connectivity because they cannot connect to eNBs because of the long distance between eNBs in the network topology. The mobile eNB is sent at second 300 as a relief. When the mobile eNB starts approaching the disaster location (second 450), the 70 UEs start connecting, but with high delays due to the handshaking between disconnected UEs and the mobile eNB. After some time, the network recovers its previous performance.

VIII. Conclusion

The stringent requirements of PPDR voice services are met by the legacy PSNs which are based on LMR technologies. However, due to their limitations in supporting broadband services, the need for migration toward new technologies has emerged. Due to the current massive advancement in LTE technologies, it is considered as a very promising candidate to serve the striving, tightly-constrained needs of PSNs. However, LTE networks are not capable of supporting various PS services to meet their strict requirements. Therefore, extensive

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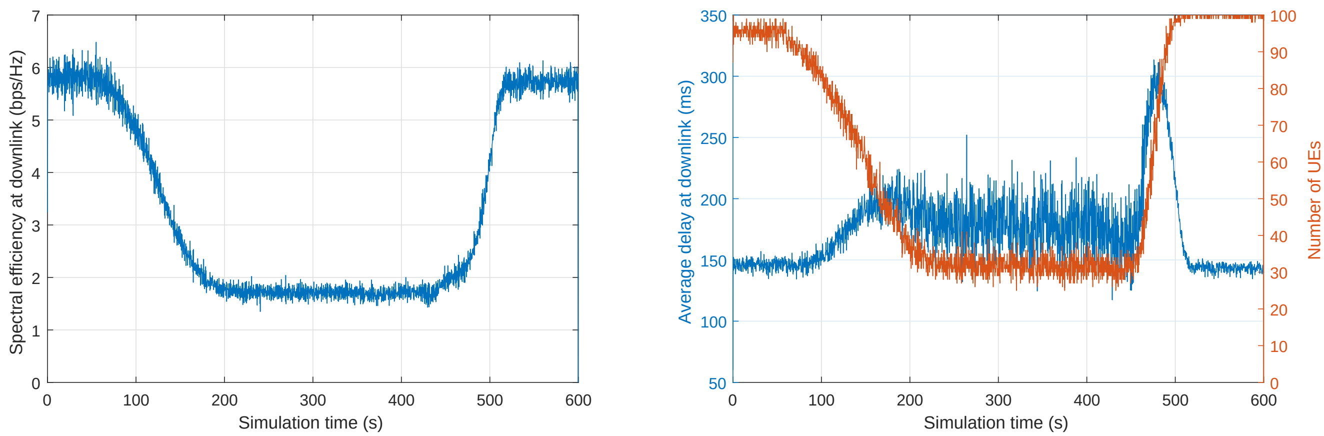

(a) Downlink spectral efficiency

(b) Number of connected UEs and average delay

Fig. 12: Simulation results of a scenario where relief, disaster, and disaster relief are combined. Simulation results at the uplink show a similar trend.

efforts have to be exerted from research community and regulating organizations. This work provided a comprehensive survey of LTE-based mission-critical networks and up-to-date literature review of exerted efforts to enable such networks.

This paper has discussed the legacy PSNs and their limitations before pointing to the potentials that LTE technologies offer to future PSNs. Since, it is critical to study the regulated spectrum allocation for PS in the planning and development phase of LTE-based PSNs, we have highlighted the potential spectrum issues and its regulations. Due to the difficulty of building dedicated LTE-based PSNs, an evolutionary approach is needed to facilitate this migration. One key element to do that is to share hardware equipment and spectrum with commercial LTE networks which can be done in many ways, such as CWCN, MORAN, and MOCN sharing.

Many functional entities must be added to LTE systems for them to be able to support various PS services. LTE technology can be tailored for PS by capitalizing on LTE proximity services (ProSe) and Group Communication over LTE (GC) standardized architectures. Many architectures existing in literature can be also considered in PSNs such as the use of access WLANs and backhaul connections which facilitate many operations in out-of-coverage or disaster areas.

To develop optimized and efficient LTE-based PSNs, well designed schemes regarding rapid emergency deployment, spectrum management, priority management, and radio resource management must be put. These aspects were discussed in this paper and the light is shed on some future research challenges. Finally, in order to be able to test the designed protocols and architectures, a reliable simulation environment must be developed. The importance of simulations arises due to the high cost and time of running tests on LTE networks for preliminary evaluations. NS-3 has been used to design the simulation framework presented in the paper. Also, performance of LTE networks was studied in terms of throughput, spectral efficiency, and packet delay in various relief and disaster scenarios. A disaster recovery scenario was also presented to show the effect of having mobile base stations in restoring communications.

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