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Review Article

LMR and LTE for Public Safety in 700 MHz Spectrum

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This paper presents a concise overview of current public safety communication networks known as LMR (Land Mobile Radio) and emerging LTE- (Long-Term Evolution-) based broadband public safety networks to be deployed in the 700 MHz band. A broadband nationwide network for public safety based on LTE is inevitable where shared or dedicated types of LTE-based public safety networks are possible. Current LTE services do not meet mission-critical requirements and several enhancements have been defined by 3GPP to address this in Releases 12 and 13. First responders are familiar with LMR and consider it to be a reliable technology with massive deployment everywhere. Therefore, it is expected that LMR will continue to exist alongside any new LTE-based broadband public safety network. Recent LTE releases (particularly Release 15) addressed the LMR-LTE interoperability issue and described comprehensive interworking facilities. New and upcoming features and services of LTE in Releases 14 and 15, such as mission-critical data, mission-critical video, and aerial user equipments, are also directly applicable to public safety. The paper endeavours to provide a quick yet meaningful review of all these issues. It also offers a look ahead at the new and rapidly advancing virtualization technologies, such as software-defined radio access network, and radio access network slicing, as enablers for future public safety networks.

1. Introduction

Public safety organizations have the responsibility to protect people's lives in natural and man-made disasters as well as in emergency situations. Such organizations include law enforcement agencies, emergency medical services, and fire departments; they are the first to arrive on the scene of emergency and are commonly referred to as *first responders*. The ability of first responders to flawlessly communicate among themselves and to access as well as share critical information in timely fashion influences their ability to save lives [1].

Public safety networks are perceived as mission-critical. They are required to be dependable, resilient, and secure, while satisfying other strict requirements concerning network coverage, system accessibility, and end-to-end performance. These crucial operational demands are the primary drivers for the design and engineering of the "*public safety grade*" network. Basic services provided by public safety networks include functionalities such as push-to-talk, group call, direct call, and dispatch services, which differentiate public safety services from typical user services over commercial networks [2].

The safety of public as well as the first responder personnel is based on the first responder's immediate access to reliable voice communications. *Push-to-Talk* (PTT) provides near instant call setup by allowing half-duplex communications between first responders, using a push button to instantaneously switch from voice reception mode to transmission mode. *Direct call* for off-network (or infrastructure-less) peer-to-peer communications, i.e., voice communications directly between two radio devices, must be provided in all operational environments. A *group call* entails the communication of speech to all group members. The permission to speak is administered by a dispatcher. *Dispatch services* consist of personnel with supervisory authority who manage and coordinate the activities of the first responders.

The mission-critical aspect of public safety communications places unique demands on the underlying radio technologies. When a first responder needs to use the PTT service and presses the button on their radio device to request to talk, they must have the confidence that their voice communication will be successful with very high probability. In an emergency situation when the network may be congested, their call must go through anyway or lives may be lost.

Due to longer propagation distances, the 700 MHz band is an attractive option to build systems for public safety networks. For public safety, 20 MHz of dedicated spectrum is available for broadband while 12 MHz is available for narrowband communications in the 700 MHz band. *Land Mobile Radio* (LMR) communication systems for public safety are typically voice-centric narrowband systems. They operate in either the UHF, VHF, 700 MHz, or 800 MHz and 12.5 kHz is the standard bandwidth. *Long-Term Evolution* (LTE) is a widely deployed broadband technology offering high-data rate applications currently not supported in LMR.

Local public safety agencies in the U.S. have the flexibility to design and run their own public safety communication networks. Failures due to lack of interoperability between these disparate systems is considered a major problem for public safety. For example, interoperability issues on site after shooting at Columbine High School in 1999 forced first responders from different public safety agencies to use runners to carry written messages from one agency's command center to another, which greatly impacted their reaction time. Public safety networks also suffer from scalability issues such as holes in coverage, which affects their ability to always meet the mission-critical standards [3]. Hence arises the need for a single nationwide wireless communication network for all public safety agencies. Such a public safety network can be either based on sharing an existing nationwide commercial LTE network via upcoming technologies like radio access network slicing or can be a completely separate nationwide wireless network dedicated for public safety agencies such as FirstNet. FirstNet will be the first LTE-based dedicated nationwide public safety network in the U.S. that will operate in the 700 MHz spectrum.

As public safety embraces LTE, LMR features like direct call, group call, and PTT will need to be replicated onto LTE. Although LTE already provides services like PTT over cellular, over-the-top PTT, push-to-video, and push-to-x, these services do not meet the requirements of the mission-critical public safety radio users. To address public safety applications, 3GPP has defined several LTE enhancements in Releases 12 and 13 like proximity services, group communication system enablers, and mission-critical PTT. It may take several years for the transition from LMR to LTE. In the meantime, public safety agencies will most likely be using a mix of LMR and LTE networks, and effective interoperability solutions for these systems will be required.

3GPP has defined additional mission-critical services like mission-critical data and mission-critical video in Release 14. In addition to evaluating further mission-critical related topics like interworking between LTE and LMR for voice and data in Release 15, 3GPP is also investigating LTE's capability to provide connectivity to unmanned aerial vehicles as aerial user equipments (UEs), which could be vital to using unmanned aerial vehicles for public safety operations. Unmanned aerial vehicles are also being considered for deployment as aerial base stations in LTE-based networks to restore critical communications during disasters. Enabling technologies like software-defined networking, network functions virtualization, software-defined radio access network, and radio access network slicing will also play an important role in shaping future public safety networks. *The contribution of this work includes presenting a brief overview of 700 MHz spectrum, LMR, and LTE in relation to public safety communications; exploring shared and dedicated type of LTE-based public safety networks; highlighting existing non-mission-critical public safety services over LTE as well as mission-critical enhancements to LTE such as device-to-device communications (or proximity services), group communication system enablers, and mission-critical PTT; discussing coexistence of LMR and LTE and examining solutions for their interoperation; highlighting new and upcoming features and services of LTE directly applicable to public safety such as mission-critical data, mission-critical video, and unmanned aerial vehicles as aerial UEs; and providing a look ahead at the emerging virtualization technologies, such as software-defined radio access network, and radio access network slicing, as enablers for future public safety networks.*

An overview of legacy and emerging public safety communication technologies is presented in [1]. Introduction of novel capabilities in LTE for public safety has been discussed in [2]. Policies leading to present day public safety communication systems, alternative directions for the future, and steps toward a more effective policy are highlighted in [3]. Suitability of LTE for mobile broadband public safety services is examined in [4]. Public safety use cases are described in [5] along with current status of related activities in 3GPP standards, and future challenges in public safety. Legacy public safety networks and their limitations, potential of LTE for future public safety networks, and rapid emergency deployment in LTE-based public safety networks are surveyed in [6] along with some future research challenges.

A high-level discussion of LMR, LTE, and Voice over LTE (VoLTE) is provided in [7] along with recommendations for possible FirstNet architectures. Operational contexts and requirements of public safety organizations, different wireless communication technologies used by public safety organizations, technology standards and regulatory frameworks governing public safety organizations, and potential evolution of communication technologies in the public safety domain are discussed in [8]. Some aspects related to public safety communications that are reviewed in this paper that have not been explored in [1–8] include existing non-mission-critical public safety services over LTE including over-the-top push-to-talk, push-to-video, and push-to-x; LMR-LTE interoperability solutions for public safety including interworking function, inter-RF subsystem interface, and radio over IP; current research issues including mission-critical data, mission-critical video, and use of unmanned aerial vehicles as aerial LTE UEs for public safety operations; and enabling technologies for future public safety networks including software-defined radio access network, and radio access network slicing.

The rest of the paper is organized as follows. A brief overview of 700 MHz radio spectrum, LMR, and LTE in

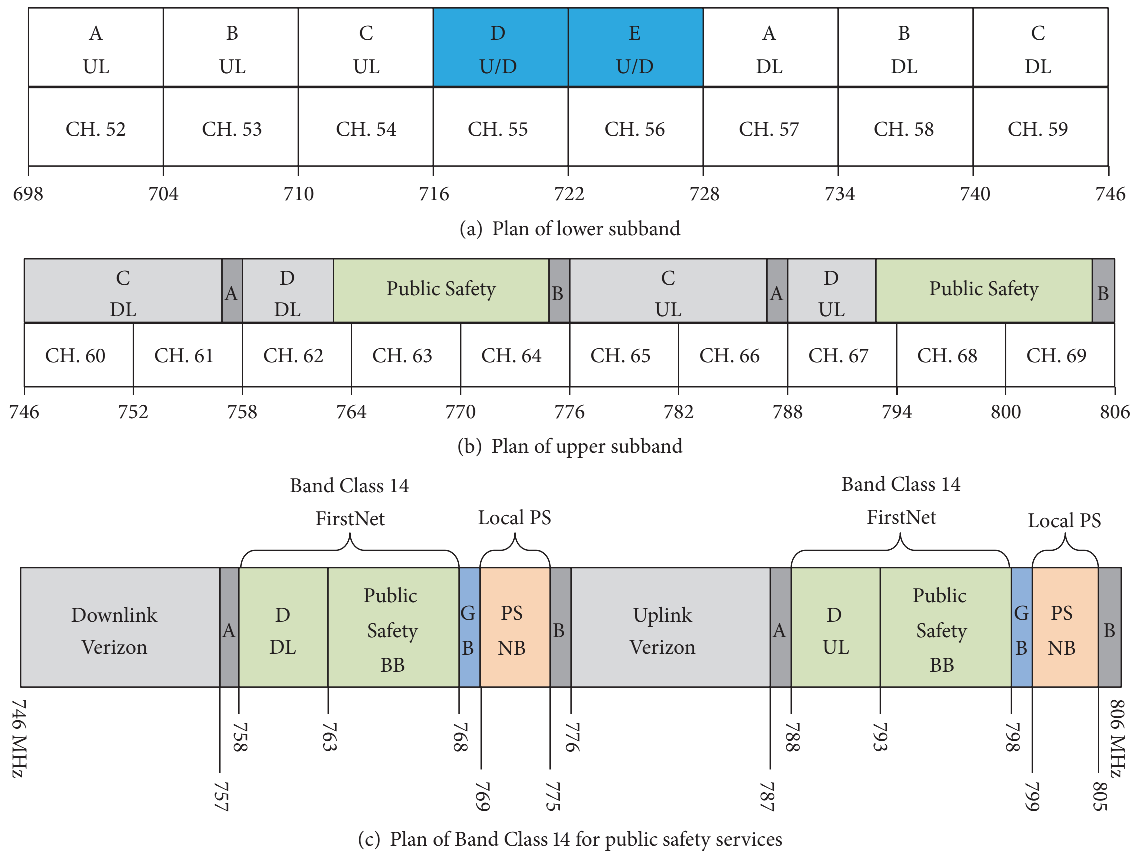


Figure 1: 700 MHz spectrum.

perspective of public safety communications is provided in Sections 2, 3, and 4, respectively. Section 5 discusses shared and dedicated type of LTE-based networks for public safety. The existing non-mission-critical public safety services over LTE are briefly described in Section 6. Section 7 gives details of LTE enhancements for mission-critical services while LMR-LTE interoperability solutions are discussed in Section 8. Section 9 presents current research issues and Section 10 highlights enabling technologies for future public safety networks. The conclusions are summarized in Section 11.

2. 700 MHz Spectrum for Public Safety

Wireless signals in the 700 MHz band have good propagation characteristics, which makes this band an attractive option to build wireless systems for commercial as well as public safety networks. The 700 MHz band is made up of two subbands: the lower 700 MHz subband and the upper 700 MHz subband. Figures 1(a) and 1(b) illustrate the spectrum allocation, uplink (UL) and downlink (DL) frequency, and band gap for these subbands. In Band Class 14 in the U.S., 20 MHz of dedicated spectrum in the 700 MHz band is allocated for public safety as illustrated in Figure 1(c). This broadband (BB) spectrum, highlighted using green colored blocks, is intended for an LTE-based public safety network. The D block will be reassigned for utilization by Public Safety BB. Consequently, 10 MHz will be available for downlink and 10 MHz will be available for uplink for Public Safety BB in Band Class 14. Narrowband (NB) spectrum, shown in orange colored blocks, is designated for narrowband public safety networks, such as LMR systems for voice communication. To prevent any interference, guard bands (GBs) of 1 MHz are positioned between narrowband, broadband, and commercial spectrum [1].

3. LMR for Public Safety

LMR is a wireless communication system meant for terrestrial users operating portable or mobile radio units like two-way digital radios or walkie-talkies. Public safety LMR systems are typically voice-centric and are purposely built to support individual and group communications. In a traditional LMR network configuration, shown in Figure 2, the first responders are connected to dispatch services and to each other via trunked radio access points or repeaters.

LMR started as a mechanism for sending analog voice notifications from an AM base station to a mobile radio receiver and quickly transformed into a two-way FM system. During the next major development that came under the Association of Public-Safety Communications Officials (APCO) International's Project 25 (P25) [9], LMR shifted to digital (or analog) radios, which could operate in 12.5 kHz channels on either the VHF, UHF, 700 MHz, or 800 MHz

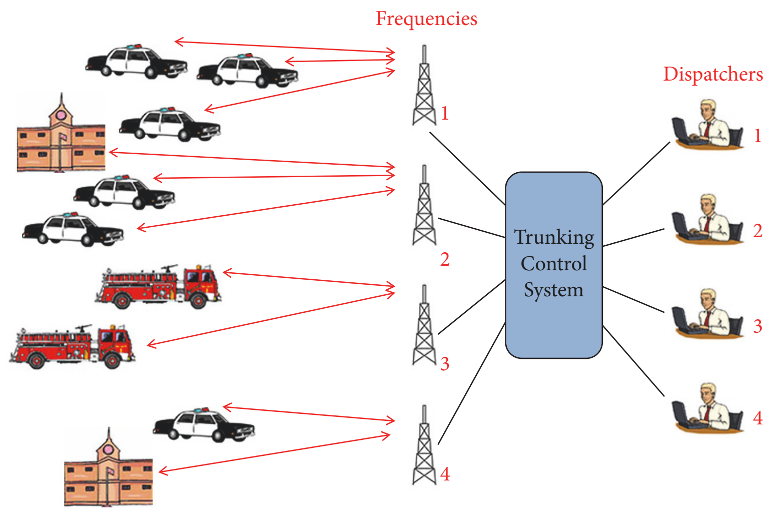
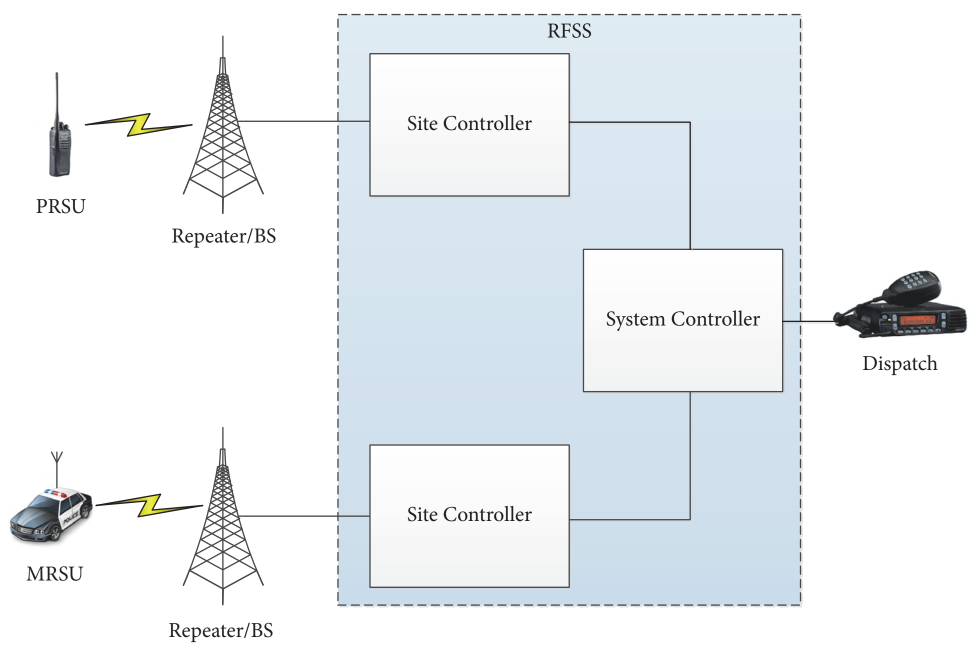


FIGURE 2: A traditional LMR network.



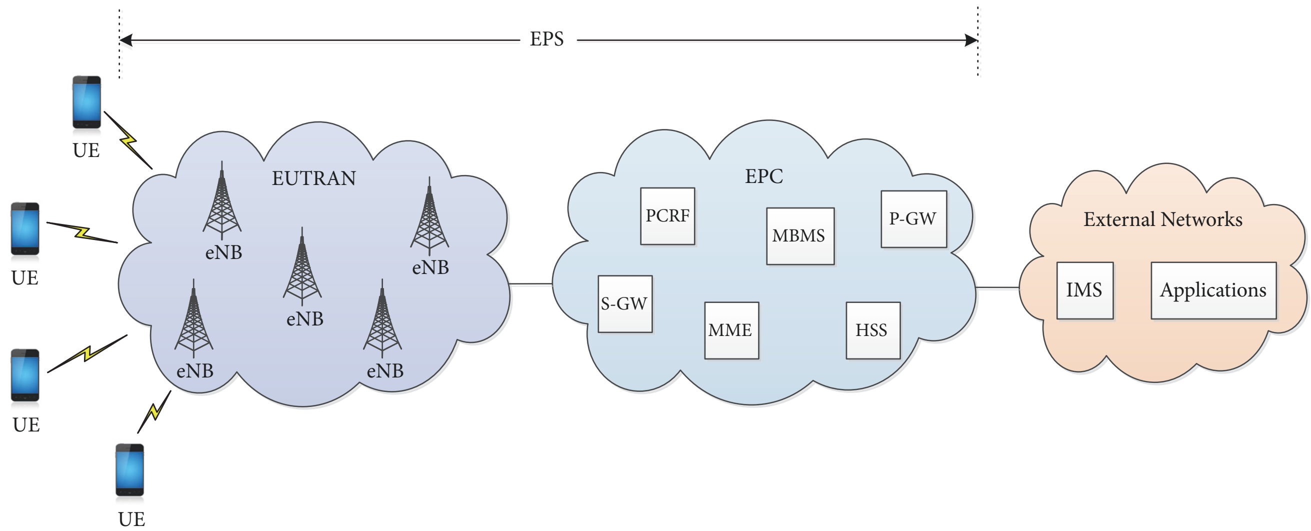
RFSS – Radio Frequency Subsystem BS – Base Station
PRSU – Portable Radio Subscriber Unit MRSU – Mobile Radio Subscriber Unit

FIGURE 3: System-level representation of LMR network.

bands. P25 forms the core function of majority of LMR radio communication systems for public safety [7].

P25 radios use analog mode to communicate with legacy radios, and either digital or analog mode for communication with other P25 radios. P25 supports voice and low-data rate communications limited to a maximum of 9600 bits/s. It does not subscribe to any cellular radio structure; instead, the coverage is based on strong wide-coverage transmitters with extensions and repeaters. The usual coverage radius of a base station is a few kilometers depending on the terrain. P25 offers a prolific set of features including PTT, direct call, group call, and others. At the operational level, features offered by P25 exhibit real demands of public safety operations since it was designed with end users' needs as requirements [8].

P25 radio systems are either conventional or trunked. A *conventional* P25 system consists of a simple infrastructure of repeaters that repeats radio calls from one frequency channel to another. A *trunked* P25 system is characterized by a central controller in the infrastructure, which assigns calls to available channels. Instead of giving each user a dedicated channel, channels are assigned to users as needed. System-level representation of LMR system is shown in Figure 3.



EPS – Evolved Packet System
PCRF – Policy and Charging Rules Function
S-GW – Serving Gateway
UE – User Equipment
EUTRAN – Evolved UMTS Terrestrial Radio Access Network
EPC – Evolved Packet Core
HSS – Home Subscriber Server
P-GW – Packet Data Network Gateway
MBMS – Multimedia Broadcast Multicast Service
IMS – IP Multimedia Subsystem
MME – Mobility Management Entity
eNB – evolved NodeB

Figure 4: System-level representation of LTE network.

The LMR system consists of mobile or portable subscriber units, and repeaters or base stations connected to a Radio Frequency Subsystem (RFSS).

Terrestrial Trunked Radio (TETRA) [10] is a well-established narrowband technology that delivers mission-critical communications to first responders in Europe. The TETRA technology has been standardized by the European Telecommunication Standards Institute keeping in view the requirements of the public safety agencies. TETRA for Police (TETRAPOL) [11] is another technology for public safety communications that competes with TETRA to provide narrowband public safety networks in Europe. Other professional mobile radio technologies including TETRA and TETRAPOL are not discussed here in detail since the focus of this paper is on LMR.

4. LTE for Public Safety

LTE has been broadly deployed as the worldwide mobile broadband standard. The primary benefit in using LTE for public safety is to take advantage of all technological advances being constantly introduced into commercial cellular systems. LTE is a broadband technology that allows high-data rate applications currently not supported in LMR. LTE offers an all-IP system architecture and flexible air interface that supports carrier bandwidths from 1.4 MHz to 20 MHz [2]. LTE is currently able to transmit data at 300 Mbps on the downlink and 75 Mbps on the uplink. It is expected that the data rate of LTE-based networks will increase substantially over the next few years.

Figure 4 illustrates the system-level block representation of LTE. An LTE network consists of two key parts: the Evolved Universal Mobile Telecommunications System (UMTS) Terrestrial Radio Access Network (E-UTRAN) [12] and the Evolved Packet Core (EPC) [13]. Together, E-UTRAN and EPC comprise the Evolved Packet System (EPS). EPS employs EPS bearers to provide IP connectivity to a UE for accessing the Internet. E-UTRAN controls the radio transmission functions, whereas EPC handles the session and mobility management functions.

E-UTRAN comprises base stations named evolved NodeBs (eNBs or eNodeBs). EPC consists of a Mobility Management Entity (MME) for control functions including location management, a Serving Gateway (S-GW) for managing user traffic from/to the E-UTRAN to/from the EPC, and a Packet Data Network Gateway (P-GW) for providing IP connectivity to external IP networks by setting up EPS bearers between the UE and P-GW. Home Subscriber Server (HSS) is a central database that contains information related to users' subscription. IP Multimedia Subsystem (IMS)—an IP-based service control platform—is used to support advanced multimedia services. The Policy and Charging Rules Function (PCRF) entity controls the treatment and charging functionalities of different data flows over EPS bearers.

Multimedia Broadcast Multicast Service (MBMS) is a point-to-multipoint service for transmitting data from a single source to multiple receivers. MBMS was introduced in Release 6 and has been updated in Release 9 [14], where it is known as *evolved MBMS* (eMBMS). The main constituents of eMBMS include Broadcast/Multicast Service Center (BM-SC), MBMS Gateway (MBMS-GW), MME, Multicell/Multicast Coordinating Entity (MCE), and eNB. BM-SC controls broadcasting services to end users and serves as point of entry to the mobile network for content providers transmitting content from external networks. MBMS-GW broadcasts to eNB within the service area and eNB distributes the data to end users. MCE manages admission control and allocates radio resources for the MBMS session. eMBMS is being exploited by 3GPP for public safety operations over LTE and will play a vital role in providing LMR-like group communication services over LTE.

5. LTE-Based Networks for Public Safety

In LMR, first responders communicate over infrastructure and spectrum that is dedicated to public safety. However, these public safety networks do not always meet the mission-critical standards due to coverage holes. Many first responders like police and firefighters routinely carry cell phones as backup in case their public safety network fails to provide coverage. Also, public safety agencies in the U.S. design and run their own public safety communication networks, which leads to interoperability failures between these disparate systems [3].

To overcome these coverage and interoperability issues, a single nationwide wireless network is required for all public safety agencies. One option is to share an existing nationwide commercial LTE network either by sharing infrastructure or by prioritizing public safety traffic to guarantee capacity for public safety in case of an emergency. Another option will be to build a dedicated nationwide LTE-based wireless network that will be exclusive for public safety agencies. Yet another option can be to create a new nationwide wireless network to serve both public safety and commercial subscribers. The business case of such a network is discussed in [15].

5.1. Sharing LTE for Public Safety. An LTE-based public safety network can share a nationwide commercial LTE network via passive or active infrastructure sharing. Passive sharing, such as sharing sites or masts, does not need active coordination between different network operators. Active sharing involves sharing of active elements or intelligence of the network, such as RAN (Radio Access Network) or EPC sharing.

All 3GPP LTE releases support active infrastructure sharing, generally referred to as network sharing. The sharing scenarios can be divided into three main categories [16]:

(i) Geographically split network sharing: In this case, each operator has its EPC and RAN with no overlapping coverage. The networks of both operators (operator A and operator B) are interconnected, i.e., RAN-A is connected to EPC-A and EPC-B and similarly RAN-B is connected to EPC-A and EPC-B.

(ii) Multiple EPCs sharing a single RAN: In this case, each operator has its own EPC but these operators share a single RAN. A single RAN can be shared by multiple EPCs using RAN slicing. This is an upcoming technology that can be used for enabling future public safety networks and is discussed later in this paper.

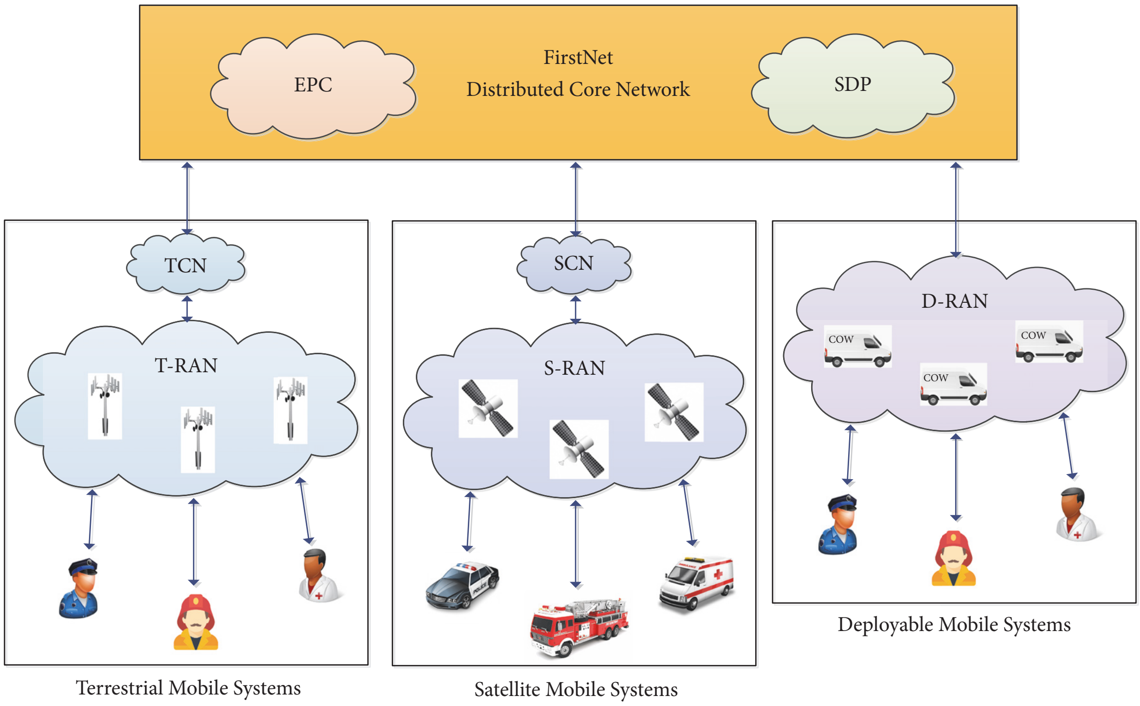
(iii) Multiple RANs sharing a common EPC: In this case, each operator has its own RAN but these operators share a common EPC.

5.2. Dedicated LTE-Based Network for Public Safety. FirstNet is an LTE-based wireless network that gives first responders their own separate nationwide broadband network. The First Responder Network Authority, created by the U.S. Congress in February 2012, is charged with overseeing the construction, operation, and maintenance of FirstNet—the country's first nationwide public safety broadband network. In the spring of 2017, a giant step forward for FirstNet was the start of a public-private partnership between AT&T and First Responder Network Authority to build a $46.5 billion broadband network. AT&T has been tasked to build, deploy, operate, and maintain this network under a 25-year agreement. After roughly a year of partnership, FirstNet is starting to come alive as AT&T announces the nationwide launch of its dedicated network core in March 2018. FirstNet's own EPC built on dedicated (or physically separate) hardware implies that first responders have a separate broadband wireless network and that its traffic is isolated end-to-end, as the FirstNet core totally segregates public safety traffic from all commercial traffic.

FirstNet is an LTE-based wireless broadband network exclusive for public safety services that operates in Band Class 14 of the 700 MHz spectrum. Salient features of FirstNet comprise PTT, direct communication mode, group calls, full duplex voice system, talker identification, and emergency alerting. As shown in Figure 5, FirstNet comprises distributed core, terrestrial mobile systems, satellite mobile systems, and deployable mobile systems. Distributed core incorporates an EPC network and a service delivery platform to dispense different services to end users. The terrestrial mobile systems consist of terrestrial-based communication, while satellite mobile systems will employ satellite communication links to connect to the satellite core network. Deployable mobile systems are mainly comprised of cells on wheels (or vehicles), which provide services in areas with network congestion or fill coverage holes [1].

FirstNet vehicular networks are split into five categories: vehicle network system (VNS), cell on light truck (COLT), cell on wheels (COW), system on wheels (SOW), and deployable aerial communications architecture (DACA). These FirstNet vehicular systems are envisioned to serve a vital part in arranging coverage extension for the nationwide public safety broadband network. Such deployments will provide necessary coverage and capacity in areas without terrestrial coverage, or where normal coverage disappears during natural or man-made disasters.

During disasters, such as earthquakes, critical communication facilities are likely to be without power. After a few hours, widespread communication outages can be expected as backup batteries and generators at these facilities begin to fail. Terrestrial communication facilities can also be damaged resulting in significant communication outages. DACA has the potential to dramatically improve emergency response in such disaster situations. It is envisioned as an aerial capability that is deployable within the first few hours after a disaster to temporarily restore critical communications. In the presence of DACA systems, first responders on the ground can continue to provide emergency services while repair crews restore the terrestrial communication infrastructure [17].



EPC – Evolved Packet Core
T-RAN – Terrestrial-Radio Access Network
TCN – Terrestrial Core Network
SDP – Service Delivery Platform
S-RAN – Satellite-Radio Access Network
SCN – Satellite Core Network
COW – Cell On Wheels
D-RAN – Deployable-Radio Access Network

Figure 5: FirstNet's architecture for public safety communications.

6. Existing Non-Mission-Critical Public Safety Services over LTE

Non-mission-critical services over cellular (or LTE) provide users with the possibility to create or access talkgroups and set up voice, data, or video calls within these talkgroups by pushing a key on the handset. However, these cellular services do not satisfy the demands of the mission-critical public safety radio users in areas of guaranteed and seamless network coverage and capacity in rural and urban localities during incidents.

6.1. Push-to-Talk over Cellular (PoC). PTT services over cellular have been available for many years with commercial network solutions. The concept of carrier deployed PTT or *Push-to-Talk over Cellular* (PoC) or cellular PTT has continued with Sprint in their QChat-enabled service and Kodiak-enabled services for Verizon and AT&T [18]. Verizon offers a PoC service on their network called PTT+. This service is provided via a hosted solution from Kodiak Networks.

PoC is a mobile telephony service for one-to-one and one-to-many half-duplex communications over cellular phones emulating two-way push-to-talk LMR radios. A single person can speak at a time and the rest of the participants hear this verbal communication. Other participants can reply to this speech once it has ended. *Floor control* handles the contention of the *right-to-speak* among various participants. Recipients hear the sender's voice either via *auto answer* in which case they do not require any effort on their side or through *manual answer* after being prompted to accept the connection.

Initial PoC systems were launched in the early 2000s to operate over 2G or 2.5G cellular networks. Cellular networks have quickly progressed to LTE, which supports mobile data applications requiring high data rates. To deliver high-quality one-to-one and one-to-many voice communications, the latest broadband PoC technology leverages LTE broadband cellular networks. Broadband PoC can operate on a wide range of cellular devices including ordinary smartphones or special rugged smartphones having a dedicated PTT button. Organizations that use LMR can employ broadband PoC for LMR augmentation [19].

6.2. Over-the-Top Push-to-Talk (OTT PTT). In *Over-the-Top* (OTT) PTT architecture, the PTT system is independent of the carrier's wireless network. OTT PTT applications work on a variety of devices and across multiple carrier networks as these are application-layer-enabled systems. These are typically cloud-based solutions that can be implemented immediately and are cost competitive and scalable [18]. Google Play has more than 150 applications available for download that offer PTT functionality. The main advantage of OTT PTT applications is their ability to work on multiple access technologies such as Wi-Fi and LTE.

OTT PTT solutions overlay the cellular network and are not integrated or optimized. Since these solutions utilize the Internet as a means to access the cellular network like any other third-party data application, they are not subject to any Quality of Service criteria. Carrier deployed PoC, on the other hand, provides tight integration between the wireless network and PoC system, resulting in faster call setup times and better performance during periods of high network congestion.

6.3. Push-to-Video (PTV). Video utilises and amplifies a human's capability to collect a vast amount of visual information. A few seconds of video can provide much more data regarding an incident and the possible outcomes of a situation that cannot be described in voice communications or shared with still images. For first responders at the frontline, *Push-to-Video* (PTV) communications will mean improved situational awareness leading to improved first responder safety, which will in turn result in greater public safety.

The Group Communications solution from Nokia provides a push-to-video feature over cellular (or LTE) to enhance situational awareness. It supports the ability for groups of first responders to share live video feeds from a disaster scene.

High bandwidth, low latency, dedicated throughput, unlimited availability, and geographic coverage are the key requirements for effective use of PTV communications over LTE. A dedicated public safety LTE-based mobile broadband network such as FirstNet has great potential in this area.

6.4. Push-to-X (PTX). Push-to-X (PTX) is an evolution of PoC. However, it is more than just "pushing" voice to a user via PTT; it leverages the same application to push data like images or to push video to another user or groups of users. For instance, a first responder may wish to transmit information, other than speech, for example, data, text messages, GPS coordinates, a map, a video file, live audio, streaming audio, live video, streaming video, etc., to the talkgroup or to a colleague with the push of a button.

AT&T has recently upgraded their Enhanced PTT (EPTT) service. The upgrade features PTX functionality that enables sending highly secure texts, photos, videos, voice recordings, files, and location data to groups on FirstNet and AT&T network.

Today's public safety mobile devices for LMR are restricted to voice communication and are not capable of transmitting multimedia data to first responders. Expway and Bittium are offering LTE broadcast-enabled mobile devices, which support push-to-talk, high-definition push-to-video, and large file delivery for public safety communications.

7. LTE Enhancements for Mission-Critical Public Safety Services

As public safety adopts broadband technologies such as LTE, all existing features and applications need to be replicated onto that broadband platform, while preserving interoperability with existing narrowband public safety networks such as LMR. LMR employs a number of features like direct call, group call, and PTT, which were not taken into consideration when LTE was designed. Next-generation public safety communications in the U.S. can be envisaged as a ubiquitous 700 MHz LMR narrowband network overlaid with a 700 MHz LTE broadband network. LMR is expected to persist as the lifeline for public safety agencies. LTE will provide them access to high-data rate applications that cannot be sustained over narrowband wireless technologies like LMR.

3GPP concentrated on two major areas in LTE Release 12 to address public safety applications: *Proximity Services* (ProSe) [20] and *Group Communication System Enablers for LTE* (GCSE_LTE) [21]. An objective of 3GPP was to safeguard the quality of LTE while incorporating these features.

7.1. Proximity Services (ProSe). When the network coverage is absent, a public safety UE can automatically use proximity services. Even in the presence of network coverage, the UE can be manually set by the user to employ direct communication. In *conventional LTE communication*, the data path of two UEs, communicating in close proximity with each other, goes through the operator network where eNBs and/or gateways are involved. In *network-assisted direct communication* between UEs in close physical proximity that are served by the same eNB, the data path is routed locally for their communication. *Direct communication* between two UEs without network supervision moves the data path off the access and core networks onto direct links between the UEs. In direct communication, a communication link is established between the two users without traversing the network; this saves network resources while enabling mission-critical communication among the first responders even when they lack network coverage [1]. Direct communication does not need any support from the network, and communication is carried out by utilizing information locally available at the UEs. Network assisted direct communication needs network assistance for authorizing the connection.

The ProSe-based direct communication between ProSe-enabled UEs has been standardized in Release 13 in 3GPP's technical specification TS 23.303. The 3GPP system enablers for ProSe encompass the following functions [22]:

(i) EPC-level ProSe discovery
(ii) EPC support for WLAN direct discovery and communication
(iii) Direct discovery
(iv) Direct communication
(v) UE-to-Network relay.

7.2. Group Communication System Enablers for LTE (GCSE_LTE). A *group communication service* is meant for providing an efficient method to convey the same message to multiple users in a controlled fashion. Group communications is extensively used in LMR systems for public safety operations. The basic purpose of this service in LMR is to deliver PTT functionality; so a group communication service based on 3GPP architecture that uses LTE should support PTT voice communications with similar performance [23].

3GPP's technical specification TS 23.468 [24] describes how a Group Communication Service Application Server (GCS AS) may use the 3GPP system enablers to provide a

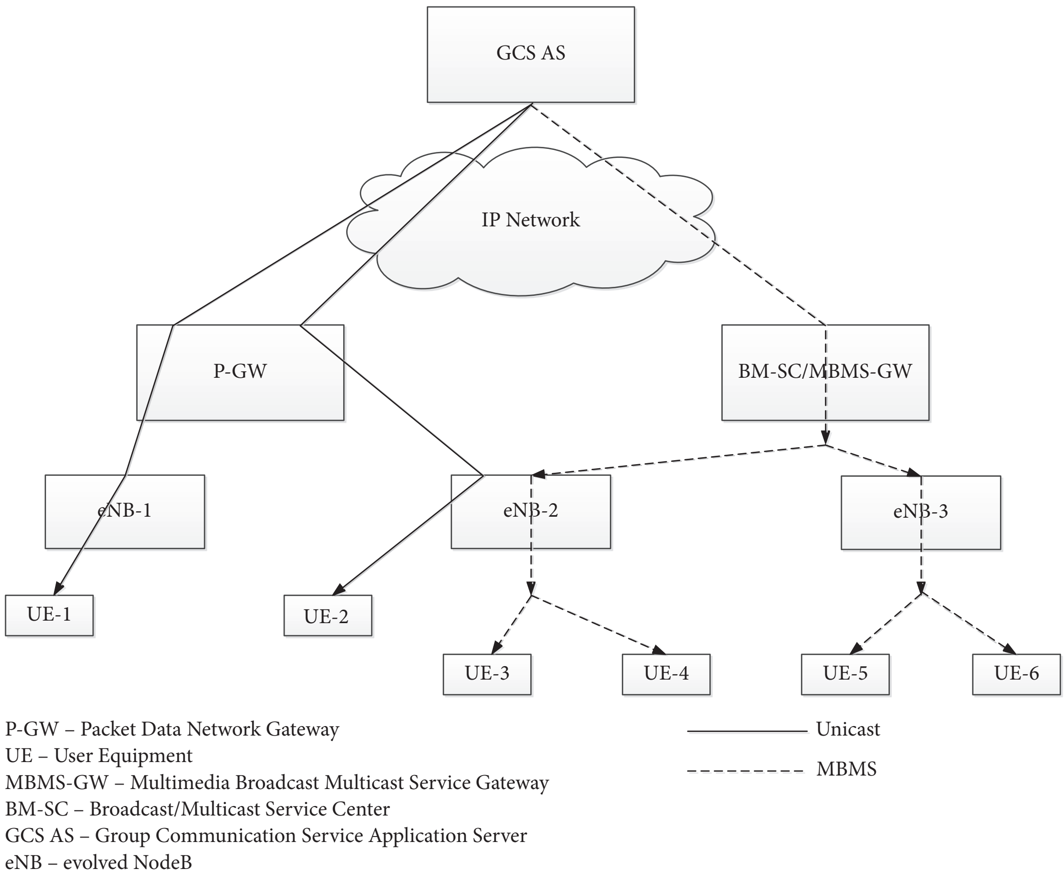


Figure 6: Combination of unicast and MBMS delivery for group communications.

group communication service. These enablers are known as *group communication system enablers*. The GCS AS employs EPS bearer services and may also employ MBMS bearer services. The UE uses an EPS bearer service to send data to the GCS AS in uplink. In downlink, the GCS AS may use the UE's individual EPS bearer service and/or MBMS bearer service to transfer data. Figure 6 shows a situation where the GCS AS employs a combination of unicast and MBMS delivery for different UEs belonging to a single group. UE-1 and UE-2 receive DL traffic through unicast whereas UEs 3–6 receive DL traffic via MBMS. Different delivery modes are used for UE-2, UE-3, and UE-4, even though they are connected to the same eNB (i.e., eNB-2). Unicast is used for UE-2 since it is in an area having low MBMS signal strength.

7.3. Mission-Critical Push-to-Talk (MCPTT). The *Mission-Critical Push-to-Talk* (MCPTT) service offers an enhanced PTT service over LTE that is appropriate for mission-critical scenarios. It emulates the behavior of Push-to-Talk service delivered by LMR. MCPTT is meant for providing voice communication between several users during a group call where each user can attain access to the permission to talk in a controlled fashion. However, it also offers direct (or private) calls between pairs of users [25].

First responders operate in groups and perform different tasks. Their tasks and operations are controlled, assisted, or coordinated by a dispatcher. For their communications, first responders are organized in groups. To enable them to coordinate quickly, people working together converse in the same MCPTT group. People with different functions converse in separate MCPTT groups. The routine public safety tasks are handled by standard procedures using dedicated MCPTT groups. However, MCPTT groups are also created for tackling large incidents.

3GPP has been diligently working to develop technical enhancements for LTE that support MCPTT. MCPTT builds upon service enablers: Group Communication System Enablers for LTE (GCSE_LTE) and Proximity Services (ProSe). The end user is anticipated to have similar experience whether MCPTT is employed under coverage of an EPC network or in direct communication when there is no network coverage. FirstNet is promising a mission-critical voice service—a VoLTE service with enhanced priority—in future in its roadmap. However, this is not MCPTT. Although 3GPP has completed its standardization of MCPTT in technical specification TS 22.179, implementation by manufacturers and service providers, such as FirstNet, has still to occur. LTE off-network communications is still not mature enough to match LMR direct call (or talk-around) service.

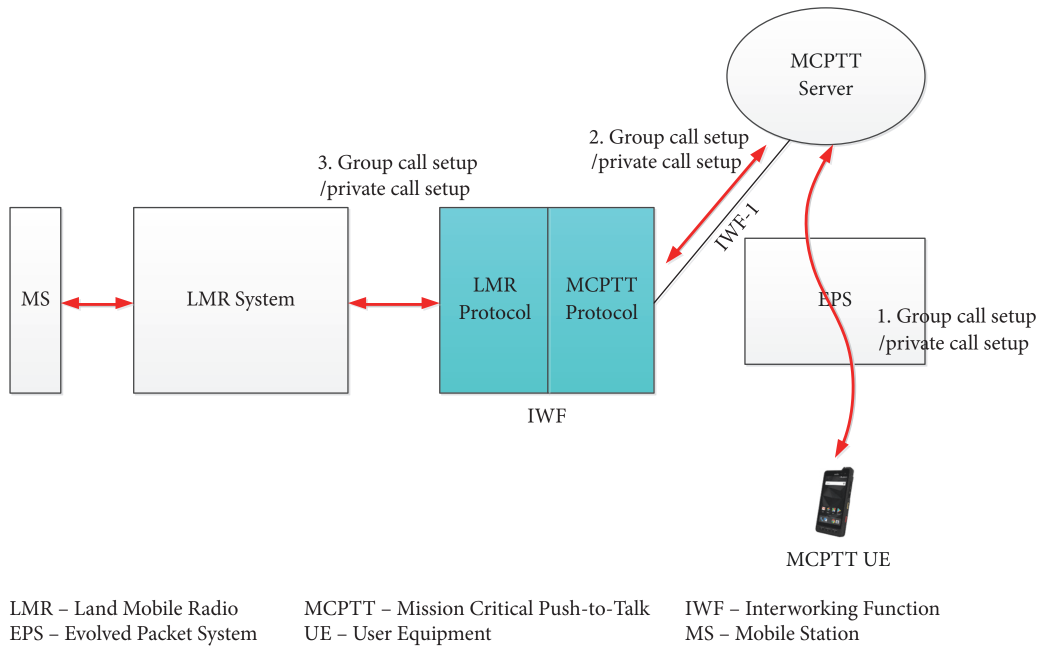


Figure 7: General interworking between LTE and LMR.

7.4. Open Mobile Alliance-Push-to-Talk over Cellular (OMA-PoC). Open Mobile Alliance (OMA) develops specifications for the application layer called service enablers. OMA enablers provide a standardized approach to tasks such as data gathering and transporting information from a network to a device or server. They are network agnostic, i.e., they are devised to work over any kind of network layer.

OMA's *Push to Communicate for Public Safety* (PCPS) is a PTT specification for LTE [26]. It has been adopted by 3GPP for use in defining the MCPTT requirements. PCPS has evolved from the *OMA-Push-to-Talk over Cellular* (OMA-PoC) enabler [27]. OMA-PoC employs Real-time Transport Control Protocol (RTCP) to carry PTT control information, Real-time Transport Protocol (RTP) for voice packets, and Session Initiation Protocol (SIP) as the call control protocol.

8. LMR-LTE Interoperability for Public Safety

LMR handsets usually transmit using 3 to 5 Watts of power, whereas an LTE handset may transmit at about 1 Watt. This simply results in longer range for LMR systems. For an LTE network to support the same coverage area as an LMR network, more sites spaced closer together need to be installed that will result in higher costs. Due to prohibitive infrastructure costs, it will not be easy for an LTE broadband network at 700 MHz to replace LMR.

LTE will not replace LMR any time soon. In the initial version of FirstNet, LTE will be a complimentary enabler that will sit on top of LMR. It may be several years before the transition from LMR to LTE is made. It is highly likely that public safety agencies will be using a mix of LMR and LTE networks in both the short and long term and will need to have effective interoperability solutions. The ultimate goal will be to achieve standards-based interworking between legacy PTT on LMR and MCPTT on LTE.

A report published in January 2018 by the LMR-LTE Integration and Interoperability Working Group of National Public Safety Telecommunications Council (NPSTC) has identified the following requirements for LMR-LTE interoperability [28]:

(i) First responders operating on LMR and LTE networks shall be able to communicate with each other

(ii) Consoles operating on LMR and LTE networks shall be able to monitor and participate in the voice communications on interworked LMR and LTE talkgroups

(iii) First responders and consoles shall have access to multiple LTE talkgroups to coordinate operations and many of these LTE talkgroups will need to be interconnected with LMR talkgroups to support these operations.

8.1. Interworking Function (IWF). 3GPP has studied and identified solutions in their technical report TR 23.782 [29] suitable for interworking between LTE mission-critical systems and non-LTE mission-critical systems that satisfy the MCPTT requirements. LMR system specifications define the equipment and subsystems that constitute the network including base stations and terminals, whereas, in LTE, the MCPTT server delivers centralized support for MCPTT services. In order to realize communication between these different systems, an *Interworking Function* (IWF) is introduced to support protocol translation, identity mapping, routing, and so on. Figure 7 illustrates a solution based on IWF. It is assumed that the interworking group, consisting of group members from the MCPTT/LTE system and the LMR system, has been created and configured before a group call is initiated on this interworking group. Following are some of the interworking scenarios between LTE and LMR systems that have been discussed in this report along with related issues and their solutions:

(i) LTE UE initiates private communication to LMR Mobile Station (MS)

(ii) LMR MS initiates a private communication to LTE UE

(iii) LTE UE or LMR MS initiates a group communication.

8.2. Inter-RF Subsystem Interface (ISSI). The TIA-102.BACA-A [30] specification defines how RFSS can be connected via an IP interface to allow wireline interoperability. The *Inter-RF Subsystem Interface* (ISSI) is an IP based connection that uses SIP for call control and media is handled via RTP. ISSI specifications were defined to achieve network interoperability by interconnecting RFSSs from different vendors. This allowed the implementation of a P25-based LMR network that consisted of RFSSs from multiple vendors. Although ISSI was originally meant for integrating two different P25 systems, the PTT application vendors have leveraged it as a way of moving radio traffic between a P25 system and a PTT service.

Integration of OTT PTT into LMR via ISSI is available. A crucial problem with OTT PTT is its lack of interoperability. For example, a user of Harris BeOn PTT cannot directly communicate with a Motorola Wave PTT's user; everyone needs to have the same application.

PoC services from Sprint, Verizon, and AT&T provide integration into LMR and feature rich PTT services. Verizon's PoC service, PTT+, offers ISSI-based LMR interworking via a virtual private network connection. These PoC services, however, do not provide interoperability between solutions from different vendors or even within the same vendor if the PoC service is provided by different carriers. This means that a user of AT&T's and a user of Verizon's PoC services cannot communicate with each other over PoC. First responders will benefit from using a globally recognized MCPTT implementation from 3GPP when it becomes available in future rather than an OTT PTT application or a PoC service.

If an LTE network running OMA-PoC as the native PTT protocol needs to interoperate with an existing P25 network, a P25 to OMA-PoC interoperability gateway is required that employs ISSI as the interworking protocol between the P25 network and the gateway. AT&T's Enhanced PTT or EPTT service is based on OMA's PCPS and is powered by Kodiak's PoC technology. It supports interoperability with LMR and allows AT&T EPTT subscribers to communicate with LMR radios by using an ISSI-based interoperability gateway. The ISSI gateway provides fast and reliable setup of communication sessions between the EPTT solution and LMR system.

8.3. Radio over IP (RoIP). *Radio over IP* (RoIP) is an application of Voice over IP (VoIP) technology to a two-way radio network. It is a generic term and does not describe any specific implementation or standard. RoIP is an expansion of the use of VoIP with additional control functions needed in LMR systems such as PTT.

RoIP offers a low-cost and reliable solution that meets the basic needs for PoC-to-LMR interoperability. RoIP has limited capabilities; for example, it does not support the passing of device IDs between networks. RoIP relies on a donor radio for connecting LMR and LTE networks. The advantage of the donor radio approach is that any radio technology (P25, TETRA, etc.) can be supported. However, RoIP systems require one donor radio for each LMR radio channel to be shared.

PoC vendors have integrated with RoIP systems to bridge their PoC systems to the LMR world. RoIP gateways can be connected to PoC servers that are hosted locally or in the cloud. Two types of RoIP gateways are available for providing interoperable PTT voice services between LTE and LMR including vendor-specific and third-party vendor-agnostic solutions. Motorola's WAVE and Harris' BeOn are examples of vendor-specific RoIP, while vendor-agnostic RoIP solutions include Mutualink and ESChat. JPS Interoperability Solutions also provides a modular vendor-agnostic RoIP gateway with multiple RoIP interfaces for PoC to LMR interoperability [31]. Figure 8 illustrates AT&T's EPTT system connected to an LMR system via JPS's RoIP gateway. Note that an RoIP gateway can connect any LMR talkgroup to a PoC talkgroup whereas the entire LMR network can be connected to the PoC network through an ISSI gateway.

9. Current Research Issues

3GPP has added additional mission-critical services in Release 14 that was completed in 2017. They include *Mission-Critical Data* (MCData) [32] and *Mission-Critical Video* (MCVideo) [33] over LTE. The MCData and MCVideo specifications offer equipment vendors and network operators a detailed set of standards that are available for implementation.

In Release 15, which is the first release of the 5G system, 3GPP is presently evaluating further mission-critical related topics including

(i) interworking between 3GPP defined mission-critical system and legacy mission-critical systems like P25 for voice and Short Data Service (SDS)

(ii) video push

(iii) video pull

(iv) off-network File Distribution Service (FDS)

(v) data streaming.

3GPP is also evaluating the ability for Unmanned Aerial Vehicles (UAVs) to be served as UEs using LTE network deployments in Release 15, which could be vital to employing UAVs for public safety operations in an LTE-based public safety network. The objective of the study in TR 36.777 [34] is to investigate the capability of LTE to provide connectivity to UAVs as aerial UEs.

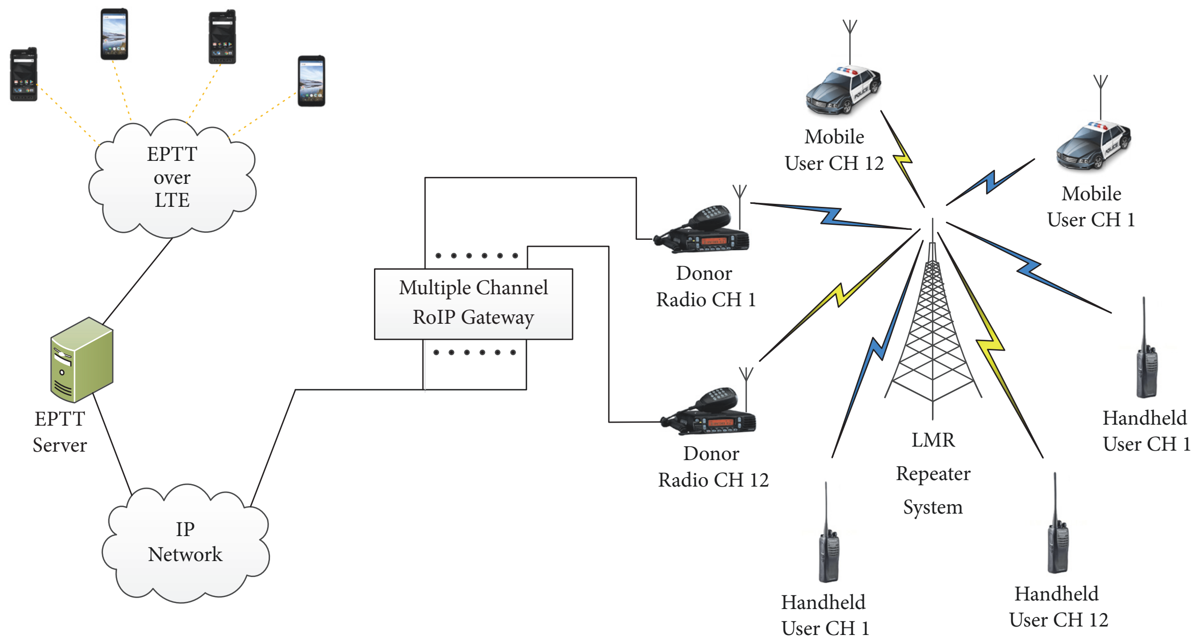


FIGURE 8: PoC to LMR interoperability via RoIP gateway [31].

The public safety oriented 3GPP specifications are titled MCPTT over LTE, MCData over LTE, MCVideo over LTE, etc. 3GPP is considering removing the "over LTE" text so that the same specifications can be reused for 5G work. Removing the LTE limitation from stage one requirements will help evolve the mission-critical services in stages two and three to support the 5G network.

9.1. Mission-Critical Data (MCData). The MCData service supports communication between a pair of users (i.e., one-to-one communication) and several users (i.e., group communication), where each user is able to

(i) share data using SDS

(ii) share files using FDS.

SDS is provided in both on-network and off-network modes while FDS is provided only in on-network mode.

SDS can deliver messages over the signalling channel or over a media bearer. SDS over media bearer can be standalone where the media bearer is set up for the purpose of delivering one message only and then disconnected afterwards or the media bearer can be established as a session for a group to carry multiple messages among group members. As a short message service, there is no pre-check for permission to transmit.

FDS can be session-based when all recipients are required to make mandatory download, or http upload-based where the file is temporarily stored in the controlling MCData server followed by distribution of notification of the file availability to the target recipients. In the latter case, the distribution control is managed and the recipient clients can manage their own reception. There is also provision for mandatory download with this method.

9.2. Mission-Critical Video (MCVideo). MCVideo defines a service for mission-critical video communication using LTE transport networks. Although this service is designed for transport over commercial and dedicated LTE networks, it is not expected to be limited to use over LTE.

MCVideo service includes

(i) video capture and encoding of the video information

(ii) secure streaming and storing of the video information

(iii) video decoding and rendering of the video information

(iv) processing of the video information, including the ability to annotate video frames and recognize video features

(v) mission-critical and public safety level functionality (e.g., group sessions, affiliations, end-to-end confidentiality, and emergency type communications) and performance (e.g., low latency)

(vi) transmission and control of the parameters relevant to those functions

(vii) secure operation such that video information can be reasonably unimpeachable when used in evidentiary procedures

(viii) definition and configuration of MCVideo groups and applications

(ix) configuration of the MCVideo users' profiles and of the MCVideo UEs

(x) interoperability with other services and systems.

While the streaming of video is part of the MCVideo service, the non-real-time or offline transfer of a video clip stored as a file containing video data is covered by the MCData service. An MCVideo UE is a device that provides video acquisition (e.g., has a camera), video rendering (has a display), or both and normally also has some encoding/decoding, communication and storage capabilities.

9.3. LMR–LTE Interworking/Interoperability. As discussed in Section 8, 3GPP's IWF will adapt LMR data and signaling to MCPTT data flows for connecting a P25 ISSI to the public safety LTE broadband network. To interconnect MCPTT over LTE to local P25 LMR networks, every single ISSI connection to the IWF would need to be separately and securely connected, which will make management and cost of this implementation unfeasible. The use of an ISSI hub has been proposed as an efficient way to achieve this interworking as it will be cost-effective and easier to secure a single point of entry into local P25 LMR networks [18].

9.4. Unmanned Aerial Vehicles (UAVs). 3GPP has mainly focused on the use of UAVs as aerial UEs and is working on specifying enhancements to improve terrestrial LTE networks for providing connectivity to UAV UEs. On the other hand, research is also being carried out to explore the role of UAVs as aerial base stations that can be deployed on-demand to boost network coverage. The use of UAVs as aerial UEs or aerial base stations can be vital for public safety applications during natural or man-made disasters.

9.4.1. UAV UEs. In disaster situations, UAVs could be deployed as aerial UEs of an LTE-based public safety network to relay images or videos of the disaster-hit area to augment the situational awareness of first responders on the scene or where the building or infrastructure may be temporarily inaccessible due to a hazard such as an earthquake or a chemical spill. The performance of the LTE network in the presence of UAV UEs is evaluated in 3GPP TR 36.777 in the following three scenarios:

(i) Urban macrocell with UAV UEs

(ii) Urban microcell with UAV UEs

(iii) Rural macrocell with UAV UEs.

The main issue with a UAV UE in the sky is the generation of uplink interference to multiple neighboring cells/eNodeBs. This uplink interference can degrade the performance of the existing UEs on the ground if not properly controlled or mitigated. Understanding the impact of uplink as well as downlink interference in the presence of UAV UEs is a key objective of the study in TR 36.777. Other aspects of LTE that are investigated include mobility performance and UAV identification. After the completion of this study, 3GPP has started a follow-up work item to specify enhancements to improve the efficiency and robustness of terrestrial LTE network for delivering efficient connectivity solutions for UAV UEs [35].

9.4.2. UAV Base Stations. As mentioned earlier in Section 5, DACA systems can be employed to temporarily restore critical communications during disasters such as earthquakes, hurricanes, or tsunamis, when terrestrial communication facilities are damaged resulting in communication outages. The main requirement in such scenarios is to provide broadband communication between first responders and between first responders and victims. Due to their mobility, UAVs serving as aerial base stations are a good fit for providing emergency communications where needed through a quickly deployable low-cost communication infrastructure.

A scenario in which different types of UAVs, including balloons, quadcopters, and gliders, serve as Unmanned Aerial Base Stations (UABSs) to provide emergency broadband connectivity after a disaster is investigated in [36]. The potential benefits of UABSs in the post-disaster scenario are investigated by evaluating the improvements in capacity and coverage of an LTE network that are gained after the deployment of UABSs. Once deployed, these UABSs form new small cells to improve network coverage. Unlike the fixed LTE communication infrastructure such as macro- or microcells, the positions of the UABSs can be adjusted and optimized to achieve better network performance. It should be noted that 3GPP has not yet provided any specifications for the standardization of aerial base stations.

10. Enabling Technologies for Future Public Safety Networks

The virtualization technologies can have tremendous advantages for public safety wireless networks in terms of multi-tenancy, programmability, and flexibility. The virtualization technologies such as *Software-Defined Networking* (SDN) and *Network Functions Virtualization* (NFV) act as key enablers for a Software-Defined RAN (SD-RAN) that provides the platform for RAN slicing thereby allowing public safety operators to effectively share existing RANs deployed by commercial operators.

10.1. SDN and NFV. The principal aim of SDN is to separate the control and data planes to achieve a programmable network. A centralized SDN controller executes all control tasks to facilitate network configuration and management. NFV is a strategy for the virtualization of network functions. The conventional network functions implemented as standalone boxes of specialized hardware and software are transformed into software components or virtual network functions running on virtual machines in the cloud. By employing SDN and NFV in the RAN, these virtualization technologies serve as key enablers of SD-RAN, which in turn is the key enabler of *RAN slicing*. RAN elements can be used as *service* offered to multiple core networks; the physical resources (i.e., base stations) can be shared by abstracting and slicing them into virtual RAN resources. This can enable the RAN to be shared by multiple operators resulting in significant savings on infrastructure costs.

10.2. Software-Defined RAN. In active sharing of network resources discussed earlier in Section 5, mobile network operators can share RAN to provide services using part of the available resources. However, the requirements of operators in terms of radio resources can dynamically change based on the needs of their subscribers, making RAN management a significant challenge. Using a *Software-Defined RAN* that is based on virtual network functions, operators can introduce programmability in the RAN to greatly simplify the control and management of RAN operations.

An open-source SD-RAN platform, referred to as FlexRAN, is proposed in [37] that incorporates an application programming interface for separation of control and data planes in the RAN. It offers a flexible control plane that supports other RAN management applications to be built over the FlexRAN controller. It provides flexibility to dynamically realize various degrees of coordination among base stations. It is transparent to the UEs, enabling easier deployment and evolution.

10.3. RAN Slicing in LTE. In RAN slicing based on SDN, NFV, and cloud computing, a slice orchestrator has been proposed that is responsible for instantiating slices from the EPC down to the RAN. Based on the slice provider requests, it instantiates a slice by selecting appropriate virtual network functions, e.g., core network functions such as forwarding of packets, session management, mobility management, and security, that have been virtualized. Each slice can have its own SDN controller to set up communication paths and manage the traffic within that slice. Resources such as infrastructure and radio spectrum can belong to the same or different network operators [38].

In an architecture for RAN slicing in LTE proposed in [38], the slice orchestrator instantiates instances of the EPC by selecting a set of virtual network functions or physical network functions for an instance. These EPC instances are connected to the shared RAN/eNodeB via the classical S1 interfaces or the new interfaces proposed by 3GPP in TR 23.799 [39]. By using the slice ID indicated by a UE that is hard encoded in the UE's SIM, the RAN/eNodeB steers the slice traffic to the appropriate EPC instance. Also, the eNodeB uses the slice ID to provide the appropriate slice resources such as the appropriate MAC schedular instance to satisfy the Quality of Service (QoS) required by a UE.

In the structure of the eNodeB under this solution, an abstraction layer in the form of a Resource Mapper (RM) is added. It provides an interface between the shared physical resource blocks and the Slice Resource Manager (SRM). Each slice has its own SRM that is responsible for scheduling UEs in its slice over virtual resources or virtual resource blocks. The RM maps the virtual resource blocks to physical resource blocks according to the amount of resources allowed to each slice. This RAN slicing architecture assumes that the slice orchestrator is employing an application programming interface such as FlexRAN to configure eNodeBs in real time.

10.4. RAN Slicing for Public Safety. To limit the time and cost of deployment as well as guaranty public safety requirements, a new communication architecture can be envisaged that introduces the notion of integrating a shared RAN with a dedicated one. Such a shared RAN is based on the concept of resource virtualization and RAN slicing. The architecture of a public safety network employing this concept is proposed in [40] and is illustrated in Figure 9, where RAN resources are shared with commercial networks. It is based on the concept of *multi-operator core network*—this is one of the network sharing configurations defined by 3GPP [41] in which only the RAN is shared.

The public safety and commercial networks maintain separate EPCs. *Public Safety EPC* (PS-EPC) has two connections via separate S1 interfaces with shared-RAN and dedicated-RAN whereas *Commercial EPC* (C-EPC) is linked with shared-RAN only as dedicated base stations are unable to support commercial UEs. The shared-RAN steers the traffic toward the appropriate EPC over the corresponding S1 interface based on a slice ID encoded in UE's SIM. The slice ID is also used over the X2 interface between the *Shared Base Station* (S-BS) and *Dedicated Base Station* (D-BS) for handover purposes.

The RAN management in the shared base station administers the resources in the shared-RAN. The Layer Resource Manager (LRM) coordinates among the shared base station and dedicated base stations in its coverage area for resource usage. Two slices are considered: commercial (*C-Slice*) and public safety (*PS-Slice*). Each S-BS comprises two slice resource managers to schedule respective UEs over virtual resources. A resource manager finally translates the virtual resources to physical resources. With this architecture, a public safety operator can exploit the nationwide RAN of a commercial operator based on appropriate service level agreements, while increasing access point density in few desired areas by deploying extra D-BSs.

11. Conclusions

First responders around the world are still largely using narrowband voice-centric communication networks such as LMR. These networks are designed to provide wide coverage and make extensive use of repeaters and device-to-device communications. The ease of use, reliability, and familiarity of these LMR networks will ensure that they will remain in existence for a long time to come. The primary aim of introducing a broadband public safety network is to take advantage of all recent radio technology advances. Also, a single nationwide wireless network for all public safety agencies can overcome critical issues like interoperability failures in current narrowband public safety networks.

LTE is a natural choice as a platform for introducing a range of new services to first responders. An LTE-based broadband nationwide public safety network can either share an existing nationwide commercial LTE network via upcoming technologies like RAN slicing or can be a completely separate wireless network dedicated for public safety agencies such as FirstNet. However, current LTE services for public safety like PoC, OTT PTT, PTV, and PTX do not meet mission-critical requirements, and 3GPP has addressed this via several recent enhancements such as proximity services,

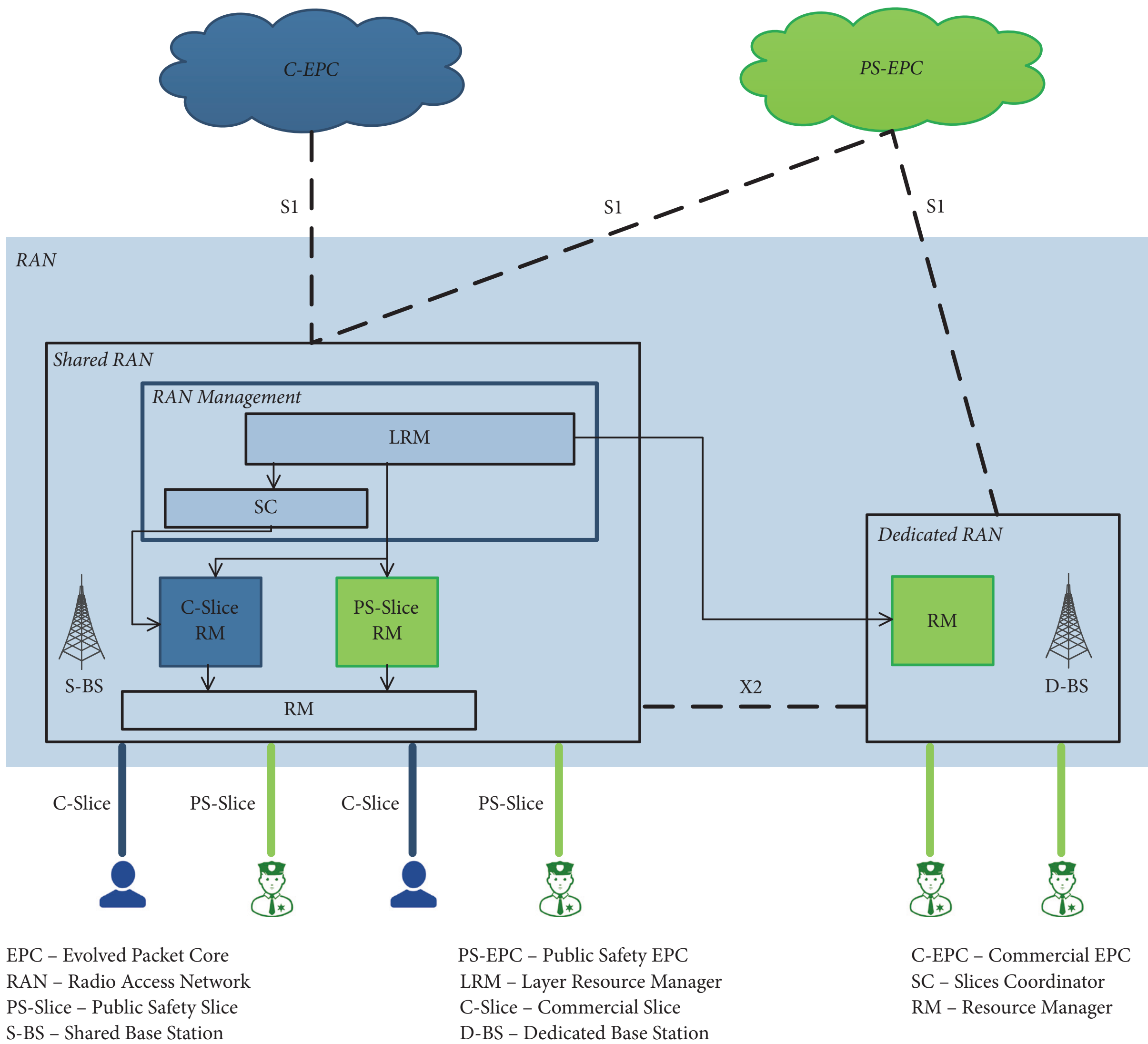


Figure 9: Network architecture employing RAN slicing [40].

group communication system enablers, and mission-critical PTT.

LTE will not replace LMR anytime soon and LMR is expected to continue to exist alongside any new LTE-based public safety network. However, LMR and LTE are quite different and getting them to interoperate effectively and seamlessly will need some innovative thinking. Existing interoperability solutions only provide integration of LMR with non-mission-critical LTE services like PoC and OTT PTT via ISSI and RoIP. Achieving standards-based interworking between legacy PTT on LMR and MCPTT on LTE will be critical. 3GPP has recently identified solutions suitable for interworking between LTE mission-critical systems and non-LTE mission-critical systems such as LMR.

Upcoming features and services of LTE such as mission-critical data, mission-critical video, and aerial UEs are also directly applicable to public safety. UAVs are also being considered as aerial base stations in LTE-based public safety networks that can be deployed on-demand to restore critical communications during disasters. In this paper, we provided a quick yet meaningful review of all these issues. We also offered a look ahead at the emerging virtualization technologies, such as SD-RAN, and RAN slicing, as enablers for future public safety networks.

A reasonable approach that is likely to dominate is to use the existing LMR voice-centric infrastructure as default mode of operation in an LMR-LTE integrated network. LTE is capable of providing a range of radio services that are not currently supported in LMR. For example, LTE can support radio bearers with variable QoS classes. Voice quality can be maintained even when the overall quality of the radio channel degrades. LTE can support rich multimedia environment through its IMS subsystem and MBMS. Also, LTE offers advanced network management capability with flexible access control. Other services will include execution of functions related to data analytics and mission-critical scene analysis. It is also likely that integrated LMR-LTE networks of the future will take advantage of upcoming virtualization techniques such as SDN, NFV, SD-RAN, and RAN slicing. In the near future, LTE will be part of 5G and that will provide an even wider range of facilities including support for internet of things, virtual reality, and augmented reality. The interoperation of LMR and 4G/5G networks will also be imperative to the evolution and advancement of future public safety networks.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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