Abstract—The fifth-generation (5G) communication systems will enable enhanced mobile broadband, ultra-reliable low-latency, and massive connectivity services. The broadband and low-latency services are indispensable to public-safety (PS) communication during natural or man-made disasters. The existing systems have limited capacity, and hence their evolution is desired. Recently, the third generation partnership project long-term evolution (3GPP-LTE) has emerged as a promising candidate to enable broadband PS communications. In this article, we present six major PS-LTE enabling services and the current status of PS-LTE in 3GPP releases, and discuss the spectrum bands allocated for PS-LTE in major countries by international telecommunication union (ITU). Finally, we propose a disaster-resilient three-layered architecture for PS-LTE (DR-PS-LTE). This architecture consists of a software-defined network (SDN) cloudlet layer to facilitate edge computing or to enable emergency communication link, and a radio access layer. The proposed architecture is flexible and combines the benefits of SDNs and edge computing to efficiently meet delay requirements of various PS-LTE services. Simulation results verified that with DR-PS-LTE architecture, delay is reduced by 20% as compared with the conventional centralized computing architecture.

I. INTRODUCTION

The fifth-generation (5G) communications system is targeting broadband and ultra-reliable communications to meet users’ diverse requirements. During a disaster, public safety (PS) organizations such as police (road, railway, and airport), military, guards (border, coastal, customs), and hospitals demand broadband and low-latency communications to timely provide emergency services. Currently, PS organizations rely on narrow band Terrestrial Trunked Radio (TETRA)-based systems which can only support voice services. By enabling fast and broadband communications among PS users and organizations, real-time video can be transmitted to increase the recovery chances of PS users [1]. To achieve high efficiency and replace the existing TETRA networks, third generation partnership project long-term evolution (3GPP-LTE) broadband standard is adopted to support voice and broadband video applications to meet the PS user demands.

The 3GPP objective is to upgrade the existing LTE-based architecture in order to enable broadband PS communications. To upgrade the existing services, 3GPP TS 22.179 Release 13 [2] has recently introduced mission-critical push-to-talk (MCPTT) services. In this release, MCPTT enables the direct mode communication and also adds the device discovery feature to find neighboring users either by using network assistance mode or direct-mode without network assistance. Moreover, relay capability has also been included to provide out-of-coverage service to the users. To achieve these targets, we need a promising architecture that can meet the desired bandwidth and latency requirements during emergency situations. Hence, in this paper we propose the disaster-resilient architecture for PS-LTE which has the capability to fulfill these requirements.

The rest of the paper is organized as: Section II discusses the evolution of TETRA-based networks, the related works, and our contributions. Section III describes the PS-LTE spectrum allocation and current status of the 3GPP standardization related to PS-LTE. In Section IV, the key enabling services for PS-LTE are summarized. Section V describes the existing and the proposed disaster-resilient architecture for PS-LTE. The conclusions are presented in the last section of the article.

II. EVOLUTION OF TETRA-BASED PUBLIC-SAFETY NETWORK AND RELATED WORKS

Recently, there has been growing interest in improving communication technologies for PS communications and the existing TETRA-based systems. The major motivation is to provide PS communications services till the completion of the evolution phase from the TETRA to the LTE. The evolution plan in Europe, specifically Finland, has five main steps to completely implement hybrid networks [3] that could achieve almost similar performance like broadband LTE for emergency communication services. These steps are: 1) a mobile virtual network operator (MNVO) set up to meet increased data requirements. Initially, the externally available broadband services will be used, but in future LTE core will replace them to provide PS services, 2) critical content will be served via TETRA, while non-critical content will be offered via...
broadband communications, 3) dedicated broadband in some areas will start functioning for PS services using LTE core, 4) excellent voice services will be provided in TETRA and LTE-based networks, 5) LTE-based broadband services will completely take over the TETRA-based services after the completion of evolution from TETRA to LTE.

To achieve the aforementioned goals, future PS standards needs to be developed based on LTE. For example, in [4], the major driving factors for wideband spectrum allocation for public safety agencies, and with the pros and cons of each available frequency bands are summarized. Moreover, in [5] authors proposed device-to-device (D2D) discovery scheme for proximity services that discovered around 63% more users as compared with random access schemes with the same allocated bandwidth. Hence, this scheme is spectral and time efficient as compared with other schemes in the literature. Furthermore, major enabling communication technologies for PS-LTE were discussed in [6]. To increase spectrum efficiency, they came to the conclusions that millimeter wave (mmWave) band, introduction of massive multiple-input and multiple output (MIMO), and UAV can be the potential candidates for PS communications. However, they ignored the detailed discussions on the current status of 3GPP PS-LTE, and a suitable architecture for PS-LTE systems.

In [7], the authors extended the existing LTE-based architecture for provisioning of multimedia services to the life saving officers. The main challenge was to exploit the benefit of broadband services by satisfying PS service requirements. To enable multimedia services, major steps involved in architecture evolution from the shared commercial and PS network to the independent PS network are presented. Under that architecture, they proposed dynamic evolved multimedia broadcast multicast service (eMBMS) activation solution to improve the spectral efficiency. Simulations results proved that the proposed system spectral efficiency is always high. However, this architecture could not meet the strict low-latency requirements and is not flexible enough to be centrally updated. To solve this challenge, we propose a three-layered disaster-resilient PS-LTE (DR-PSLTE) architecture, that consists of a software-defined network (SDN) layer to provide centralized control, an unmanned air vehicle (UAV) cloudlet layer [8] to facilitate edge computing (EC) or to enable emergency communication links, and a radio access layer. The propose architecture can meet the strict latency requirements by processing important functions at the edge and can also be centrally managed using SDN functionality.

In this context, this article offers a complete overview of PS-LTE and design guidelines on deploying PS-LTE systems. In particular, our major contributions are threefold; 1) we review the current status of PS-LTE in the 3GPP standard releases, 2) we present the communication scenarios and the key enablers for PS-LTE, 3) we propose a DR-PSLTE architecture that suits well for the emergency situations.

III. PS-LTE Spectrum Allocation and 3GPP Releases Status

In this section, we summarize the spectrum bands allocated for PS communications in major countries located in three different regions, and the status of the 3GPP releases related to PS-LTE.

A. PS communications spectrum allocation

In PS communications (PSC), delay and bandwidth requirements of each emergency service differ from each other. The sharing of the existing available limited spectrum among PS users and non-PS users is not an efficient and sufficient solution to meet the demands of emergency services. Hence, a dedicated broadband spectrum is desired for PS users. ITU divides the world into three ITU regions to efficiently manage the spectrum. The frequency bands reserved for PSC in the major countries are summarized in Table I. The band allocation has two main categories: contiguous and non-contiguous, in which adjacent and non-adjacent frequency bands are allocated, respectively. The world radio conference (WRC-15) with Resolution 646 is the agreement between united nations and ITU [6] in which they encouraged the PS organizations to use frequency range 694-894 MHz for broadband PSC. Since different countries have different operational frequency ranges

| ITU Regions | Major Countries | Frequency Band | Bandwidth (MHz) |
|-------------|-----------------|----------------|-----------------|
| Region 1    | Europe          | 410-430/450-470 MHz (400 MHz) | No dedicated band (Use commercial LTE bands) |
|             | UK              | 733/758-788 MHz (700MHz) | 40 (20MHz + 20MHz) |
|             |                 | 60 (30MHz + 30MHz) | |
| Region 2    | Americas        | 25-50 MHz (VHF Lower Band) | 6.3 MHz |
|             |                 | 150-174 MHz (VHF Upper Band) | 3.6 MHz (non-contiguous) |
|             |                 | 220-222 (220 MHz band) | 0.1 MHz |
|             |                 | 450-470 (UHF Band) | 3.7 MHz (non-contiguous) |
|             |                 | 470-512 MHz (T-Band) | 6 to 12 MHz blocks (contiguous in specified markets) |
|             |                 | 758-769/788-799 MHz | 22MHz(11 MHz + 11 MHz)(contiguous) |
|             |                 | 768-775/798-805 (700 MHz) | 14 MHz (7 MHz + 7 MHz) (contiguous) |
|             |                 | 806-809/851-854 MHz | 6 MHz(3 MHz + 3 MHz) (contiguous) |
|             |                 | 809-815/854-860 MHz (800 MHz) | 3.5 MHz (1.75 MHz + 1.75 MHz) (non-contiguous) |
|             |                 | 4940-4990 MHz (4.9 GHz) | 50 MHz (contiguous) |
|             |                 | 5850-5925 MHz band (5.9 GHz) | 75 MHz (contiguous) |
| Region 3    | Australia       | 4940-4990 MHz (4.9 GHz) | | 50 MHz (contiguous) |
|             | Japan           | 4940-4990 MHz (4.9 GHz) | 50 MHz (contiguous) |
|             | South Korea     | 718-728/773-783 (700 MHz) | 20 MHz (10 MHz + 10 MHz) |
and spectrum requirements the dedicated bands in very high frequency (VHF), ultra high frequency (UHF), 700 MHz, 800 MHz, and 4.9 GHz bands might be used to enable PSC in most of the countries. For spectrum harmonization across the world, dedicated broadband spectrum for PSC is desired.

South Korean government plans to build a dedicated broadband network for PSC. They have a plan to reserve 20 MHz dedicated spectrum in the 700 MHz band. Similarly, other countries in Region 3 such as Japan and Australia also reserved dedicated spectrum for this purpose. On the other hand, UK did not reserve any specific bands for PSC, but has decided to use the existing LTE bands.

### B. Status of PS-LTE key enabling services in 3GPP releases

In recent years, 3GPP has given a high priority to PSC because it is rapidly evolving by taking more requirements and input from the global critical communications industry. Here, we provide an overview on the development achieved for PSC in 3GPP, and also provide a brief overview of the goals to be achieved in the future.

In 3GPP Release 12 key enablers such as ProSe, group communication, mission critical services, and public warning systems (PWS) for PSC are introduced. In Release 13, the first technical specifications (TS) of Isolated E-UTRAN operation for public safety (IOPS) are determined, whereas more MC communication services like MC data and video are introduced in Releases 14 and 15, respectively. These services are helpful to cope with the disasters by provisioning emergency communications to the PS officers.

Since Release 11, 3GPP has led the development of TSs in cooperation with PS industry partners to adapt LTE according to PS requirements. Several TSs have been released for different services. For example, ProSe and group communication system enabler (GCSE) are introduced in 3GPP TS 22.278 and 3GPP TS 22.468 in Release 12, respectively. Similarly, in Release 13 MCPTT and IOPS are adopted and explained in 3GPP TS 22.179 and 3GPP TS 22.346, respectively. In Fig. [1] we briefly summarize most of the PS-LTE related 3GPP TS and technical report (TR) documents for ProSe, GCSE, PWS, and MC services which would be helpful for researchers starting their research in PS-LTE.

### IV. Public Safety Communication Service Key Enablers

In this section, we discuss the PSC service key enablers such as ProSe, GCSE, MCPTT, IOPS, and priority services. Moreover, we also describe their needs in PS-LTE system with key components necessary for their implementation.

#### A. ProSe in PS-LTE

3GPP supports ProSe in PS-LTE to enable direct communications among neighboring users as shown in Fig. [2](a). 3GPP ProSe features consist of ProSe discovery and ProSe direct communication. The former finds the neighbor users by broadcasting a beacon whereas the ProSe direct communication enables to establish communication links among the discovered neighbors.

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**Fig. 1:** 3GPP technical specification and reports on PS services.

**Fig. 2:** PS-LTE services: (a) proximity services (ProSe); (b) group communication system enabler (GCSE); (c) mission critical communication; (d) Isolated UMTS terrestrial radio access network (E-UTRAN) operation for PS (IOPS); (e) public-warning system (PWS); (f) priority services.
users that lie in the surroundings [9]. We summarize several 3GPP services and LTE network functions related to ProSe such as ProSe broadcast, ProSe group, and ProSe relay as shown in Fig. 2(b). To enable ProSe discovery in LTE-based systems, users required 360 KHz of bandwidth to transmit the information. In ProSe group and broadcast communications, data is transmitted from one-to-many communications and that feature can work without discovering the nearby users. ProSe relay is beneficial in users’ range extension and there can be either user-to-user relay or user-to-network relay.

The resilience of PS networks can be enhanced by enabling LTE-based isolated E-UTRAN operation for PS (IOPS). This concept is introduced to continue communications even when the backhaul connectivity to the core network is lost [10]. It comprises of isolated E-UTRAN, local evolved packet core (EPC), backhaul links, and an application server as shown in Fig. 2(d). The isolated E-UTRAN has a nomadic eNB (NeNB) which has the capability to move and provide communication links during the emergency and disaster situations. IOPS

C. MCPTT in PS-LTE

Fig. 2(c) shows the mission critical communication services that provides emergency communication services during a disaster in lieu of malfunction base station. D2D communication links will be established to provide alternative communication links. For instance, wireless video surveillance camera can send data towards PS officers without using a base station by enabling D2D communications. The main target of MCPTT is to enable reliable communications among PS users and officers over LTE. Firstly, MCPTT was introduced in 3GPP Release 13 to provide only voice services. In latency perspective, the mouth-to-ear latency (time gap between spoken and listened by a user) should be less than 300 ms, whereas allocated bandwidth for each country is discussed in Table 1. MCPTT in Release 13 includes features such as user authentication and service authorization, group calls on-network and off-network (broadcast group calls, emergency group calls, emergency alerts). 3GPP Release 14 brings further enhancements by introducing MC video and data services, short data service (SDS) and file distribution (FD) on-network services. Currently, Release 15 is in progress and is expected to be finalized by 2018. Some of the working items in Release 15 are: enhanced MCPTT group call setup procedure with MBMS and inter-working with TETRA and other legacy systems. Hence, for MCPTT numerous future research challenges exist, which need researchers’ attention.

D. Isolated E-UTRAN operation for PS (IOPS) LTE

The resilience of PS networks can be enhanced by enabling LTE-based isolated E-UTRAN operation for PS (IOPS). This concept is introduced to continue communications even when the backhaul connectivity to the core network is lost [10]. It comprises of isolated E-UTRAN, local evolved packet core (EPC), backhaul links, and an application server as shown in Fig. 2(d). The isolated E-UTRAN has a nomadic eNB (NeNB) which has the capability to move and provide communication links during the emergency and disaster situations. IOPS
provides resilience and service availability for networks during a disaster situation. The isolated-EUTRAN is either an E-UTRAN without normal connectivity with EPC or a NeNBs with EUTRAN functionality [11]. The NeNB is intended for PS-LTE to provide coverage extension and increase capacity. IOPS can provide services even if the backhaul connection to the centralized macro core is completely or partially lost. IOPS provides mission critical communication (MCC) service to PS users via isolated base stations without backhaul communications. In [11], 3GPP summarizes the various IOPS scenarios with no, limited, signaling only, and normal backhaul.

E. Public warning system (PWS) in PS-LTE

The public-warning system (PWS) as shown in Fig. 2(e) is one of the important use case for PS-LTE. For example, earthquake sensor nodes are installed to gather the shock information and transmit it to the PS officers to enable PS operations. The PS officers request mobile operators to broadcast public warning alerts to the users in their vicinity. Public warning system (PWS) is an alert based system which is used for the delivery of short messages in case of emergency or disaster situations for the purpose of PS. This notification alert can be used for many purposes such as recovery of missing persons, things, documents, providing information about the shelter position in a tsunami or other man-made disaster. Many PWSs have been deployed all over the world such as commercial mobile alert system (CMAS), earthquake and tsunami warning system (ETWS), Korean public alert system (KPAS), European (EU)-ALERT, and Austria public alert system. The notification latency varies with these systems, but usually it should be delivered within 4 seconds to the user in the notification area.

F. Priority services in PS-LTE

The provisioning of priority services to PS users is necessary in disaster situation. For instance, unlike the conventional mobile users during a disaster situation, we need to prioritize the PS users to enable MCC services as shown in Fig. 2(f). During the disaster situation, the MCC services are related to police car, ambulance, and fire brigade that need prioritization for timely provisioning of emergency services. Prioritization of emergency users, compared with non-PS users, in terms of radio resource allocation and connection establishment in PS-LTE is required to efficiently tackle an emergency and disaster situation.

V. PS-LTE Architecture

The 3GPP presents the internet protocol (IP)-based EPS architecture to support packet-switched services. The EPS network architecture consists of: 1) E-UTRAN 2) EPC. E-UTRAN is the radio access part which connects users with EPC, where EPC controls the establishment of the bearer services and other important core network operations. Fig. 4 (a) presents the network elements and the interfaces among different elements in EPC and E-UTRAN.

A. PS-LTE architecture components

The network elements in EPS are connected by standardized interfaces to provide inter-operability among vendors. The EPC consists of logical nodes: P-GW, S-GW, MME, HSS, and PCC. P-GW allocates IP addresses and maintains QoS provisioning. S-GW passes on IP packets and also terminates the interface towards E-UTRAN, manages eNB handovers, and
cares about mobility interface. MME is the control node for LTE radio access that has responsibilities like user tracking and P-GW, S-GW selection. PCC manages policy and charging enforcement function (PCEF). X2 interface is used to connect eNBs with each other, whereas S1 interface is used to connect eNBs with EPC. In Fig. 4 (a), control plane (CP) is represented by dashed lines and solid lines represents the user plane (UP), whereas eNBs are connected to the MME by S1-MME interface. S1/S8 interface provide UP tunneling and tunnel management between S-GW and PDN GW. Finally, S7, S11, SGi are reference interfaces between PCC and P-GW, between MME and S-GW, and between P-GW and PDN, respectively as shown in Fig. 4 (a).

The architecture discussed above has limitations of implementation in PS-LTE. The two major limitations are: 1) no central management of network devices and 2) high latency because processing needs to be done from EPC. For instance, the two important use-cases for PS-LTE such as lifeline communications and ultra-reliable communications cannot be then implemented under the existing LTE architecture. The lifeline communications and ultra-reliable communications demands energy efficient and low-latency, respectively. For example, for ultra-reliable communications, the public-safety organizations demands real time video and high quality pictures transmission with very low-latency and also needs to prioritize the PS users over other traffic. Similarly, in lifeline communication use case, there is a chance that the users acts as a lifeline by enabling infrastructure-less D2D communications. For this situation, the energy efficient D2D communication is crucial to save user from disaster. Hence, there are two main challenges in PS-LTE, one is the provisioning of low-latency and other is the energy efficiency.

The existing LTE architecture is not suitable to enable these emergency services because the existing LTE architecture has high latency. However, the 5G system is targeting low latency for successful implementation critical communications services. Thus, we need to upgrade the architecture by proposing easily adoptable flexible architecture with a support for low-latency applications. Moreover, the six key enabling services discussed above also need frequent updates based on emergency situation and priority. In emergency situations, the existing architecture is not suitable because of low flexibility, high delays, and no central control. To overcome these limitations, we propose a three-layered disaster-resilient architecture that consists of the SDN layer for central control and management, the UAV cloudlet layer to facilitate EC or to provide emergency communication links, and a radio access layer. This architecture combines the benefits of SDN and EC. Thus, it has the capability to easily add and manage the new entities into the architecture and can process the emergency data with low-latency using edge computing. Moreover, the algorithms and proposals can be easily managed centrally from the central station.

B. Proposed disaster-resilient PS-LTE architecture

The proposed three-layered disaster-resilient PS LTE (DR-PSLTE) architecture is presented in Fig. 4 (b). We extend the SDN architecture [12] by adding additional UAV cloudlet layer to enable EC. The details of the three layers in the DR-PSLTE are: 1) The SDN-layer centrally manages the network synchronization and resource management of the disaster area. Moreover, it also centrally manages the control signals to the lifeline provisioning PS officers. The SDN layer has EPC components such as context-aware radio resource management (RRM) entity to allocate situation-based resource allocation, control plane S/P-GW, and PCC functions. The details of each component are referred in Section V-A 2) the UAV cloudlet layer is comprised of UAV ad-hoc network to enable emergency communication links for PS users. Moreover, the UAVs are equipped with cloudlet (small data centers) to provide the EC services. It brings most of the UP and CP processing closer to the edge (end user), which results in low latency compared to the centralized only data processing. The edge computing services provided by UAV layer are beneficial for the security personal as it reduces the processing time and communication delay. Moreover, the security personal can offload their highly computational tasks to the UAV cloudlet that in turn reduce the battery consumption of their hand held devices. Furthermore, this improves the agility of cloud services by bringing the computing functionality to the network’s edge; 3) the radio access network (RAN) layer consists of various types of eNBs such as home eNBs (HeNB), remote radio head (RRH), portable nomadic small cell (PNSC), and the user-plane gateways, and provide the radio services to the emergency users. The PNSC can independently perform the basic EPC functions to provide emergency services. It is connected with S-GW using wireless backhaul.

In the proposed DR-PSLTE, the SDN layer facilitates flexible deployment and central management of new emergency services because it has the overall view of the network situation. The SDN layer partitions the control and data planes and moves the necessary functionality to the cloud. Then these functions runs as the applications in the SDN controller, and hence can be easily managed centrally and updated easily from anywhere with more efficiency. Moreover, SDN controller allow the operators to centrally control and decide the action path for PS officers to save the emergency users based on the deployment situation. It also centrally manages data received from the security personalas. Furthermore, the DR-PSLTE is beneficial to by-pass the malfunctioning base stations traffics by having complete network information in the cloud. The major interfaces among the network elements for CP and UP are S1 and X2 as shown in Fig. 4 (b).

In the DR-PSLTE architecture, we introduce the UAV layer with the functionality of EC to reduce the latency in processing of emergency services. The UAV accompanied by cloudlet enabled distributed processing to reduce the end-to-end latency in the key enabling emergency services such as MCPPT, PWS, and ProSe in PS-LTE. The cloudlet in UAV helps the PS officers to offload their high computational and energy consuming data analytic tasks from mobile to UAV at the edge. The offloading tasks to UAV cloudlet layer includes energy consuming image or video recognition software that usually run on PS officers mobile devices to monitor the victims status and positions during disaster. Hence, in turn this improves
energy efficiency and satisfy the real-time processing requirements for disaster monitoring, detection and management.

UAV layer can increase the coverage of the disaster unaffected base stations by acting as a Relay. This layer can also provide emergency backhaul communication links, when the existing backhaul is not responding and eNBs are in IOPS mode. Other benefits include the efficient management of local radio resources, ease in network up-gradation, and low operating costs. Hence, in short the proposed DR-PSLTE architecture can help to reduce the latency, improve energy consumption or save power, and can extend the coverage in disaster-hit areas.

Therefore, the proposed DR-PSLTE architecture leverages the concept of SDN and UAV cloudlet to exploit the benefits of both centralized and distributed processing. The DR-PSLTE architecture brings up and parts of the CP functionality to the edge servers, whereas some centralized controllers are still managed by SDN to have the global scope of EPC and other PS-LTE enabling functionality.

C. Numerical results

We analyze the computing and communication latency, and energy consumption of the proposed DR-PSLTE architecture. In this section, we obtain the numerical results by performing various MATLAB based simulation trials. Each task performed at conventional centralized computing (CC) or using proposed EC based DR-PSLTE are defined by two numerical values \( \{C_j, D_j\} \), which represent the number of computation cycles required to achieve the desired result and the data size to be forwarded, respectively. Two main types of latencies are considered here: computation and communication latency, where these latencies depend on computation capability of a node and on allocated bandwidth (or achievable effective data rate \( R_{eff} \), respectively.

The CC enabled system requires the information to pass through several networks that contributes to delays such as radio network \( T_{Radio} \), backhaul network \( T_{Backhaul} \), core network \( T_{Core} \), and transport \( T_{Transport} \). Whereas in the proposed EC based DR-PSLTE architecture, it has only radio network \( T_{Radio/EdgeComputing} \) delay besides the computation delays as shown in Fig. 5(a). Thus, compared with conventional CC, the proposed DR-PSLTE architecture has the advantages of achieving lower latency and saving energy for mobile devices by enabling context-aware computing due to EC. For the proposed DR-PSLTE architecture delay and energy is computed as

\[
T_{j}^{DR-PSLTE} = \left( \frac{C_j}{F_{EC}} + \frac{D_j}{R_{eff}} + T_{Radio/EdgeComputing} \right),
\]

\[
E_{j}^{DR-PSLTE} = (C_j \times e_{CPU}^{EC} + D_j \times e_{EC}^{d}),
\]

where \( F_{EC} \) denotes the CPU frequency of the EC server, \( R_{eff} \) is the achievable effective data rate, \( e_{CPU}^{EC} \), and \( e_{EC}^{d} \) is the energy consumed per CPU cycle and energy consumed per data unit by EC server, respectively. In this paper, we use \( F_{EC} = 5 \times 10^{9} \) Hz, \( R_{eff} = \{1, 2, 3\} \) Mbps, \( C_j = \{10, ..., 1000\} \times 10^{3} \), \( D_j = \{1, ..., 100\} \times 10^{3} \), \( T_{Radio/EdgeComputing} = 2 \) ms, \( e_{EC}^{cpu} = 0.1 \), and \( e_{EC}^{d} = 0.1 \). \[14\], \[15\], where low value of \( e_{EC} \) represents that EC has no restrictions in terms of energy.

Similarly, the delay and energy consumed in the conventional CC architecture is calculated as

\[
T_{j}^{CC} = \left( \frac{C_j}{F_{CC}} + \frac{D_j}{R_{eff}} + T_{Radio} + T_{Backhaul} \right) + T_{Core} + T_{Transport},
\]

\[
E_{j}^{CC} = (D_j \times e_{EC}^{d} + D_j \times e_{BS}^{d} + C_j \times e_{CPU}^{CC} + D_j \times e_{BS}^{d}),
\]

where \( F_{CC} \) denotes the CPU frequency of the CC server, and \( e_{CPU}^{CC} \) is the energy consumed per CPU cycle, \( e_{BS}^{d} \) and \( e_{EC}^{d} \) are the energy consumed per data unit transmission by BS and edge computing server, respectively. Simulation results are calculated by considering \( F_{CC} = 50 \times 10^{9} \) Hz, \( T_{Backhaul} = 2 \) ms, \( T_{Core} = 1 \) ms, \( T_{Transport} = 3 \) ms \[13\]. \( e_{BS}^{d} = 0.1 \), \( e_{CPU}^{CC} = 0.1 \), and \( e_{EC}^{d} = 0.1 \).

From Fig. 5(b) we can notice that the proposed DR-PSLTE outperforms the conventional CC architecture by deploying UAV cloudlet to enable EC. In result, due to shorter communication loop the processing delay is reduced by 20%, which in turn helps to promptly process emergency computation services at the edge as compared with the conventional CC to save the victims. This trend continues even by varying the effective data rate \( R_{eff} = \{1, 2, 3\} \) Mbps or the available system bandwidth. That is by increasing the available bandwidth or effective data rate, delay reduces when compared at the same processing frequency.

We also compared the proposed DR-PSLTE architecture energy consumption performance with the conventional CC architecture. Fig. 5(c) demonstrate that energy consumption increases when more data needs to be transmitted. However, we can notice that the proposed DR-PSLTE energy consumption is quite much less than conventional CC when compared at various range of maximum computation cycles, that is \( C_j^{max} = \{1, 10, 100\} \) MHz. The reason is quite obvious as in the proposed DR-PSLTE system, the users’ want to send an information will only establish communication link with the UAV cloudlet at the edge to save energy consumption. Hence, this system can be adopted in the PS-LTE system to enable emergency communications. We tested the performance for single node case. But these results can be easily extended for more number of nodes, because more edge nodes lead to a lower congestion and latency due to the availability of larger number of nodes for a fixed demand. These simulations are performed by ignoring the UAV battery constraints and network management issues.

The joint utilization of SDN, UAV, edge computing raise challenges like inter-working of SDN, UAV, and edge computing network because of utilizing different communication technologies. So, data exchange among these nodes to be conducted in multi-protocol environment. Moreover, the comprehensive system-level evaluation of the developed DR-PSLTE architecture is a tough task. The developed architecture is a complex system featured by heterogeneous RAN, UAV 3D mobility models, UAV-ground integration, context-aware
resource allocation schemes, power control schemes, channel models, and integration of multiple-type communication protocols. However, the SDN layer in DR-PSLTE can reduce this toughness as this would ease the network development and manages important functions by the software-defined functions. Finally, the important challenge that occur during UAV scheduling is the joint network performance optimization of UAV and edge computing. These are the important challenges and research directions that needs proper attention and extensive research works.

VI. CONCLUSION

3GPP LTE is a key enabler for the emergency communication services in PS situations. In this article, we proposed a disaster-resilient architecture for PS-LTE that plays a key role in providing the emergency communication services in disaster affected areas. It combines the benefits of software-defined networks and cloudlets, which help to meet the QoS and latency requirements of PS users by enabling centralized and distributed processing. Furthermore, we briefly discussed the communication services enabler in PS-LTE. Finally, the 3GPP status of various PS-LTE related services such as proximity services, emergency call, IOPS, public warning system, and mission critical services were presented. Simulation results shows that the proposed DR-PSLTE architecture achieved 20% less delay and has low energy consumption as compared with the conventional centralized computing. In the future, we will extend our work to address the limitations of UAV placement and UAVs group management by effectively placing the UAV cloudlet node in the network for optimum system performance. Furthermore, the management and synchronization of huge number of deployed UAVs also needs attention. Moreover, the comprehensive system-level evaluation of the developed DR-PSLTE architecture is a one of the important task that needs attention.

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