Toward Moving Public Safety Networks

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Fourth generation LTE has been selected by U.S. federal and EU authorities to be the technology for public safety networks that would allow first responders to seamlessly communicate between agencies and across geographical locations in tactical and emergency scenarios.

ABSTRACT

Fourth generation LTE has been selected by U.S. federal and EU authorities to be the technology for public safety networks that would allow first responders to seamlessly communicate between agencies and across geographical locations in tactical and emergency scenarios. From Release 11 on, 3GPP has been developing and specifying dedicated nationwide public safety broadband networks that will be scalable, robust, and resilient, and can address the specific communication needs of emergency services. In this realm, the requirements and scenarios for isolated E-UTRAN with no or limited backhaul access to the core network are still in progress. In this article, we survey possible public safety use cases with the induced network topologies, discuss the current status of the 3GPP standards, and highlight future challenges. We further elaborate on the need to support mobile backhauling in moving-cell scenarios and describe two LTE-based solutions to enable dynamic meshing among the base stations.

INTRODUCTION

MOTIVATION

Long Term Evolution (LTE), specified by the Third Generation Partnership Project (3GPP), is becoming the technology reference for fourth generation (4G) cellular networks, as it is increasingly adopted by all major operators all over the world.

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

While existing PS solutions (e.g., Project 25, P25, and terrestrial trunked radio, TETRA) are mature and provide reliable mission-critical voice communications, their designs cannot meet the new requirements and the shift to higher bandwidth applications. In addition, LTE systems were suited to commercial cellular networks in the initial 3GPP releases but not to PS services and the corresponding requirements like reliability, confidentiality, security, and group and device-to-device communications. Therefore, the question raised is whether LTE suffices to be an appropriate solution for PS networks. To address those issues, 3GPP has started to define the new scenarios that LTE will have to face, and has released several studies and specificationson proximity-based services, group and device-to-device communications, mission-critical push-to-talk (MCPTT), and isolated Evolved Universal Terrestrial Radio Access Network (E-UTRAN). These studies define the requirements regarding user equipment (UE) and evolved NodeB (eNB — LTE base station) to provide PS services depending on the E-UTRAN availability and architecture.

In particular, the studies on isolated E-UTRAN target use cases when one or several eNBs have limited or no access to the core network (Evolved Packet Core, EPC) due to a potential disaster, or when there is need to rapidly deploy and use an LTE network outside of the existing infrastructure coverage.

However, 3GPP studies do not define how such isolated eNBs of a single set should communicate together, and leave that to the use of other technologies and vendor-specific solutions.

CONTRIBUTION

In this article, we discuss possible directions and challenges to evolve the LTE network architecture toward 5G in order to support emerging PS scenarios. Starting from the current status of standards on mission-critical communications and focusing on an isolated E-UTRAN case, we delineate two innovative solutions that allow for interconnection of eNBs using LTE, while qualifying the requirements defined by 3GPP for PS scenarios. Such solutions present several advantages when compared to dedicated technologies (e.g. WiFi, proprietary RF links), in that they support network mobility scenarios, and topology split and merge while being cost effective.

The first solution utilizes legacy UEs and evolves them in order to operate as active elements within the network (UE-centric), thus being capable of associating with multiple eNBs and restoring the disrupted links between them.

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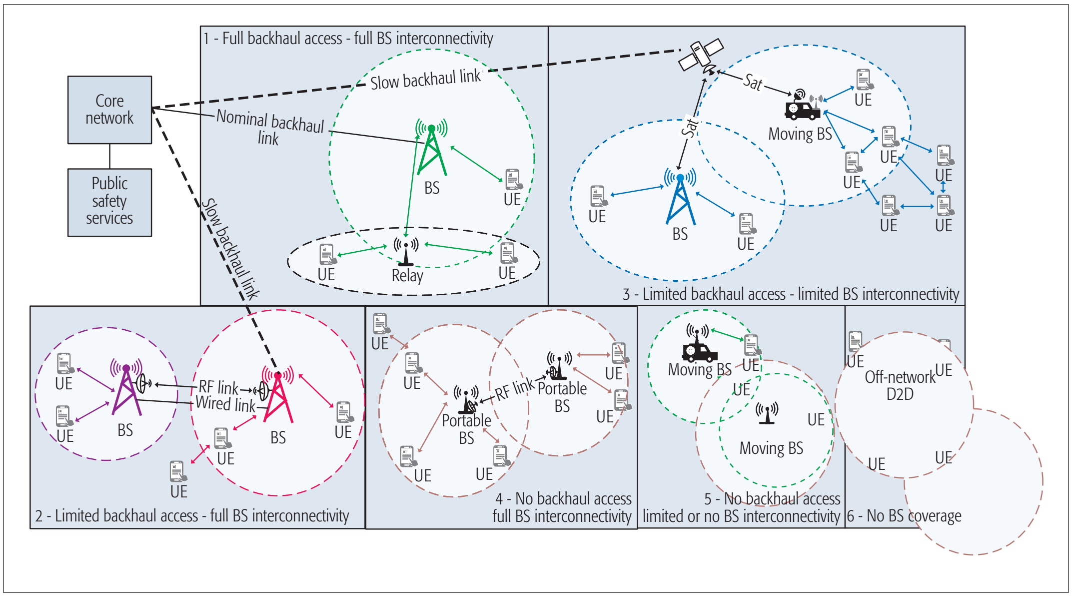

Figure 1. Public safety use cases. *Case 1*: a planned network with fixed BS deployment and backhaul connectivity. *Case 2*: a planned network with fixed BS deployment and limited backhaul connectivity. *Case 3*: a network with fixed BS deployment and moving cells with limited backhaul connectivity assisted by satellite links, proximity services, and device-to-device communications. *Case 4*: no backhaul access in an unplanned network deployment of portable BSs. *Case 5*: moving cells in an unplanned network deployment. *Case 6*: missing BS coverage and proximity services.

In nominal conditions, a nationwide broadband wireless PS network relies on a wired network supporting fixed wireless base stations providing planned coverage and bringing services to mobile entities relying on seamless access to the core network.

The second solution relies on extension of the eNB functionality to allow it to detect and connect directly to neighboring eNBs by encompassing multiple virtual UE protocol stacks (network-centric). These two solutions evolve and restore already existing and potentially disrupted wireless air interfaces such as Uu (eNB-UE radio interface), Un (eNB-relay radio interface), and X2 (inter-eNB logical interface). They create connectivity links among eNBs that can be used to form dynamic mesh networks allowing the size of an isolated E-UTRAN to be extended in fixed and mobile scenarios.

Use Cases and Topologies

Public safety users and first responders encounter a wide range of operational conditions and missions. To effectively address them, they need to rely on sufficient voice and data communication services. While voice services have already been used in tactical communication systems (e.g., TETRA and P25), the absence of a technology that could offer sufficient data rate left the associated services unexploited.

In nominal conditions, a nationwide broadband wireless PS network relies on a wired network supporting fixed wireless base stations (BSs) providing planned coverage and bringing services to mobile entities (e.g., handheld UE or vehicle integrated devices) relying on seamless access to the core network.

A key requirement for the network is that it must be robust, reliable, and not prone to malfunctions and outages. Despite that, it may not survive against unexpected events such as earthquakes, tidal waves, and wildland fires, and may not cover distant lands due to costly deployment.

Figure 1 illustrates six different topologies corresponding to possible use cases that PS users may encounter depending on the operational situation. These six topologies are differentiated based on four criteria:

- Availability of the backhaul link (access to the core network from the BS)
- BS interconnections
- BS mobility
- BS availability (UEs on- or off-network)

In the nominal case (case 1 in Fig. 1), BSs are fixed and benefit from planned coverage as they receive complete services support, and experience full access to the core network and to the remote PS services with no intermissions (e.g., continuous link connectivity with the operation center, monitoring, billing). Therefore, the network can provide nominal access to PS UEs; this case refers to the majority of operations (e.g., law enforcement, emergency services, fire intervention) occurring in covered cities and (sub)urban environments where the network deployment has been previously designed and planned, and services are provided within a large coverage expansion.

In the case of backhaul link failure due to faulty equipment, power outage, or physical damages on the backhaul wires or RF antennas, the core network may not be fully accessible any longer to the fixed BSs (cases 2 and 3). However, depending on either the type and position of failure, or the availability of backup solutions (e.g., satellite backhaul as given in case 3),[1] the BSs may still maintain adequate interconnectivity with each other. Portable BSs (fixed once deployed) can be exploited in order to provide coverage on site, where fixed BSs have not been fully deployed yet or have faulty operation (case 4). In the same way, moving BSs can be utilized in a more dynamic fashion (e.g., for a fight against a fast moving forest wildfire, in vehicular communication on land or at sea [1, 2]) where it is not possible to plan inter-BSs links (case 5). In these cases of portable or moving BSs use,

[1] In such a case, the communication protocol is usually improved by a performance-enhancing proxy (PEP) as specified in Internet Engineering Task Force (IETF) RFC 3135 and RFC 3449.

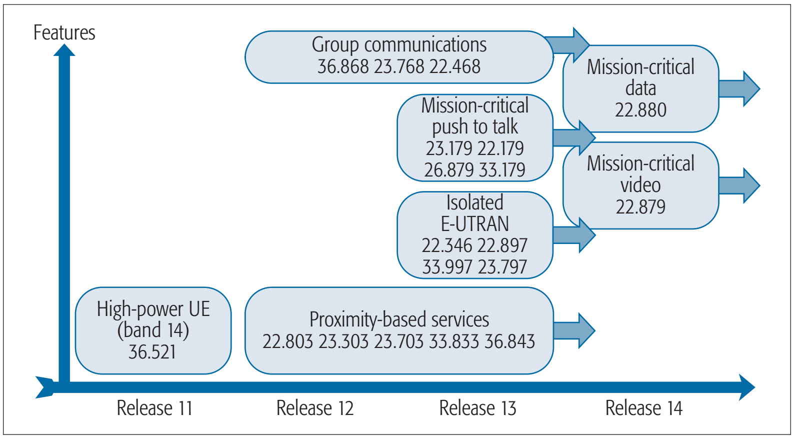

Figure 2. 3GPP PS oriented work items.

it can be hard or impossible to maintain a good connectivity with the macro core network (cases 3, 4 and 5).

Finally, it is likely that due to mobility, users would get out of the coverage service area provided by the BSs (cases 2, 3, and 4), or that in-time service provisioning to users would fail due to intense mobility (case 6). Therefore, due to their own inherent limitations (access to the core network, inter-node connectivity, BSs and UEs mobility), all previous topologies may not be able to provide the same services with a sufficient level of quality to users. For instance, the billing and monitoring services might not be available in some cases. Nevertheless, PS users must be able to use vital services like voice and data group communications in all situations regardless of the network topology dynamic. That is why PS wireless communications cannot rely solely on a planned network of fixed BSs.

Standards Development

The simmering interest of public authorities in LTE for PS use has encouraged 3GPP to tackle this subject and to evolve LTE specifications. Specifically, significant standardization activities have been conducted after the creation of the First Responder Network Authority (FirstNet) in the United States. As illustrated in Fig. 2, the first work dedicated to PS was launched in 3GPP Release 11 with the introduction of high-power devices operating in band 14 (used in the United States and Canada for PS) to extend the possible coverage servicing area. Since then, several work items have been defined in Releases 12 and 13 to study and address the specific requirements of a broadband PS wireless network, not least of which are:

- Guaranteed access: A PS network should be accessible at any time.
- Quality of service (QoS): Guarantee and priority should be ensured for critical calls.
- Reliability: PS networks should provide the services as defined with no interruption when online.
- Resiliency: A PS network should be able to evolve with technology advancements and changes to operational requirements.
- Roaming: UEs should be able to seamlessly use the deployed PS network as well as commercial networks in case of unavailability of the first.
- Spectrum efficiency, capacity, coverage: Spectrum has to be effectively shared to provide the required capacity and coverage.
- Talk around/simplex: Users should be able to communicate even in the case of broadband network unavailability or disruption.

The gaining momentum of LTE networks around the globe has relied on its architecture to provide packet-based network services that are independent of the underlying transport-related technologies. A key characteristic of the LTE architecture is the strong dependence of every deployed eNB on the EPC for all types of services that are provided to the covered UEs. However, this feature prevents UEs from seamless communication service when an eNB is disconnected from the EPC as eNB service to the UEs is interrupted even for local communications. To tackle the aforementioned shortcoming, 3GPP has launched two series of work items: the first one refers to device-to-device communications for enabling proximity-based services (ProSe), and the second one refers to the continuity of service for PS UEs by the radio access network (RAN) and eNBs in the case of backhaul failure for enabling operation on isolated E-UTRAN.

As defined in 3GPP technical specification (TS) 22.346, isolated E-UTRAN aims at the restoration of the service of an eNB or a set of interconnected eNBs without addressing their backhaul connectivity. The goal of isolated E-UTRAN operation for PS (IOPS) is to maintain the maximum level of communications for PS users when eNB connectivity to the EPC is either unavailable (no backhaul) or non-ideal. Isolated E-UTRAN can take place on top of nomadic eNBs (portable BSs, c.f. TS 23.797) deployments or on top of fixed eNBs suffering failures. It should support voice and data communications, MCPTT, ProSe, and group communications for PS UEs under coverage as well as their mobility between BSs of the isolated E-UTRAN, while maintaining appropriate security.

Subsequent to TS 22.346, TS 23.797 provides a solution to the no backhaul IOPS case relying on the availability of a local EPC co-located with the eNB or on the accessibility of the set of eNBs. PS UE(s) should use a dedicated universal subscriber identity module (USIM) application for authentication and use the classical Uu interface to connect to these IOPS networks. If an eNB cannot reach such a local EPC, it must reject UE connection attempts. However, the aforementioned solution does not address issues of scenarios with non-ideal backhaul connectivity. Moreover, requirements for the inter-eNB link connectivity are not specified, even though the operation for a group of interconnected eNBs is defined.

In this article, we advocate the need for novel inter-eNB wireless connectivity as a key for the efficiency of isolated E-UTRAN operation that would allow broadening the network and enhancing the level of cooperation between adjacent nodes, leading to better service provision to the users. We also consider moving cells and meditate on eNB mobility, which is often encountered by (highly) mobile PS entities, in a potential split and merge network.

Future Challenges in Public Safety

Given the wide range of applications, PS communications must be able to provide to a large extent flexibility and resiliency. Being able to adapt under various circumstances and mobility scenarios that are characterized by disrupted communication links (e.g., damaged S1 interface and no EPC network access) and volatile infrastructure operation is of utmost importance. Although there is increasing interest in the development of public safety solutions for isolated E-UTRAN scenarios both by industry and academia, there are still open challenges. Next, we discuss the main ones.

Moving Cells and Network Mobility

In a crisis or tactical scenario, it is vital that field communications can be highly mobile and rapidly deployable to provide network access and coverage on scene. Currently, E-UTRAN is considered fixed, and detection as well as discovery of a network while moving cells are being deployed remains unspecified. When high mobility occurs, the problem becomes network availability as link connections to the EPC servers are dropped. Moreover, due to the limited coverage of moving cells as compared to fixed eNBs [1], enabling inter-cell discovery features for proximity awareness is required as a tool of network intelligence for self-healing. eNBs must be able to search for other eNBs in their proximity either directly or relying on the assistance of enhanced UEs (i.e., UEs with extended capabilities that can interconnect between two eNBs) and eventually synchronize to the most suitable one and re-establish access to the network.

Device-to-Device Discovery and Communications

In the absence of network coverage (off-network case), PS UEs need to discover and communicate with each other by taking partial control of the functionality of the network [3]. UEs should be able to provide network assistance when infrastructure nodes (i.e., eNBs) are missing due to network and/or terminal mobility, or unavailable due to outage and malfunctioning. In such situations, UEs are promoted to assist with time synchronization reference (e.g., based on sidelink power measurement or UEs' own timing), authentication, detection, network discovery, and attachment functions, among others. In addition, UEs may need to request the identity of neighboring UEs (i.e., who is here) belonging to different PS authorities, which calls for over-the-air sensing and self-reconfiguration functionality at the UE side. What is more challenging for PS-UEs is the support of (stored) data relaying from (isolated) neighboring UEs to either other UEs (UE-to-UE relay) or the network (UE-to-network) when they are in coverage.

Programmability and Flexibility

Programmability and flexibility in future PS systems shall allow the rapid establishment of complex and mission-critical services with specific requirements in terms of service quality. A high degree of programmable network components will be able to offer scalable and resilient network deployment on the fly without the need for previous network planning by using network function virtualization and software-defined networking (SDN). Thus, it will result in availability of open network interfaces, virtualization of networking infrastructure, and rapid creation and deployment of network services with a flexible and intelligent control and coordination framework. Such a control and coordination framework is required to manage the entire life cycle of the PS network from configuration and deployment to runtime management and disposal. This is very challenging as it has to optimize the resource allocation across multiple eNBs, manage the topology (especially during the network split and merge), and determine the IP addressing space among the others.

Traffic Steering and Scheduling

The decisions about traffic steering concern control plane actions enabled to form a wireless mesh network. Selecting one or a subset of eNBs to steer the data plane traffic allows users to be connected to the best suited network according to their QoS requirements and the network resources availability. Aimed at overall network optimization, traffic steering techniques can be leveraged to balance the network load, and satisfy carrier and user demands by properly enabling data offloading, interference management, and energy saving policies. Furthermore, the control and data planes should be decoupled as the routing decision and eNB selection are performed at the higher layers while data transfer is operated at the lower layers. Therefore, a novel mechanism to support the BS meshing by giving access to the forwarding table at the lower layers is required. It can be implemented either locally or over the network. In the former case, the forwarding table can be built simply based on the routing table. In the latter case, an SDN approach can be applied to interface between the control and data planes.

Optimization of Performance Metrics to Support Sufficient QoS

A PS network requires provision of sufficient services when a serving eNB currently experiences interruption on backhaul connectivity. Apart from the initiation of isolated E-UTRAN operation, such as exploitation of inter-eNB connectivity links for recovery of system connectivity, a PS network also requires a mechanism to invoke the appropriate complementary resources (e.g., additional bandwidth, alternate communication links, complementary bearers) for self-healing operation and re-establishment of disrupted end-to-end bearers. For more efficient operation of the network, it is important that the same mechanism makes decisions by considering not only the availability of the complementary resources, but also the indicators and the metrics that characterize communication performance (latency, throughput, spectral efficiency, etc.) on the links and priority-level assignment on the Evolved Packet System (EPS) bearers.

Toward Moving Public Safety Networks

In current LTE architectures, eNBs are perceived as the active elements responsible for management and control of the RAN. On the opposite side, UEs are passive clients from the eNB per-

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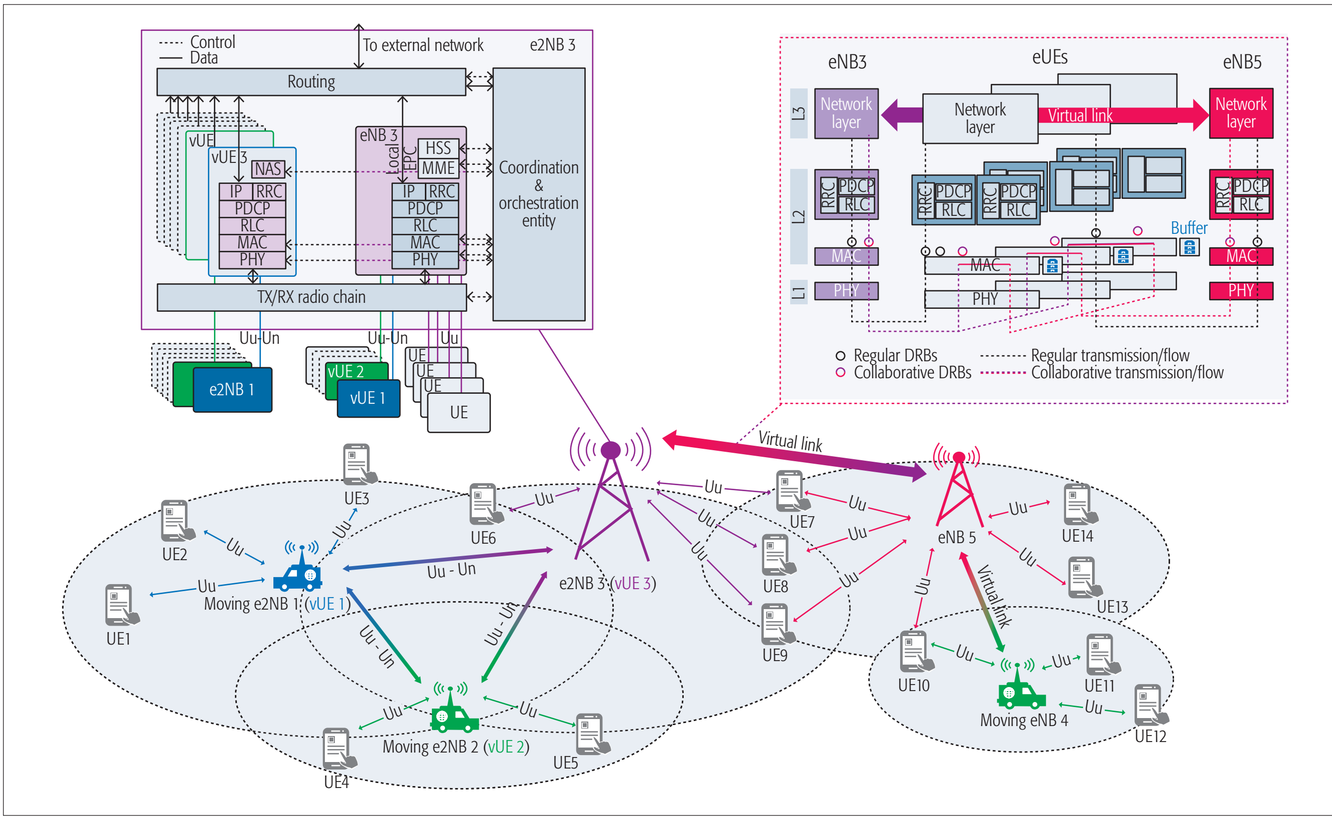

Figure 3. eUE and e2NB architecture for public safety: meshing of isolated or moving eNBs is enabled either (i) by leveraging eUEs as intermediate packet forwarders (UE-centric), thus creating virtual links between eNBs; or (ii) by leveraging e2NBs' functionality of encompassing multiple UEs (network-centric), thus restoring disrupted eNB-eNB communication.

spective, obeying certain rules and complying with the eNB's policies. Thus, the relationship between eNBs and UEs follows the master-slave communication model that is designed to meet the requirements of a fixed network topology. However, network mobility is increasingly gaining interest, and mobile scenarios where portable or moving cells are essentially required for rapidly deployable networks render networking elements with enhanced capabilities more and more attractive. We advocate the need to address those future mobility objectives as a means to meet PS requirements in an isolated E-UTRAN operation. In this direction, the role of legacy eNBs and UEs should be reconsidered within the network.

Following this approach, we delineate two novel solutions that allow inter-eNB link connectivity to be realized and the disrupted air interface to be restored by utilizing:

- Evolved UEs (denoted as eUEs)
- Enhanced eNBs (denoted as e2NBs)

The first refers to a UE-centric network-assisted solution. UEs are assigned enhanced capabilities of associating with multiple eNBs using multiple UE stacks, and thus interconnecting adjacent eNBs. They act as 3GPP UE terminals, maintaining their initial operation, and also as slaves from the eNB perspective. The second concerns a network-centric solution. The eNB stack is extended with several UE stacks, in what we call an e2NB, allowing it to discover and connect to neighboring eNBs, forming a wireless mesh network. A potential but achievable topology is illustrated in Fig. 3, along with a concise depiction of the eUE and e2NB architectures.

Evolved UEs

Evolved UE, like legacy UE, interprets the scheduling information coming from the eNB on the downlink control and signaling channels so as to enable traffic routing and forwarding relying on the allocated physical resource blocks (RBs). Moreover, they report measurements of channel state information (CSI) and buffer status report (BSR) back to the eNB. Furthermore, eUEs have enhanced capabilities of associating with multiple eNBs and thus interconnecting adjacent eNBs [4]. As a consequence, eUEs can also be used to extend the cell servicing area and provide backhaul access to core-isolated eNBs and hence to isolated E-UTRAN scenarios. eUEs can act as intermediate nodes so as to forward the traffic originating from or destined to eNBs. They belong to the control of the RAN of the bridged eNBs.

Enhanced eNB (e2NB)

The e2NB solution relies on the legacy 3GPP eNB and UE functions [2]. The e2NB solution consists of:

- The ability to provide service to mobile UEs and maintain the legacy eNB operation as a standalone node
- The ability to form a wireless mesh network when it is in close proximity to other e2NBs while maintaining service for the mobile entities

The former is achieved by extending the eNB functionality with that of the core network (i.e., mobility management entity, MME, and home

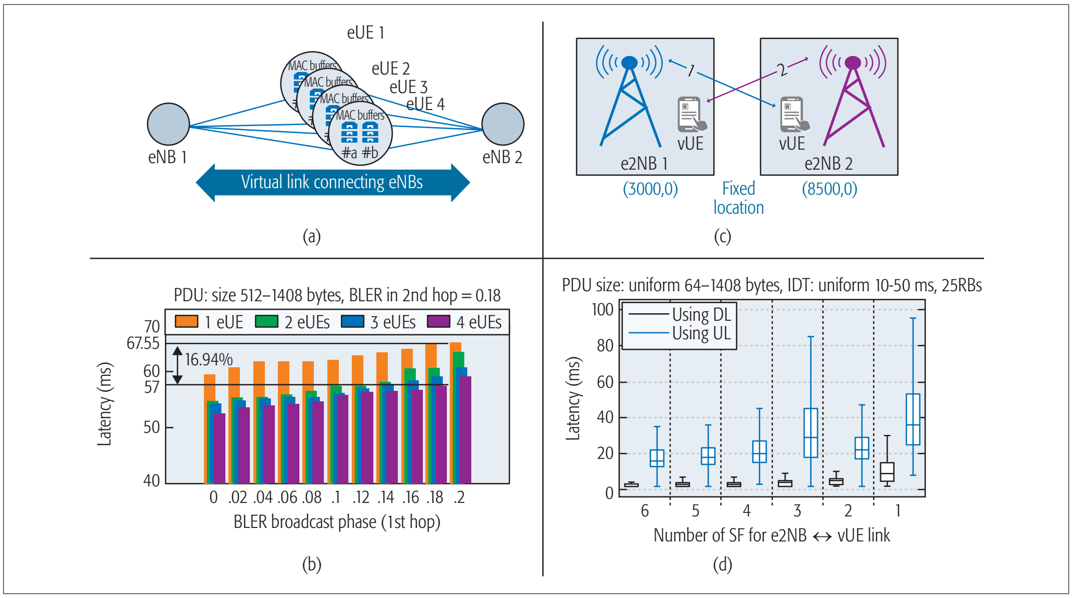

Figure 4. Logical topology for the performance evaluation scenario in OAI: a) four eUEs are leveraged to interconnect two eNBs; b) performance results for latency in the eUEs scenario; c) two e2NBs establish link connectivity using vUEs; d) performance results for latency in e2NB-vUEs scenario.

WiFi solutions are promising if the higher layers and protocols allow for efficient and dynamic meshing, similar to the proposed LTE-based solutions (eUE and e2NB). However, additional dedicated equipment and antennas are needed for WiFi backhauling, thus increasing the cost of BSs.

suscriber server, HSS), which allows it to manage UEs and provide PS services as is proposed by the 3GPP isolated E-UTRAN no-backhaul solution. The latter leverages the Uu and Un interfaces of the 3GPP UE and relay node. An e2NB encompasses multiple virtualized UEs (vUEs), integrating full LTE UE stacks, and one eNB. They share the radio resources and front-end. VUEs are used to discover other e2NBs and can be instantiated on demand to connect to the neighboring eNBs using Uu interface and UE connection procedures before switching to the Un interface. The discovery and on-the-fly connection features allow the e2NB to surpass the classical LTE relay [5] by enabling BS mobility and multiple connections to neighbors, re-establishing inter-eNB connectivity.

Evaluation of Feasibility and the Impact on Latency

In order to evaluate the performance of the above isolated E-UTRAN solutions in a practical and real setting, an implementation prototype of the proposed solutions was tested using the OpenAirInterface platform [6]. Specifically, OpenAirInterface is an open source software implementation of the 4G mobile cellular system that is fully compliant with the 3GPP LTE standards and can be used for real-time indoor/outdoor experimentation and demonstration. After thorough experimentation, results demonstrated the feasibility of the proposed approaches, as these have been presented in [2, 4]. Indicatively, in Fig. 4 we demonstrate two topologies for the isolated E-UTRAN problem where backhaul connectivity is not present. In Fig. 4a, four UEs are leveraged to restore the link connectivity between two eNBs. Performance evaluation results reveal (as shown in Fig. 4b) a significant reduction in latency (up to 16.94 percent), which depends on the number of active cooperating eUEs (up to 4).

In Fig. 4c, two e2NBs enable inter-eNB connectivity utilizing vUE operation. Two vUE-e2NB links are created allowing use of a subset of uplink and downlink subframes (SFs) from one e2NB to the other (six scenarios in Fig. 4d). An important finding that concerns latency performance is that whether using uplink (UL, UE to eNB) or downlink (DL, eNB to UE), the latency improves as the number of available SFs increases. More importantly, DL shows significantly lower latency performance overall as this is not only related to the resource allocation policy but also to the scheduling choice of using the UL or DL path. Thus, flows with different QoS requirements should be mapped on the corresponding link; for instance, low-latency services (e.g., voice calls) should go over DL paths.

Discussion

Some research articles provide insight into solutions when no backhaul is available, providing inter-eNB connectivity relying on WiFi links and including D2D communications that are not yet defined by the ProSe specifications of 3GPP studies [7]. Other technologies are usually used to establish wireless backhaul supporting fixed LTE networks: point-to-point (PTP) RF or free space optics (FSO) links, and point-to-multipoint (PTMP) RF links. In the case of portable BSs, satellite backhaul links are sometimes used. However, we can easily see that these wireless solutions are not adequate for the establishment of a network of BSs enabling voice and data communications in moving cell scenarios.

For instance, Table 1 shows the main differentiating criteria. Despite great performance, PTP and PTMP solutions usually require line-of-sight wireless connectivity with careful network planning, which makes them not applicable to moving cell scenarios. Satellite backhauling, on the other hand, provides the best possible coverage, but may require dedicated tracking antennas and suffers from high cost and high latency (≥ 200 ms) that limit voice and data services [8]. WiFi solutions are promising if the higher layers and protocols allow for efficient and dynamic mesh-

BS back-hauling	PTP/PTMP/FSO	SAT	WiFi	eUEs	e2NBs/vUE
Frequency band	ISM or licensed	Licensed	ISM, possibly licensed	Licensed	Licensed
Link latency	Very low	High	Low–medium	Low–medium	Low
BS mobility support	No	If tracking antenna	If omni-antennas	Yes	Yes
Cost	+++	++++	++	++	+
Topology	Star/mesh	Star	Star/mesh	Mesh	Mesh

Table 1. Main characteristics of base station backhauling solutions.

ing, similar to the proposed LTE-based solutions (eUE and e2NB). However, additional dedicated equipment and antennas are needed for WiFi backhauling, thus increasing the cost of BSs. In addition, commodity WiFi works on industrial, scientific, and medical (ISM) bands, and thus can experience more interference compared to LTE using licensed bands.[2] Studies on commercial networks have shown that WiFi latency is on average a bit higher and has more jitter than that of LTE, although results might differ for PS networks [9]. Moreover, carrier aggregation and full duplex communications are expected to greatly increase LTE global throughput in such mesh topologies, although similar techniques could be used for WiFi.

Some Reflections and Conclusion

Commoditization and virtualization of wireless networks are changing network design principles by bringing IT and cloud computing capabilities in close proximity of network and users. This will facilitate the deployment and management of PS networks by offering a service environment so that adequate (e.g., missing) network functions and applications can be dynamically instantiated for isolated network segments to maintain communication, service, and application as desired [10]. Packet core network functions (e.g. MME, HSS), IP multimedia subsystem (IMS), routing, and topology management are network functions that can be enabled at the BS to restore communication links. Traffic steering, video analytics, content sharing, and localization are examples of network applications that can extend BS functions in order to preserve user service and applications.

In this article, we elaborate on innovative solutions in the context of public safety networks to support efficient isolated E-UTRAN operation. We identify the shortcomings in the state-of-the-art technology, which is currently unable to sufficiently deliver seamless and continuous backhaul connectivity in moving cell scenarios, thus depriving first responders and tactical forces of critical communications. Specifically, we indicate that in the volatile and dynamic environment for public safety communication, the following are needed:

- Evolving UEs as active network elements to restore disrupted air interfaces between bridging eNBs
- Enhancing the role of legacy eNBs to encompass dual protocol stack operation for enabling base station meshing, which is of utmost importance to preserve the integrity of communication

Reviewing the open challenges that pose significant requirements in the field of services provision, we outline the most important and discuss related open research directions.

[2] To solve this problem, certain countries define their own licensed bands for PS WiFi.

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References

[1] Y. Sui *et al.*, "Moving Cells: A Promising Solution to Boost Performance for Vehicular Users," *IEEE Commun. Mag.*, vol. 51, no. 6, June 2013, pp. 62–68.

[2] R. Favraud and N. Nikaein, "Wireless Mesh Backhauling for LTE/LTE-A Networks," *MILCOM 2015*, Oct. 2015, pp. 695–700.

[3] R. Liebhart *et al.*, *LTE for Public Safety*, Wiley, 2015.

[4] A. Apostolaras *et al.*, "Evolved User Equipment for Collaborative Wireless Backhauling in Next Generation Cellular Networks," *2015 12th Annual IEEE Int'l. Conf. Sensing, Commun., and Networking,* June 2015, pp. 408–16.

[5] Y. Yuan, *LTE-Advanced Relay Technology and Standardization*, Springer-Verlag, 2013.

[6] N. Nikaein *et al.*, "Demo: Openairinterface: An Open LTE Network on a PC," *Proc. 20th ACM Annual Int'l. Conf. Mobile Computing and Networking*, ser. MobiCom '14, 2014, pp. 305–08; http://doi.acm.org/10.1145/2639108.2641745.

[7] K. Gomez *et al.*, "Enabling Disaster-Resilient 4G Mobile Communication Networks," *IEEE Commun. Mag.*, vol. 52, no. 12, Dec. 2014, pp. 66–73.

[8] M. Casoni *et al.*, "Integration of Satellite and LTE for Disaster Recovery," *IEEE Commun. Mag.*, vol. 53, no. 3, Mar. 2015, pp. 47–53.

[9] J. Huang *et al.*, "A Close Examination of Performance and Power Characteristics of 4G LTE Networks," *Proc. 10th ACM Int'l. Conf. Mobile Systems, Applications, and Services*, ser. MobiSys '12, ACM, 2012, pp. 225–38; http://doi.acm.org/10.1145/2307636.2307658.

[10] Y. C. Hu *et al.*, "Mobile Edge Computing — A Key Technology Towards 5G," ETSI White Paper No. 11, tech. rep., Sept. 2015; http://www.etsi.org/images/files/ETSIWhitePapers/etsi_wp11_mec_a_key_technology_towards_5g.pdf.

Biographies

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