Chapter 1

Public Safety Networks: Enabling Mobility for Critical Communications

1.1. Introduction

Long Term Evolution is becoming the technology reference for 4G cellular networks, as it is increasingly adopted by all major operators all over the world. Currently, LTE is 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 towards 5G. Moreover, LTE is expected to be an important part of the 5G solution for future networks and also play an essential role in advancing Public Safety (PS) communications. In US, LTE has been chosen up as the next appropriate communication technology to support public-safety and it is likely to be the same in EU. Moreover, several vendors (e.g. Ericsson, Nokia-Alcatel, Huawei, Cisco) are now starting to propose LTE-based public-safety solutions and some of them have been put to real field experimentation.

While existing PS solutions (e.g. P25 and 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 system is a commercial cellular network and was not suited in the initial 3GPP (3rd Generation Partnership Project) specification releases to support PS services and the corresponding requirements like reliability, confidentiality, security, group and device-to-device

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communications. Therefore, the raising question 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 it has released several studies on proximity-based services, group and device-to-device communications, Mission Critical Push-To-Talk (MCPTT), and Isolated E-UTRAN. These studies define the requirements regarding user equipment (UEs) and evolved Node B (eNBs) to provide PS services depending on the E-UTRAN availability and architecture.

Particularly, 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 a LTE network outside of the range of the existing infrastructure. In these situations, the isolated E-UTRAN must maintain relevant services accessible for the PS UEs despite the lack of full EPC connectivity (e.g. local routing and frequency resource management). 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.

In this chapter, possible directions and challenges to evolve the LTE network architecture towards 5G are discussed in order to support emerging public-safety scenarios. Starting from the current status of standards on mission-critical communications and focusing on isolated E-UTRAN case, two innovative solutions that allow for inter-connection of eNBs, while qualifying the requirements defined by 3GPP for PS scenarios, are delineated. Such solutions present several advantages when compared to dedicated technologies (e.g. WiFi, proprietary RF links), by means of supporting network mobility scenarios, topology split and merge while being less expensive.

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. 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 re-store already existing and potentially disrupted wireless air-interfaces such as X2, Uu and Un, and create connectivity links among eNBs that can be used to form dynamic mesh networks of eNB base stations. Thus, allowing to extend the size of an isolated E-UTRAN in fixed and mobile scenarios.

1.2. Uses cases and Topologies

PS 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 communications 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 services left their use in the background.

In normal conditions, a nation-wide 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. hand-held user equipment (UEs) 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 non-prone to malfunctions and outages. Despite that, it may not survive against unexpected events such as earthquake, tidal waves and wildland fires, and it may not cover distant lands due to costly deployment. Nevertheless, first responders need efficient communications in all circumstances, especially when facing such harsh events. That is the reason why PS wireless communications cannot rely solely on a planned network of BS but must also be able to ensure minimum services when this network is not fully available.

Table 1.2 summarizes twelve cases that can arise depending on four criteria: (*i*) availability of the BSs for the UEs, (*ii*) availability of the backhaul link and access to the core network for these BSs, (*iii*) BSs mobility and (*iv*) BS interconnections. These twelve situations are also illustrated in Figures 1.1, 1.2, 1.3 and 1.4.

Scenario 1 is the nominal and ideal case where BSs are fixed and benefit from a planned coverage as they receive complete services support, experience full access to the core network and to the remote public-safety services with no intermissions (e.g. continuous link connectivity with operation center, monitoring, billing). Therefore, network can provide nominal access to PS UEs and this case refers to the majority of

Scenario	Operation	Connectivity to EPC	BS mobility	BS inter-connectivity
1	On-network	Full	Fixed	Full
2	On-network	Limited	Fixed	Full
3	On-network	Limited	Fixed	Limited
4	On-network	None	Fixed	Full
5	On-network	None	Fixed	Limited
6	On-network	None	Fixed	None
7	On-network	Limited	Moving	Full
8	On-network	Limited	Moving	Limited
9	On-network	None	Moving	Full
10	On-network	None	Moving	Limited
11	On-network	None	Moving	None
12	Off-network	-	-	-

Table 1.1. *Possible PS network topologies*

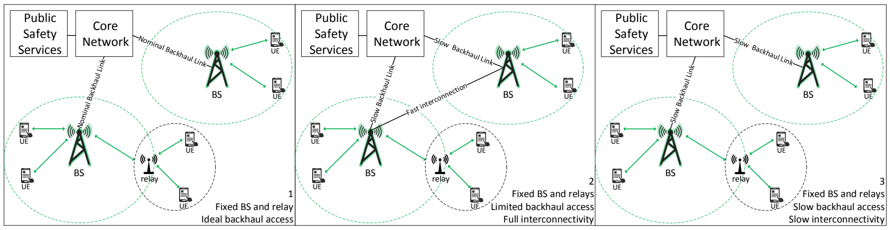

Figure 1.1. *PS topologies - scenarios 1, 2 and 3*

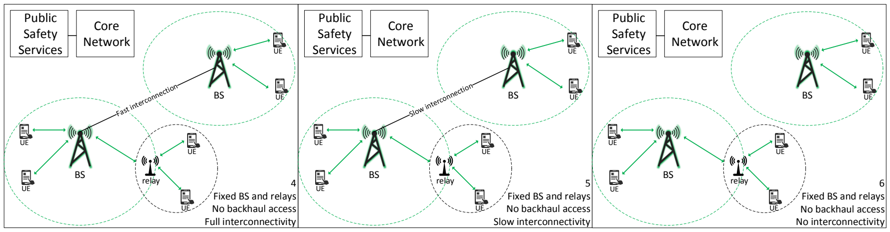

Figure 1.2. *PS topologies - scenarios 4, 5 and 3*

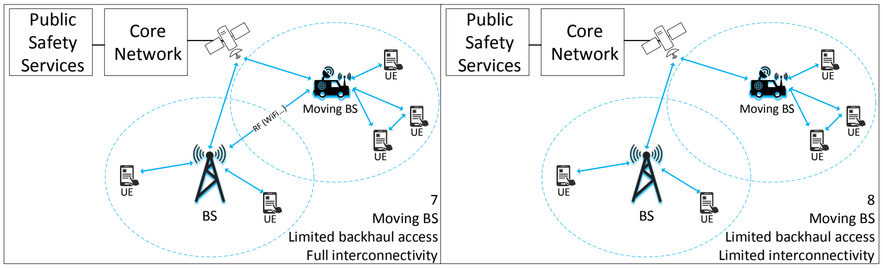

Figure 1.3. *PS topologies - scenarios 7 and 8*

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. Backhaul links (links from BS to the core network) can be realized directly by wire/fiber to the BS or by point to point (PTP) or point to multi-point links (PTMP) fast RF links. It can also include relays, that extend the coverage of the fix infrastructure if they maintain sufficient connectivity on the relay-eNB link of high quality.

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 to the fixed BSs. If it still can provide control plane functions but cannot carry data for the user plane, it is referred as limited (scenarios 2 and 3), otherwise it is

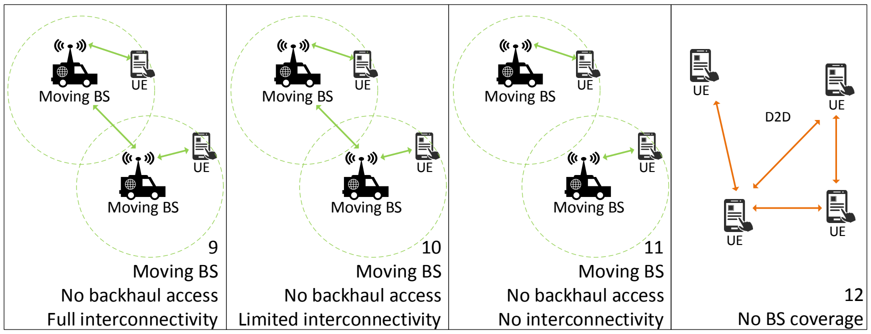

Figure 1.4. *PS topologies - scenarios 10, 11 and 12*

simply unavailable (scenarios 4, 5 and 6). The availability of the core network access to the BSs directly impacts the services provided to the UEs as they rely on and reside in the EPC. In case of limited connectivity to the core network (scenarios 2 and 3), the BS might still accept PS UEs connections, but need additional functions to be able to provide local communications (at least local routing). If there is no core network connectivity (scenarios 6), depending on the organization of the backhaul network and the outage location, the unavailability of the core network does not necessarily implies the loss of communications links between the BSs. This is not currently exploited by the standards but a full connectivity (scenarios 2 and 4) can allow to form a bigger network (not limited to a BS) [1] while a limited connectivity (scenarios 5) may ease the handover of a UE from a BS to another BS.

During intervention in areas with no network coverage due to deployment policies or faulty BSs, portable BSs can be exploited in order to provide coverage on site. These portable BSs are assumed fixed once their deployment is started and so fit in the previous scenarios.

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 communications being on land or at sea [SUI 13, FAV 15]). In such cases, it is very difficult or impossible to maintain a good link-connectivity with the macro core network (scenarios 7 to 11) and it can be hard to inter-connect the moving BSs depending on the area (size, propagation properties) and on their embedded equipment. The issues are the same as before, adding that everything is moving and that topology change can be much more frequent, with split-and-merge as well as interference problems arising when the moving nodes are getting closer.

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

Finally, it is likely that users due to mobility would get out of the coverage servicing area provided by the BSs or that in-time service provisioning to users would fail due to intense mobility (scenario 12). They will then need to rely on proximity services and device-to-device (D2D) off-network communications. Several D2D topologies exist, on- and off-network, for UE-to-UE communications and sometimes to give UEs access to the fixed network through UE-relay performing UE-to-Network communications [3GP 14].

Therefore, due to their own inherent limitations (availability of the BSs, connectivity to the EPC, BSs mobility and BS interconnections), all previous topologies may not be able to provide the same services with the sufficient level of quality to the users. For instance, the billing and monitoring services might not be available on some cases, but PS users must be able to use vital services like voice and data group communications in all situations regardless of network topology dynamics.

1.3. Standards Development

The simmering interest of public authorities in LTE for public-safety use have encouraged 3GPP to tackle this subject. Especially, significant standardization activities have been conducted after the creation of the First Responder Network Authority (FirstNet) in the USA. As it is illustrated in Figure 1.5, the first work dedicated on public-safety was launched in 3GPP Rel. 11 along with the introduction of high power devices operating in Band 14 (which is used in US and Canada for PS) and extending

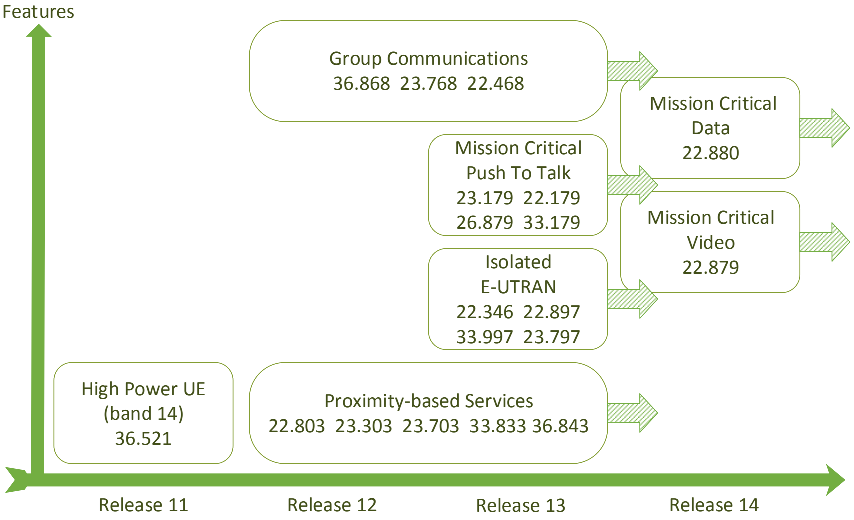

Figure 1.5. *3GPP Public-Safety oriented work items.*

the possible coverage servicing area. Since then, several work items have been defined in Rel. 12 and Rel. 13 to study and address the specific requirements of a broadband public-safety wireless network.

Nevertheless, the gaining momentum of LTE networks around the globe has relied on its architecture to provide packet-based network services which are independent from the underlying transport related technologies. A key characteristic of this architecture is the strong dependency of every Base Station (known also as eNB) on the packet core network (EPC) for all the type of services that are provided to the covered UEs. However, this feature prevents UEs from a seamless communication service when an eNB is getting disconnected of the EPC. Thus, eNB service to the UEs is interrupted even for local communications which is essentially required by first responders. 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 it has been defined in technical specification (TS) 22.346, isolated E-UTRAN aims at the restoration of the service of one eNB or a set of connected eNBs without addressing their backhaul connectivity. Therefore, isolated E-UTRAN operation focuses on adapting to the failure of the connectivity to the EPC and maintaining an acceptable level of network operation in three cases: "No backhaul" case, "limited bandwidth signalling only backhaul" case and "limited bandwidth signalling and user data backhaul" case (TS 22.346). Additionally, in the case when there is no coverage from the wireless cellular network or when it is no longer present due to unexpected disaster, isolated E-UTRAN can take place on top of Nomadic eNBs (NeNBs) deployments. NeNBs are intended for PS use providing complementary coverage or additional capacity where service was previously unavailable. In all cases, the goal of Isolated E-UTRAN Operation for Public Safety (IOPS) is to maintain the maximum level of communications for public safety users and TS 22.346 defines the associated requirements. 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, all while maintaining appropriate security (TS 33.997).

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

In this chapter, the need for novel inter-eNB wireless connectivity is advocated 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. Moreover, moving cells and eNB mobility in a potential split-and-merge network which is often encountered by (highly) mobile PS entities are considered.

1.4. 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 with disrupted communication links (e.g. damaged S1 interface and no EPC network access) and volatile infrastructure operation is of utmost importance. Although there is an increasing interest on the development of public safety solutions for isolated E-UTRAN scenarios both by industry and academia, there are still open challenges and some are discussed next.

1.4.1. *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, then the problem becomes the network availability as link connections to the EPC servers are dropped. Moreover, due to the limited coverage of the moving cells as compared to fixed eNBs, 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. All this must be done while maintaining minimal security features such as authentication which becomes a challenge in such situations.

1.4.2. *Device-to-Device Discovery and Communications*

In the absence of network coverage, public safety UEs require to discover and communicate with each others by taking partially control of the functionality of the network [LIE 15]. UEs should be able to provide network assistance when infrastructure nodes (i.e. eNBs) are missing due to network and/or terminal mobility, or when they are unavailable due to outage and malfunctioning. In such situations, UEs are promoted to assist with time synchronization reference (e.g. based on side-link power measurement or UE's own timing), authentication, detection, network discovery and attachment functions among the others. In addition, UEs may need to request the identity of the neighboring UEs (i.e. who is here) belonging to different PS authorities, which calls for the over-the-air sensing and self-reconfiguration functionality at the UE side. What is more challenging for public safety UEs is the support of (stored) data relaying from (isolated) neighboring UEs either to other UEs (UE-to-UE relay) or to the network (UE-to-network) when they are in-coverage.

1.4.3. *Programmability and Flexibility*

Programmability and flexibility in future public safety systems shall allow to rapidly establish 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 of previous network planning by using network function virtualization and software-defined networking. Thus, it will result in availability of open network interfaces, virtualization of networking infrastructure and rapid creation and deployment of network services with 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 the configuration and deployment to runtime management and disposal. This is very challenging as it has to optimize the resource allocation across multiple eNBs, to manage the topology especially during the network split and merge, and to determine the IP addressing space among the others.

1.4.4. *Traffic Steering and Scheduling*

The decisions about traffic steering concern control plane actions enabled to form a wireless mesh network and they shall be performed either at the network or higher layers. Selecting one or a subset of eNBs to steer the data-plane traffic allows users getting connected to the best fitted network according to their Quality of Service (QoS) requirements and the network resources availability. Aiming 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 or energy saving policies. Furthermore, the control and the data plane 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 (i.e. MAC/PHY). Therefore, a novel mechanism to support the BS meshing by giving access to the forwarding table at the lower layers is required. Such a mechanism can be implemented either locally or over the network. In the former case, the forwarding table can be simply built based on the routing table in a similar way as done in the standard IP forwarding mechanisms (e.g as in the multi-protocol label switching). In the latter case, a SDN approach can be applied to interface between the control and data plane.

1.4.5. *Optimization of Performance Metrics to Support Sufficient QoS*

A public safety network requires provision of sufficient services when a serving eNB currently experiences interruption on backhaul connectivity. Apart of the initiation of isolated E-UTRAN operation, such as exploitation of inter-eNB connectivity links for recovery of the system connectivity, a public safety 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 a more efficient operation on 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 (e.g. latency, throughput, spectral efficiency, etc.) upon the links and priority level assignment upon the EPS (Evolved Packet System) bearers. However, that introduces extra complexity on the decision-making process and a trade-off between optimal and quick decision needs to be attained.

1.5. LTE architectures for moving public safety networks

In current LTE architectures, eNBs are perceived as the active elements being responsible for the management and control of the radio access network. On the opposite, UEs are passive clients from the eNB perspective obeying certain rules and complying with the eNBs policies. Thus, eNBs and UEs relationship 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. Furthermore, the need to address those future mobility objectives as a means to meet public safety requirements in an isolated E-UTRAN operation is becoming essential. Towards this direction, the role of legacy eNBs and UEs should be reconsidered within the network. Depending on the situation, eNBs and UEs should be able to exchange roles in order to overcome inherent limitations that prevent seamless communication service in the whole network.

Following this approach, two novel solutions are delineated, that allow to realize inter-eNB link connectivity and restoration of the disrupted air interface by utilizing (*i*) evolved UEs (denoted as eUEs) and (*ii*) enhanced eNBs (denoted as e2NBs). The first refers to a UE-centric network-assisted solution. UEs are assigned with enhanced capabilities of associating to multiple eNBs using multiple UE stacks, and thus interconnecting adjacent eNBs. They act as 3GPP UE terminals maintaining their initial operation and also act as a slave with respect to the eNBs perspective. The second concerns a network-centric solution. eNB stack is extended with several UE stacks, in what is called an e2NB, allowing it to discover and connect to neighboring eNBs, forming a wireless mesh network.

1.5.1. *Evolved UEs (eUE)*

Evolved UEs as legacy user equipment do, interpret 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) and be utilized as intermediate nodes so as to forward the traffic originating from or destined for eNBs. Furthermore, eUEs have enhanced capabilities of associating to multiple eNBs and thus interconnecting adjacent eNBs [APO 15]. 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. They belong to the control of the radio access network (RAN) of the bridged eNBs. In sequence, a light-weight architecture is presented that employs eUEs to form a virtual MIMO and forward packets at L2/MAC for low-latency communication.

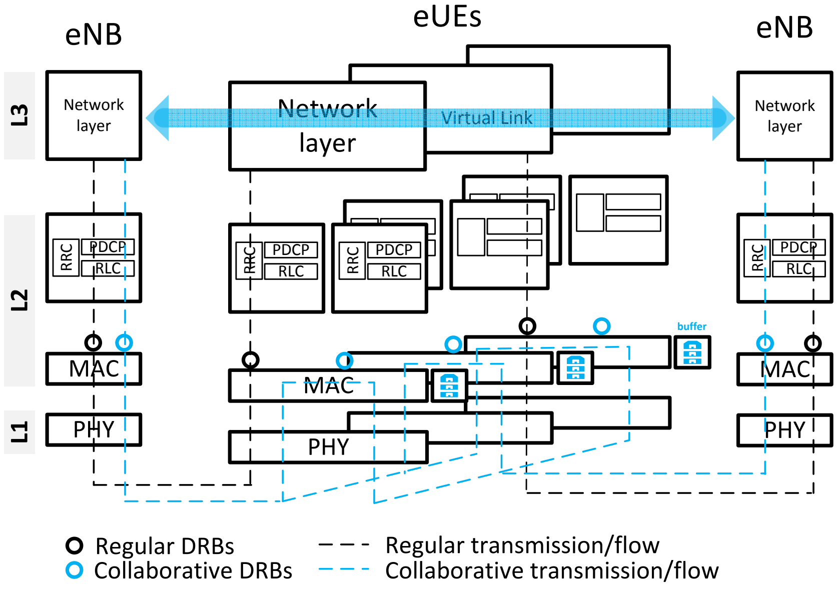

Figure 1.6. *Collaborative Transmission over a virtual link. eUEs adopt a dual protocol stack so as to be able to associate with two eNBs and perform efficiently L2 packet forwarding.*

1.5.1.1. *Flexible eUE Protocol Stack*

eUEs requires in L2 (Radio Resource Control (RRC), Radio Layer Control (RLC) and Packet Data Convergence Protocol (PDCP) sub-layers) a multiple-stack protocol in control and data-plane. This allows for eUEs to associate and communicate in parallel with multiple different eNBs and handle simultaneously regular and collaborative transmissions. Figure 1.6 illustrates the protocol stack of this mechanism that enables collaborative packet forwarding at L2 and multiple data radio bearer (DRB) reception. The goal is set to prevent packets that belong to a collaborative transmission from passing through the whole protocol stack aiming to reduce latency. At L1, a source eNB broadcasts packets to collaborative eUEs. If these packets are correctly received by the eUEs and belong to a Collaborative Data Radio Bearer, the L2/MAC of eEUs identifies their CO-RNTI (COllaborative Radio Network Temporary Identifier) and stores the packets temporarily in buffers. Then a collaborative transmission in uplink is scheduled by the destination eNB so as to activate eUEs to transmit the requested PDUs identified by their sequence numbers.

1.5.1.2. *Virtual Overlay - eUEs Enable Mesh Networking*

eUEs are used as a service by the network to enable a virtual overlay wireless mesh on the top of cellular topology that is abstracted by the eUEs collaboration[2]. Multiple eUEs can collaboratively participate to form VLs. A VL can be perceived into two phases: a broadcast point-to-multipoint (P2MP) phase from (source) eNB to eUEs and a cooperative multi-point-to-point (MP2P) phase from eUEs to (destination) eNB. Figure 1.7 illustrates the layered structure of a wireless mesh in a large scale.

Specifically, the interaction among the layers that is dynamically enabled by the eUEs requires a novel architecture to suggest a new type of collaborative transmission for cooperation that is realized as a CoMP (Coordinated MultiPoint) in uplink where eUEs form a virtual MIMO (Multiple Input Multiple Output) antenna for transmitting to the destination eNB. Particularly, this architecture implies the PHY layer to present a VL as a link abstraction to the MAC layer with a given probability of packet erasure, and subsequently, the MAC layer to present a VL as a channel abstraction to the network layer by enabling collaborative bearers that are used for local traffic routing between eNBs and end-to-end services.

– *Signal-level Cooperation* is operated by the PHY layer, which is responsible for identifying the optimal way to cooperate at the signal-level so that the bit error probability is minimized with respect to predefined quality constraints. Signal-level cooperation presents an interesting abstraction to higher layers: that is, a VL with a given probability of packet erasure. Moreover, cooperation at signal-level implicates

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[2] Software-defined networking techniques can be also applied to the virtual overlay network for enabling the wireless meshing.

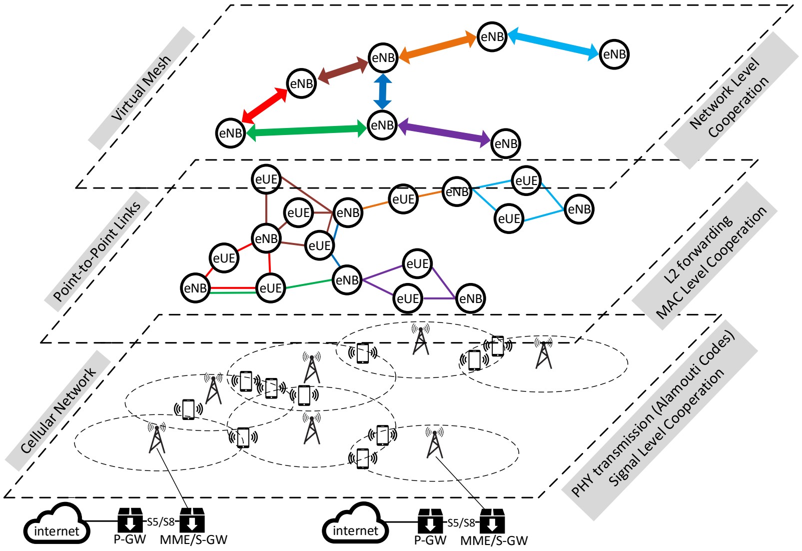

Figure 1.7. *eUEs enable mesh networking in cellular networks.*

all eUEs regardless of the perceived link quality in TX or RX mode with the interconnected eNBs.

– *Packet-level Cooperation* is operated by the MAC, or more generally Layer 2 (L2), which is responsible for packet-forwarding and scheduling. Specifically, L2 creates a virtual link by leveraging the legacy 3GPP connection establishment procedures in order to complete packet transmissions between two specific end-points. It identifies which physical links (PLs) and their respective end-points need to be activated so that the end-to-end frame error rate is minimized. The actual decision about VL establishment and PL activation is obtained by the higher layers. L2 from its side identifies and reports this induced relay selection to the higher layers. In addition to regular scheduling, MAC performs scheduling of collaborative broadcast in DL and CoMP transmission in UL[3].

– *Network-level Cooperation* The decision about local traffic routing and relay selection (control plane) over a VL can be performed either at the network or higher layers. This kind of information is passed to the MAC. Therefore, there is a need to select one or a group of eUEs that will serve as relays to enable signal and packet level cooperation (data plane).

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[3] The introduced CoMP in UL performed by users (eUEs) considers the distributed Alamouti coding as a general class for an independent yet coordinated transmission scheme.

1.5.1.3. *PHY Layer Design*

***Cell-search*:** Search procedures is the primary step to access the LTE network, and consists of a series of synchronization stages to determine time and frequency parameters required for correct timing in uplink and downlink. Standard LTE synchronization procedures allows a terminal to detect the primary and subsequently the secondary synchronization sequences (PSS, SSS) from at most 3 eNBs distinguished by their cell ID group (also known as physical layer identity) representing roots of the Zadoff-Chu sequences. [3GP 12].

***Synchronization*:** For core-isolated eNBs, over-the-air decentralized network synchronization can be utilized by allowing a designated (usually the *Donor* eNB) to provide a time reference synchronization within the network. Then, eUEs will propagate the signal to the core-isolated eNBs through a common synchronization channel. Ultimately, if a common external time reference like a GPS (Global Positioning System) signal is not available the fire-fly synchronization technique could be applied whenever a fully distributed approach is required [TYR 06].

***Coding*:** The PHY layer uses orthogonal frequency division multiple access (OFDMA) in a single frequency mesh network, where all network nodes eNBs, eUEs and UEs share the same resources both in DL and UL. In DL (eNB-to-eUE) a *Decode-and-Forward* (DF) technique is implemented. Then on the second hop in UL, a distributed Alamouti coding scheme is applied [JIN 04] to eUEs to form a virtual MIMO antenna. eUEs belonging on a VL can dynamically participate in the collaborative forwarding a-priori regardless their respective to eNBs link quality. The destination eNB specifies the same time-frequency resources for the framing allocation to the collaborative eUEs by sending them a scheduling grant with an additional information related to the PDUs sequence number, size and HARQ (Hybrid Automatic Repeat reQuest) id. Next, each eUE after having correctly decoded (positive integrity check) the requested protocol data unit (PDU) during the broadcast phase, it performs Alamouti coding independently as an autonomous antenna element and transmits the codes to the destination eNB.

1.5.1.4. *MAC Layer Design*

Collaborative packet forwarding requires a MAC mechanism to be able to manage VLs and perform packet forwarding. In such mechanism, packets are encoded in the source eNB with DF and then are broadcasted to the eUEs, where after successfully received by the eUEs, they are decoded and stored in the eUEs buffer queues maintained at the MAC layer. The reason why the packets are not forwarded directly to the destination eNB is twofold: *i*) In legacy 3GPP LTE, eNBs schedule packet transmissions, therefore eUEs cannot autonomously decide to transmit without having received a scheduling grant request by the destination eNB [4]. *ii*) If eUEs perform packet transmissions as soon as they receive them, synchronization and over-the-air signal level combination of the packets cannot be guaranteed at the second hop (eUEs-to-eNB). Figure 1.8 depicts the eUEs MAC layer which is composed of five additional functional blocks to handle the VL between two end-points, namely:

– *queuing:* It handles packet storage using MAC layer buffers. When a packet is correctly received by eUEs, it is stored locally at MAC buffers waiting to be scheduled by the destination eNB.

– *reporting:* It sends periodically the MAC buffer status report (BSR) to the destination eNB indicating which MAC PDUs have been correctly received and stored.

– *aggregation:* It is used to concatenate the requested MAC PDUs instructed by the destination eNB.

– *forwarding:* It identifies whether an incoming PDU on the intermediate eUEs is related to a VL, in which case queuing block will be instructed to store the PDU in a buffer associated with the destination eNB.

– *co-scheduling:* It schedules the outgoing PDUs on the intermediate eUEs corresponding to a VL requested by the destination eNB.

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[4] It should also be clarified here that the eUEs have already notified eNBs through a buffer status report (BSR) about their PDU availability.

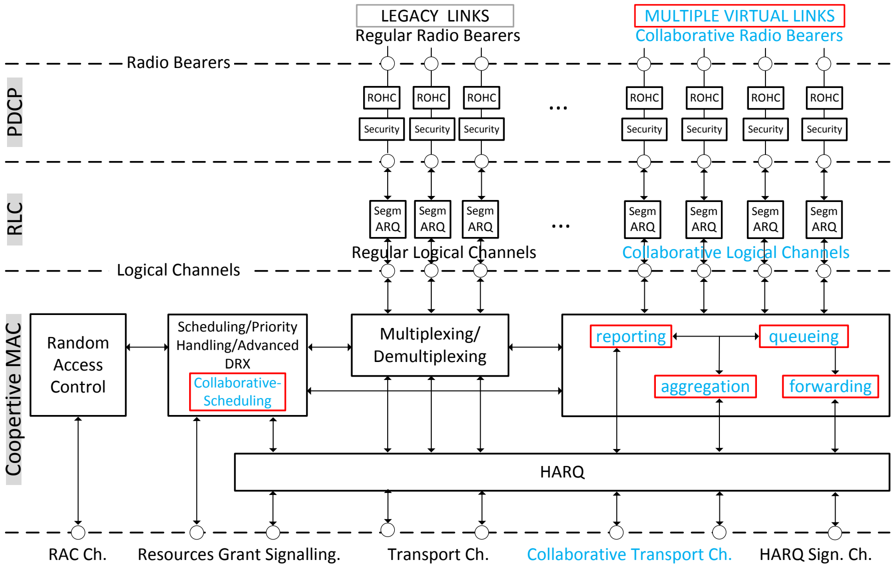


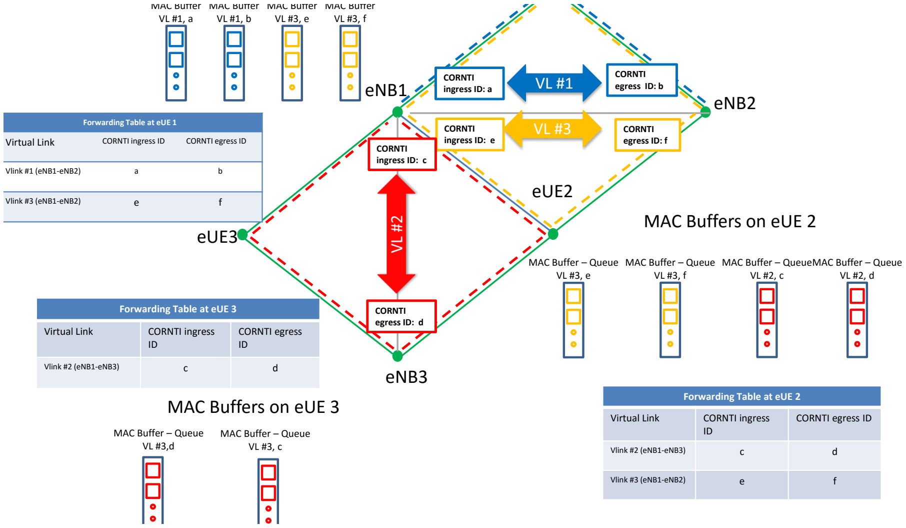
Figure 1.8. *eUE MAC layer architecture and collaborative logical channels: The functional blocks* aggregation, forwarding, reporting *and* queuing *and* co-scheduling *allow for buffer-aided collaborative packet forwarding to interconnect isolated eNBs.*

eUE Cell Association and Initialization: eUE initialization follows the same process of a legacy UE performing "*attach*" to its serving eNB and access to the core is provided by the S-GW and P-GW functionalities. The eUE retrieves configuration parameters from this certain eNB through the control-plane messaging and also a list of other eNBs to which it is allowed to attach. Then, an additional attach procedure is triggered with respect to one of the neighboring eNBs [3GP 13]. After the completion of this establishment procedure each eNB initiates the virtual data radio bearer interfaces and the corresponding PDU buffer queues.

Virtual Link Setup: When instructed by the higher layer, a VL establishment procedure is triggered by the source eNB to setup a collaborative radio bearer (CO-RB). Through this procedure, the VL will be mapped to a set of physical links (PLs) from a source eNB to eUEs and from eUEs to a destination eNB. A VL provides an abstraction to the cooperative transmission at the MAC layer and it is used as a means of hiding the information to higher layers: that is, a VL between two points is composed of several point-to-point links formed with the aid of intermediate forwarding eUEs. An eUE can participate at the same time in multiple VLs. and the MAC layer is responsible for managing them.

For that reason, a collaborative-RNTI is introduced as an identification number to differentiate a regular transmission from a collaborative one and identify that a certain packet belongs to a certain collaborative transmission via a VL. The CO-RNTI is carried as a part of the MAC header of the control packets that are transmitted from an eNB to eUE in order to establish the VL. A collaborative transmission over a VL requires at least one eUE acting as packet forwarder and two CO-RNTIs that describe the point-to-point transmission on the (eNB-eUE-eNB) physical links. Two CO-RNTIs (an ingress and an egress) can participate to form a VL setup. The ingress CO-RNTI is used by the source eNB to perform a collaborative broadcast and allow the eUEs to store the received data in the destination buffers associated with the egress CO-RNTI. The destination eNB will then schedule a collaborative transmission on this CO-RNTI based on the previously reported collaborative buffer status report (CO-BSR). Figure 1.9 illustrates a representative mesh topology where multiple VLs are being established between eNBs with the assistance of intermediate eUEs.

Virtual Link HARQ (VL-HARQ) strategy: HARQ strategy over a VL with multiple eUEs is not trivial, since the eUEs cooperate to send the same information but are physically separated. This fact creates, for example, possible loss of coherence inside the eUE HARQ buffers. To confront this problem, an HARQ strategy which tends to minimize latency and resource use while being robust is required. During the broadcast phase, the source eNB keeps sending redundancy versions (RV) of the packet with the ingress CO-RNTI, until all the eUEs have correctly detected it. In order to reduce latency, as soon as one of the eUEs correctly decodes the MAC PDU, it sends a BSR to the destination eNB. If the destination eNB decides to schedule the MAC PDU on the egress CO-RNTI, the scheduling information will be received by



Forwarding Table at eUE 1

Virtual Link	CORNTI ingress ID	CORNTI egress ID
Vlink #1 (eNB1-eNB2)	a	b
Vlink #3 (eNB1-eNB2)	e	f

Forwarding Table at eUE 3

Virtual Link	CORNTI ingress ID	CORNTI egress ID
Vlink #2 (eNB1-eNB3)	c	d

Forwarding Table at eUE 2

Virtual Link	CORNTI ingress ID	CORNTI egress ID
Vlink #2 (eNB1-eNB3)	c	d
Vlink #3 (eNB1-eNB2)	e	f

Figure 1.9. *Establishing multiple VLs over a wireless mesh network.*

all the eUEs, even to those not having correctly decoded the MAC PDU yet. Then, all the eUEs create a (virtual) HARQ process associated to the sequence number (SN) of the MAC PDU, which is contained in the scheduling information.

Adaptive Modulation and Coding (AMC): In LTE, the AMC is performed according to the Channel Quality Indicator (CQI) values that UEs report back to the eNBs so as to support the highest Modulation and Coding Scheme (MCS) that can effectively decode packets with a Block Error Rate (BLER) probability not exceeding 10% [SES 09]. For a given MCS an appropriate code rate is chosen relying on the Table 7.2.3.1 of 3GPP TS36.213. A key issue in the design of AMC policy in the two-hop topology interconnecting two eNBs is whether the MCS assigned to a specific eUE for a collaborative transmission should be the same over the two hops or different exploiting the intermediate buffer storage at the eUEs. In the 1st case, the source eNB uses that MCS that captures a representative CQI (e.g. it can be dynamically selected using metrics i.e. average or worst over the two consecutive physical links) for the eUE configuration so as to minimize packet drops and sustain adequate end-to-end communication quality and reliability. In the 2nd case, each interconnected eNB can opportunistically use a different MCS for the transmissions with the bridging eUE relying on the fact that packets are temporarily stored in the buffers in order to be transmitted with the best possible MCS over each physical link.

1.5.2. *Enhanced evolved Node B (e2NB)*

This section introduces the e2NB as an enhanced version of the standard LTE/LTE-A eNB and describes its components and functions.

As for the eUEs, the design goal is set to reuse the existing LTE air interface and to establish over-the-air inter-eNB communications. Instead, the e2NB solution relies on leveraging the 3GPP eNB functions. The key attributes of the e2NB solution consist of: (*i*) the ability to provide service to mobile UEs and maintain the legacy eNB operation as a standalone node, and (*ii*) the ability to form a wireless mesh network when it is in close proximity to other e2NBs while maintaining the service for the mobile entities. To do that, an e2NB reuses the existing LTE components but with a different composition to expand classical eNB functions [FAV 15]. The minimal involved components include:

- Single eNB;
- Single MME (Mobility Management Entity);
- Single HSS (Home Subscriber Server);
- Multiple UEs as a service, denoted as virtual UEs (vUEs);
- one radio chain (Tx/Rx).

Depending on the target deployment and use case, the remaining LTE components such as S/P-GW (Serving and Packet Data Network Gateway), PCRF (Policy and Charging Rules Function), may also be included in e2NB. Moreover, an e2NB requires two additional functions, namely:

- Coordination and Orchestration Entity (COE);
- Routing and data forwarding.

1.5.2.1. *Protocol Stack*

These components are not working independently and have several relationships that can be modeled as the protocol stack shown in Figure 1.10. It can be seen that an e2NB preserves the existing eNB and UE functions in that it does not modify the protocol stack (IP, RRC, PDCP, RLC, MAC, PHY) of the embedded eNB and UEs. To enable a standalone operational mode, an e2NB also requires the NAS (Non Access Stratum) and routing protocols. The COE acts as a connectivity manager coordinating all these layers to enable the inter-e2NB communications as well as a topology manager working with the other COEs to optimize the network. In the following, the role of each component of the e2NB is described.

eNB provides the same operations as a legacy 3GPP eNB in that it communicates with UEs through the legacy Uu air interface and with MME and optionally S-GW through the legacy S1 interface [SES 09].

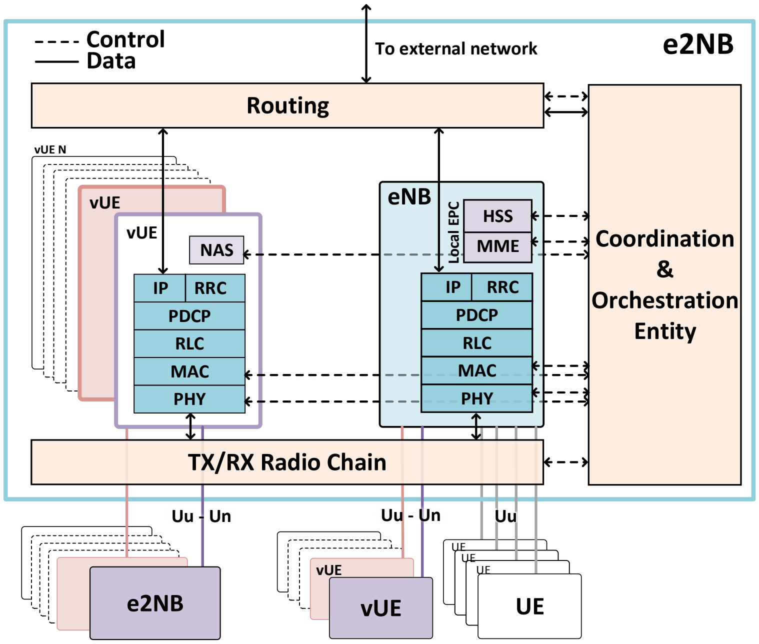


Figure 1.10. *Enhanced Evolved Node B (e2NB) Stack*

MME and HSS allow the e2NB standalone functionality and they interact with the embedded eNB. The HSS includes a database of authorized users on the network and can be accessed through the S6a interface.

vUEs establish the inter-eNB communications. A vUE includes the entire protocol stack of a legacy UE required to establish a communication with an eNB. It is used to detect the existence of an e2NB in the radio vicinity, to report the real-time radio information such as received signal strength to the COE, and to establish a connection when instructed by the COE.

Routing enables a fast routing and data forwarding at the e2NB. S/P-GW are bypassed. This allows an e2NB to send and receive IP packets directly from the eNB and vUEs PDCP layer and to perform (local) routing for each packet. Contrary to classical eNBs, an e2NB can act as an end point (e. g. gateway) and have external interfaces to be connected to other networks. The routing protocol determines data forwarding paths according to the rules provided by the COE.

COE manages the entire life-cycle of vUEs from the configuration and deployment to runtime management and disposal. It provides each of them with a IMEI and a SIM service (IMSI + cryptographic functions), allowing them to be authenticated by the other e2NBs. In addition, the COE keeps track of the e2NB connectivity (via its own vUEs and those of neighboring e2NBs connected to its eNB). This helps it to cooperate with other COEs in order to optimize the

> resource allocation across multiple e2NBs and to manage the topology in terms of network split and merge. The COE also determines the IP addressing space and provides routes according to adhoc/mesh routing algorithms. It can be seen as a local controller and could be designed following the software-define networking (SDN) principles. Finally, the COE is controlling the access to the radio front-end required by both the embedded eNB and vUEs.

The 3GPP LTE specifications define everything for over-the-air communications between UEs and eNBs using Uu interface. But there is nothing for over-the-air communications between eNBs as it is not required for the classical use cases. However, relays have been defined in Rel.10 and are able to communicate to UEs using Uu interface and to their Donor eNB (DeNB) using Un interface, but they are currently static, limited to a connection to one DeNB, and you can not chained them even though some studies have tried to express the gain of such chained architectures [ARO 11].

1.5.2.2. *PHY Layer Design*

LTE physical air-interface is organized in 10ms frames sub-divided in ten 1ms subframes (SFs). Each subframe contains 12 or 14 OFDM (Orthogonal Frequency-Division Multiplexing) symbols depending on the cycle-prefix length. An eNB has several predefined procedures regarding what it should transmit or not in the SFs of a frame. First, it has to transmit the first OFDM symbols on every SF for the control channels, namely Physical Downlink Control Channel (PDCCH), Physical Control Format Indicator Channel (PCFICH), and Physical Hybrid-ARQ Indicator Channel (PHICH). Primary and Secondary Synchronization Signals (PSS and SSS) must be transmitted in the SFs number 0 and 5 (in Frequency Division Duplex (FDD)) along with the Physical Broadcast Channel (PBCH) in SF number 0. Finally, it must transmit reference signals (RS) on all downlink (DL) SFs, even if there is no data to transmit on the Physical Downlink Shared Channel (PDSCH).

The solution chosen by the relay nodes to enable communication with their Donor eNB (DeNB) while maintaining compatibility with Rel.8 UEs is to make use of Multicast Broadcast Single Frequency Network (MBSFN) SFs [YUA 13, HOY 12]. The MBSFN SFs allow an eNB/relay to send the first symbols containing PDCCH, PCFICH and PHICH while not sending the other symbols including the RS. New control and data channels (R-PDCCH and R-PDSCH) are introduced to use the empty symbols in the MBSFN SFs for the DL communication, i.e. from DeNB to relay. For the relay to DeNB communication, the relays determine which uplink (UL) SFs have to be used for the communication with their DeNB and then use the remaining ones for the UE-to-relay communication. In FDD DL, only SFs number 1, 2, 3, 6, 7 and 8 can be used as MBSFN SFs. A relay can use the corresponding UL SFs (i.e. DL SF # + 4) to perform UL transmissions to the DeNB. Thus, in FDD, a relay performs a DL transmission to legacy UEs on SFs number 0, 4, 5, 9 and on the MBSFN SFs that are not used for the relay to DeNB link (backhaul link). In UL, a relay receives on SF number

3, 4, 8, 9 and those not used for MBSFN SFs # + 4 (as UL SFs are scheduled at DL SF # + 4). The e2NB applies the same solution as relays to maintain compatibility with the legacy UEs, and uses the MBSFN SFs to give its vUEs access to the DL channel. Then, the vUEs can receive on the MBSFN SFs that are not in use by the embedded eNB, i.e. SF number 1, 2, 3, 6, 7 and 8 in FDD. This limits the maximum number of DL SFs an e2NB can receive through all its vUEs to 6. In UL, vUEs can send at DL SF # + 4 after receiving downlink control information (DCI) with UL grant as in case of legacy UE. This leads also to a limit of 6 UL SFs per e2NB for all their vUEs in FDD. TDD can be used in the same way. It has tighter restrictions on the number of MBSFN SFs but it simplifies the radio chain architecture.

Hybrid ARQ: The e2NB HARQ mechanisms remain unchanged with respect to the relaying case. For DL, the e2NB expects to receive the ACK/NACK for both legacy UEs as well as vUEs 4ms after the transmission, and in case of NACK the re-transmission will be determined by the e2NB. For UL, HARQ acknowledgments are transmitted on PHICH for regular UEs and on R-PDCCH for the vUEs. However, the SF where the re-transmission should take place (8 ms after the initial transmission for FDD) may not be available for the UL transmission (e.g. e2NB is using the UL channel for its vUEs), even if the HARQ ACK can be received. In such a case, the corresponding UL HARQ process needs to be postponed by transmitting an ACK on the PHICH, irrespective of the outcome of the decoding [DAH 11]. By using PDCCH, an adaptive re-transmission can instead be requested in a later SF available for the same HARQ process. Note that in such a case, the HARQ round-trip time will be larger than 8ms. Because vUEs can only receive up to 6 UL SFs per frame, it is not efficient to keep the 8 HARQ processes cycle as for the legacy UEs. In particular, when the available MBSFN SFs are determined for a configured repetition period (i.e. fixed SF allocation), the COE will adjust the number of HARQ processes to the number of available UL SFs for a vUE over a frame or over the corresponding cycle.

vUE Attach Procedure: Contrary to the relay that first connects to its DeNB before starting to serve UEs and thus has full access to the DL channel, an e2NB must be able to dynamically start a connection with a neighboring e2NB without dropping the UEs it is serving. The classical UE attachment and authentication procedures remain the same for the vUE to connect to a neighbor eNB but they influence the way the COE manages the embedded eNB. A vUE needs to listen at least to PSS, SSS, MIB (in PBCH) and SIB1 to detect and identify an eNB, as well as the SIB2 to start a random access procedure. In FDD, PSS and PBCH are broadcasted on SF 0, SSS and SIB1 on SF 5, and SIB2 location is given by SIB1. If the eNBs of different e2NBs are frame synchronized, the SFs are used by the neighboring eNBs at the same time and thus a vUE listening on MBSFN SFs would not be able to detect a neighboring e2NB. In addition, a vUE needs to access the PDCCH to decode SIB1 and SIB2, which is not possible by just blanking some of the available MBSFN SFs as it give access only to the PDSCH part of the SF. To address this problem, e2NB blanks an entire 10ms frame allowing a vUE to listen to the DL channel during this time and to receive these elements from the neighboring e2NB(s). Blanking a full frame is feasible in LTE and does not result in a UE and/or vUE disconnection. Indeed, a UE/vUE becomes out-of-sync if it does not receive anything during a period defined as $200ms*N310+T310$, with the value of N310[5] and T310[6] signaled in SIB2. e2NB applies several blank frames coordinated in time to proceed with the full attachment of its vUE to a neighboring e2NB. The eNB timings related to the UE/vUE random access may be loosen to reduce the frame blanking periodicity of the connecting e2NB and make it easier to maintain an adequate QoS for the connected UEs. The vUE uses pre-defined authentication keys that are shared by all HSS of e2NBs planned to be interconnected during the operation (e.g. e2NBs of the same group). It allows the e2NBs to identify the vUEs and the group they belong to so that the appropriate policies can be applied when establishing the connection.

Synchronization: Contrary to relays that have only one backhaul link, an e2NB manages several vUEs that are connected to different e2NBs. It also has vUEs of other e2NBs connected to its eNB. Fixed relays are not necessarily synchronized at symbol-level with their DeNB. It allows them to compensate the propagation delay, and as a result increases the total number of symbols a relay can receive over a SF. Although this can work in a tree topology, it is mandatory to be symbol synchronized in a mesh topology. If e2NBs are not synchronized and rely only on the timing advance of one to another, then the SFs symbol alignment may be broken across e2NBs causing backhaul link failure [YUA 13]. To synchronize, each incoming e2NB willing to join the mesh network uses its vUE to determine the time reference of the network. It then uses self-handover techniques for keeping its UEs of being dropped when the internal eNB synchronizes itself.

1.5.2.3. *MAC Layer Design*

Resource Allocation: As long as multiple e2NBs are using the same frequency band, there is need for some resource allocation coordination to avoid unwanted interference. If the e2NB are not yet connected to each other but close enough to have their coverage area overlapping, users at edge cell car experience severe interference problems. To cope with that, eNBs traditionally use the inter-cell interference coordination (ICIC) or the evolved ICIC (eICIC) mechanisms, as defined by 3GPP. These mechanisms make use of UE reports and of the X2 interface between the eNBs. Before being connected through their vUEs, adjacent eNBs may use other links if available (e.g satellite) to restore this interface and use (e)ICIC. When an e2NB has a LTE connectivity with at least another e2NB, it use it to transport a X2 link and reduce interference for classical UEs. But the COE also needs to determine the efficient time and frequency share of spectral resources among the neighboring e2NBs to achieve

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[5] This parameter indicates the number of times the UE cannot successfully decode any frame in 20 consecutive frames (200ms).

[6] A timer, in seconds, used to allow a UE to get back in synchronization with the eNB.

a near optimal performance. The COE must be aware of the allocation of neighboring e2NBs to avoid interference and coordinate transmissions efficiently such that the transmission of an eNB could be heard by the target vUE of a neighboring e2NB. For instance, an e2NB can send to several vUEs on one SF. This e2NB must know that these vUEs are listening at that time as they cannot listen all the time. Plus, the neighboring e2NBs of the receiving vUEs must not transmit on this SF (except in case of beam-forming) to avoid interference in their direction on this SF and over the same frequency resources or it would create strong interference. But this management cannot be done by each node individually, it must be carefully computed and applied over several adjacent nodes to avoid dramatic interference. Several strategies can be used, we can for instance elect a cluster head responsible for the computing and acting as a radio resource management (RRM) unit, or rely on distributed algorithms. Of course, a trend has to be found between the adequacy of the allocated resources and the updating frequency of them to limit the overhead of control messages between COEs. The COE then needs to apply the configured allocation to its vUEs and eNB schedulers and needs to control the access to the RF front-end accordingly.

Handover: Terminal mobility may trigger a handover among the meshed e2NBs. Upon reception of the measurement report, an e2NB may initiate an X2 handover as in the standard X2 handover procedure. However, it also requires to transfer the HSS context to the target e2NB in addition to the security context so that the handed over UE can be authenticated and reattached in case of disconnection.

1.6. Evaluation of the 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, the OpenAirInterface platform is leveraged [NIK 14]. OpenAirInterface is an Open-source software implementation of the fourth generation mobile cellular system that is fully compliant with the 3GPP LTE standards and can be used for real-time indoor/outdoor experimentation and demonstration.

1.6.1. *eUE evaluation*

Topology Description: The system validation scenario consists of two eNBs and four eUEs located in an area of $500m^2$. Table 1.2 summarizes the system configuration setup Figure 1.11 illustrates the logical topology. A 5MHz channel bandwidth (25 RB) is used where the maximum data rate of the collaborative link (UL) is 12 Mbps.

Efficient L2/MAC forwarding: The MAC layer performance is measured in terms of latency, packet loss rate and throughput for different number of UEs=$\{1,2,3,4\}$ and for different BLER probabilities for the backhaul link ($1st$ hop: DL source eNB-to-eUEs) and for a bad channel configuration on the $2nd$ hop UL (eUEs-to dest eNB) characterized by a BLER probability equals to 0.18. The above setup captures a harsh scenario where eUEs assistance is validated. The traffic pattern is defined by a fixed

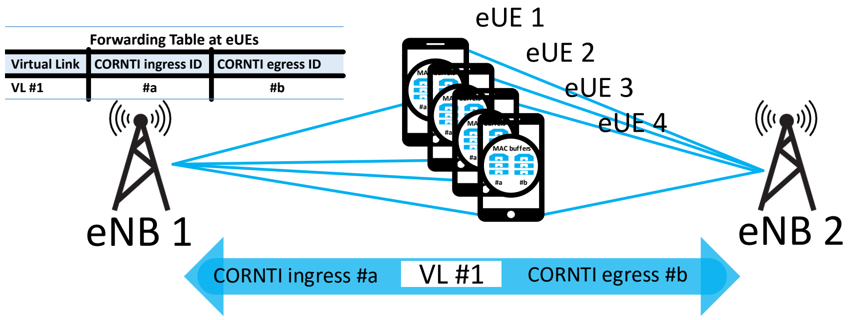
Table 1.2. *LTE-A TDD System Configuration*

Parameter	***Value***	***Parameter***	***Value***
Carrier Freq.	1.9 GHz	*Traffic Type*	UDP
Bandwidth	5MHz	*Fading*	AWGN Ch.
Frame Duration	10ms	*Pathloss*	-50dB
TTI	1 ms	*Pathloss Exp.*	2.67
UEs	$1, 2, 3, 4$	*Mobility*	Random

packet inter-arrival time of 20ms and a uniformly distributed packet size from 512 to 1408 bytes.

Figure 1.12 illustrates the obtained results for the above scenario and demonstrates clearly the eUEs contribution. As the number of employed eUEs increases, the latency and packet loss rate reduces while there is an improvement on end-to-end throughput performance. For the sake of comparison 3GPP, latency requirements for QoS Class Identifiers QCIs 1 and 4 that characterize two guaranteed bit rate (GBR) bearer types for VoIP call and Video streaming are set to 100ms and 300ms respectively [SES 09]. Using 4 collaborative eUEs the measured latency is constantly below 60ms for all BLER probabilities, thus achieving low latency.

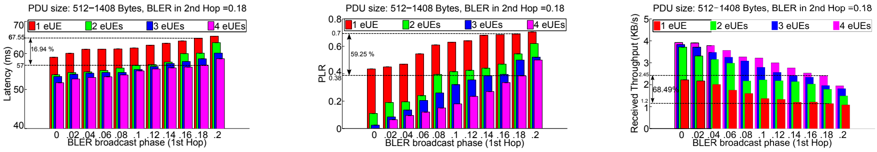
Collaborative Performance Rationale: An important finding is that as the number of eUEs increases the respective periodicity that the eNB receives the PDUs from the collaborative MAC actually decreases, thus reducing drastically the communication latency. Indicatively, experimentation results reveal a significant reduction in latency (up to 16.94%) and improvement on packet loss rate (up to 59.25%) for BLER equals to 18% on the first and second hop (see Figure 1.12.(a) and (b)). Moreover, for the considered traffic load, significant gain (up to 68.49%) on the achievable throughput is observed (see Figure 1.12.(c)).



Forwarding Table at eUEs

Virtual Link	CORNTI ingress ID	CORNTI egress ID
VL #1	#a	#b

Figure 1.11. *Four eUEs interconnecting two eNBs.*



(a) Latency. (b) Packet Loss Rate. (c) Received Throughput.

Figure 1.12. *OAI Measurement Results of a LTE wireless mesh network enabled by eUEs.*

The impact of queuing storage: Each eUE maintains for each VL two MAC buffers for the corresponding ingress and egress CO-RNTIs. Those buffers are utilized reciprocally in both directions to store the incoming PDUs identified by their ingress and egress CO-RNTIs. The absence of the buffers would cause all the PDUs to be lost as it would be impossible to be forwarded directly to the destination eNB without scheduling. In this experimentation, a maximum buffer size equals to 100 PDUs was used. As the buffer storage capacity increases, the PLR is expected to be reduced. However, this comes at a cost of increased overhead and storage for the MAC layer that needs to be attained. Another benefit from maintaining buffers is that they used to store the PDUs until their reception will be acknowledged. As the BLER increases, the PLR grows slightly constant (see Figure 1.12.(b)) as buffers aid in robust transmission and packet recovery.

The benefit of the signal level cooperation in throughput: The actual throughput benefit that is attained by the destination eNB (see Figure 1.12.(c)) is due to signal-level cooperation. The more the number of collaborating eUEs is, the more the over the air signal combining allows the destination eNB to increase its received throughput (up to $\sim$60% using 4 eUEs) even in bad communication condition with BLER up to 20%.

1.6.2. *e2NB evaluation*

The connectivity between two e2NBs working as decribed in section 1.5.2 is evaluated. Two vUE-e2NB links are created allowing the use a subset of uplink and downlink subframes (SFs) from one e2NB to the other and each of them has one classical UE connected as presented in figure. 1.13.

Due to platform constraints, two assumptions differ from the real case: (a) the propagation delay is close to zero, and (b) Tx/Rx switching time is close to zero. The later is required to use a Uu interface between the e2NBs and the vUEs, instead of a Un interface. The main difference compared to the real case is that the maximum data rate is increased as more symbols per SF can be used for the data plane.

Table 1.3. *e2NB Evaluation Emulation Parameters*

Parameter	*Value*	*Parameter*	*Value*
Carrier Freq.	0.9 GHz	*Max. Tx Pwr (dBm)*	eNB 24.7 - (v)UE 23
Bandwidth	5MHz	*Max. MCS*	DL 26 - UL 16
Pathloss at 1km	-91dB	*RLC Mode*	UM
Pathloss Exp.	3	*RLC reorder. timer*	35ms
Fading	AWGN	*SR Periodicity*	2ms - even SF only
Trans. Mode	1	*Packet IDT*	uniform $10-50$ms
Antenna	Omni 0dBi	*Packet Size*	uniform $64-1408$ bytes

1.6.2.1. *e2NB link evaluation*

The evaluation of the link between (a) and (b) is first conducted. The initial attach procedure is already completed when a Variable Bit Rate (VBR) traffic flow is started on each available data path between the e2NBs. Both e2NBs apply dynamic scheduling.

Several scenarios were applied, characterized by a different number of available uplink and downlink subframes (SF) for the e2NB to vUE links. A summary of emulation parameters is provided in Table 1.3.

The packet latency of UL and DL flows is plotted as box plots[7] on figure 1.14.A. On figure 1.14.B are shown the average goodput and max continous datarate depending on the number of available subframes.

It can be seen that using UL or DL, the latency improves as the number of available SFs increases, but also that DL shows significant lower latency overall. This is mainly due to the UL signaling overhead of dynamic scheduling (scheduling request (SR) and scheduling grant prior to data transmission). Thus, the performance depends on the resource allocation but also on the scheduling choice of using UL or DL path.

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[7] Boxes are limited by first (q1) and third quartile (q3) and contains the median. Whiskers extend from $q1 - 1,5 * (q3 - q1)$ to $q3 + 1,5 * (q3 - q1)$.

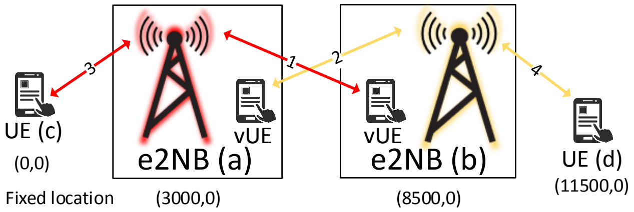
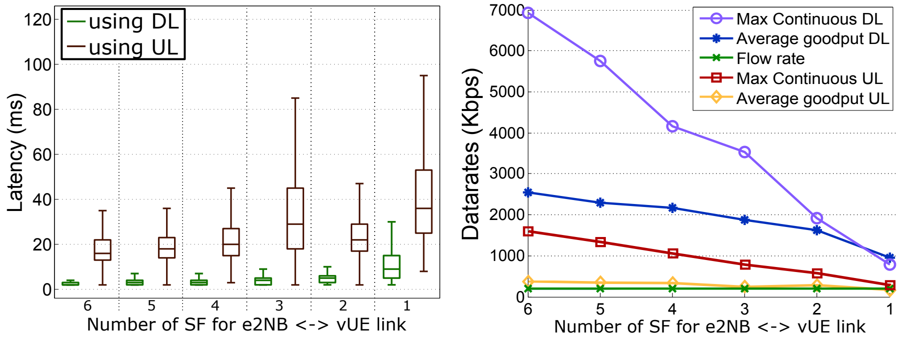


Figure 1.13. *e2NB evaluation topology : two vUEs interconnecting two e2NBs*



***(A)** Latency* ***(B)** Datarate*

Figure 1.14. *Performance of inter-e2NB backhaul link*

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.

1.6.3. *Multi-hop operation*

In this experiment, e2NB (a) and (b) are fixed and connected to UE (c) and (d), respectively (see figure 1.13). Static routes are added allowing to forward the data toward the destination in a multi-hop fashion following different combination of DL and UL links. The SF allocation is even, 3 SFs are available for DL and UL in both ways.

VBR traffic of table 1.3 and VoIP G729 traffic patterns are generated. Several emulation are run, with each time a different combination of links. First from (c) to (a) to get the performance of the first hop (classical UE UL). Then from (c) to (d) (3 hops) with the second hop between (a) and (b) using first a DL path and second a UL path. Finally, with VoIP G729 traffic pattern, additional hops are configured between (a) and (b) to simulate a wider network.

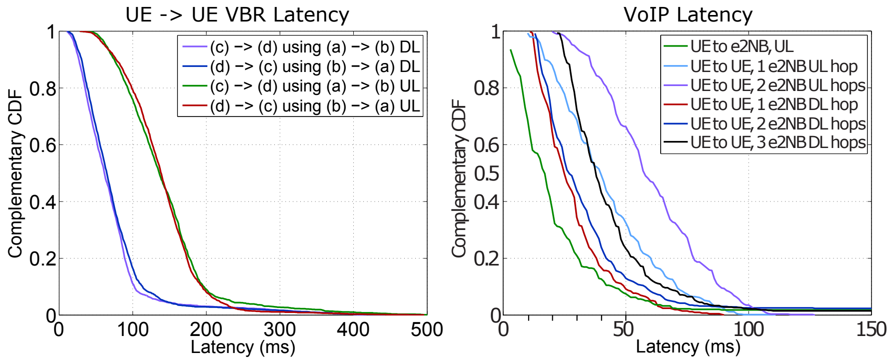


Figure 1.15. *Latency of Variable Bit Rate (VBR) flow and VoIP over multi-hop*

The results are shown in Figure 1.15 in the form of a complementary CDF (CCDF) plot, where each latency value in the plot displays the fraction of traffic with latency greater than that value. It can be seen that the end-to-end latency is almost doubled when using a UL path over a DL one for the VBR flows, confirming the previous results. Although the SF allocation of e2NBs is different, the two ways behave similarly on the end-to-end point of view. It can be seen that all the tested cases are efficient enough to satisfy the LTE QoS requirement of 100ms latency for VoIP. Using two e2NB UL hops (four hops end-to-end) is close to the limit and using a third one would not satisfy the requirement. On the contrary, some room is still available after three e2NB DL hops (five hops end-to-end) confirming that it can be used for VoIP communications over multiple hops.

1.7. Discussion

Some research papers provide insight of full solutions when no backhaul is available, providing inter-eNB connectivity thanks to WiFi links and including D2D communications that were not yet defined by the ProSe specifications of 3GPP studies [GOM 14]. Other technologies are usually used to establish wireless backhaul supporting fixed LTE networks: point-to-point (PTP) radio frequency (RF) or free space optics (FSO) links and point to multi-point (PTMP) RF links. In the case of portable BS, satellite backhaul links are sometimes used. However, it can be easily seen that these wireless solutions are not adequate to the establishment of a network of BS enabling voice and data communications in moving cells scenarios.

For instance, Table 1.7 shows the main differentiating criteria. Despite great performance, PTP and PTMP solutions often require line-of-sight wireless connectivity with careful network planning, which make them not applicable to the moving cell scenarios. Satellite backhauling, on the other hand, provides the best possible coverage but need dedicated tracking antennas and suffers from high cost. More importantly it has high latency ($\geq$200ms) that limits voice and data services [CAS 15]. WiFi solutions using omni-directional antennas are promising solutions if the higher layers

BS Backhauling	**PT(M)P/FSO**	**SAT**	**WiFi**	**eUEs**	**e2NBs**
Frequency band	ISM or licensed	Licensed	ISM, possibly licensed	Licensed	Licensed
Link Latency	Very Low	High	Low-Medium	Low-Medium	Low
BS mobility	No	If tracking antenna	If omni-antennas	Yes	Yes
Cost	+++	++++	++	++	+
Topology	Star/Mesh	Star	Star/Mesh	Mesh	Mesh

Table 1.4. *Main characteristics of base stations backhauling solutions*

and protocols allow for efficient and dynamic meshing, similar to the proposed LTE-based solutions (i.e. eUE and e2NB). However, dedicated equipment and antennas are needed for WiFi backhauling, thus increasing the cost of BS. In addition, commodity WiFi works on ISM bands and thus can experience a large interference compared to the licensed bands used for LTE. To solve this problem, some countries define their own licensed bands for the PS WiFi. Last but not least, studies on commercial networks have shown that the WiFi latency is on average a bit higher and has more jitter than that of LTE although results might differ for PS networks [HUA 12] and other studies have shown that the WiFi latency is higher than that of LTE, especially when the traffic load and number of users increase [HUA 13]. 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.

1.8. 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 the isolated network segments to maintain the communication, service, and application as desired [HU 15]. Packet core network functions (e.g. MME, HSS), IP Multimedia Subsystem (IMS), routing, topology management are those network functions that can be enabled at the BS to restore the communication links. Traffic steering, video analytics, content sharing, and localization are the example of network applications that can extend the BS functions in order to preserve user service and application.

As it has been introduced, Fourth Generation Long Term Evolution (LTE) has been selected by US federal and EU authorities to be the technology for public-safety (PS) networks that would allow first responders to seamlessly communicate between agencies and across geographies in tactical and emergency scenarios. While 3GPP has been underway to develop and specify dedicated, nationwide public safety broadband networks that will be scalable, robust and resilient, while also able to address the specific communication needs of emergency services, it has been seen in this chapter that the requirements and scenarios for isolated Evolved Universal Terrestrial Radio Access Network (E-UTRAN) with no or limited backhaul access to the core network are still in progress. In this chapter, innovative solutions in the context of public safety networks were elaborated to support an efficient isolated E-UTRAN operation. The shortcomings on the state-of-the-art technology were identified. It is currently inappropriate to sufficiently deliver seamless and continuous backhaul connectivity in moving cell scenarios, thus making first responders and tactical forces be deprived of critical communications. Particularly, in a such volatile and dynamic environment for public safety communication, (*i*) evolving UEs as active network elements to restore disrupted air-interfaces between bridging eNBs, and (*ii*) enhancing the role of legacy eNBs to encompass a dual protocol stack operation for enabling base station meshing, become of utmost importance to preserve the integrity of communication. Relying on the open challenges, we outlined the significant requirements on the field of service provision and related open research directions were discussed.

Chapter 2

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