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Performance Analysis of LTE-Advanced Relay Node in Public Safety Communication

School of Electrical Engineering

Thesis submitted for examination for the degree of Master of Science in Technology.

Espoo August 29, 2012

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ABSTRACT OF THE
MASTER'S THESIS

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Title: **Performance Analysis of LTE-Advanced Relay Node in Public Safety Communication**

Date: August 29, 2012 Language: English Number of pages:10+48

Department of Communications and Networking Engineering

Professorship: Radio Communications Code: S-72

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Relaying is emerging as one of promising radio access network techniques for LTE-Advanced networks that provide coverage extension gain with improved quality of service. It enables improved high data rate coverage for indoor environments or at the cell edge by deploying low power base station.

The need for high-quality on-the-spot emergency care necessitates access to reliable broadband connectivity for emergency telemedicine services used by paramedics in the field. In a significant proportion of recorded cases, these medical emergencies would tend to occur in indoor locations. However, broadband wireless connectivity may be of low quality due to poor indoor coverage of macro-cellular public mobile networks, or may be unreliable and/or inaccessible in the case of private Wi-Fi networks.

To that end, relaying is one of the optimal solution to provide required indoor coverage. This paper analyzes the use of nomadic relays that could be temporarily deployed close to a building as part of the medical emergency response. The objective is to provide improved indoor coverage for paramedics located within the building for enhanced downlink performance (throughput gain, lower outage probability).

For that scenario, we propose a resource sharing algorithm based on static relay link with exclusive assigned subframes at the macro base station (MBS) coupled with access link prioritization for paramedic's terminals to achieve max-min fairness. Via a comprehensive system-level simulations, incorporating standard urban propagation models, the results indicate that paramedics are always able to obtain improved performance when connected via the relay enhanced cell (REC) networks rather than the MBS only.

Keywords: Relay Node, Relay Enhanced Cell, Indoor Coverage, Emergency Telemedicine, Long-Term Evolution,Outage Probability

Acknowledgements

First and foremost, I would like to offer my sincerest gratitude to my supervisor Professor Jyri Hämäläinen for his supportive behaviour and encouragement through my master's degree studies. I deeply thankful for his solid technical assistance and invaluable guidance throughout my master thesis.

During the entire thesis work, I appreciate Zhong Zheng for his extreme patience and courage, the way he guide me like a prep student. Special thanks to him for providing a concrete and technical assistance at every stage of my thesis.

Moreover, I am thankful to all the members of student service office especially Jenni Tulensalo, Pia Sarpolahti and Sirpa Taivainen for their efforts and providing a continuous administrative support upto completion of my master studies.

Lastly, but not least, I am deeply obliged to my parents and family members for their all time support and love to me at every difficult part of my life. Henceforth, I am dedicating this thesis work to them.

Espoo, 28^{th}**August 2012**

Inam Ullah

Contents

Abbreviations

1G	*First Generation*
2G	*Second Generation*
3G	*Third Generation*
3GPP	*Third Generation Partnership Project*
4G	*Fourth Generation*
AF	*Amplify and Forward*
AMC	*Adaptive Modulation and Coding*
AMPS	*Advanced Mobile Phone Service*
AWGN	*Additive White Gaussian Noise*
BCCH	*Broadcast Control Channel*
BCH	*Broadcast Channel*
BER	*Bit Error Rate*
CAPEX	*Capital Expenditure*
CDF	*Cumulative Distribution Function*
CDMA	*Code Division Multiple Access*
CDS	*Channel Dependent Scheduling*
CEPT	*Conference of Postal and Telecommunications Administrations*
CN	*Core Network*
CP	*Cyclic Prefix*
CRC	*Cyclic Redundancy Check*
CSI	*Channel State Information*
DCA	*Dynamic Channel Allocation*
DCCH	*Dedicated Control Channel*
DF	*Decode and Forward*
DL	*Downlink*
DL-SCH	*Downlink Shared Channel*
DRX	*Discontinuous Reception*
DTCH	*Dedicated Traffic Channel*
E2E	*End-to-End*
eNB	*Enhanced Node-B*
EPC	*Evolved Packet Core*
ETSI	*European Telecommunications Standards Institute*
FDD	*Frequency Division Duplex*
FDMA	*Frequency Division Multiple Access*
FH	*Frequency Hopping*
GPRS	*General Packet Radio Service*
GPS	*Global Positioning System*
GSM	*Global System for Mobile Telephony*
HARQ	*Hybrid Automatic Repeat Request*
HeNB	*Home Enhanced Node-B*
HLR	*Home Location Register*
HSPA	*High Speed Packet Access*
HSS	*Home Subscriber Server*

ICI	*Inter-Cell Interference*
IP	*Internet Protocol*
ISD	*Inter-Site Distance*
ISI	*Inter-Symbol Interference*
ITU	*International Telecommunications Union*
ITU-R	*International Telecommunications Union - Radiocommunications*
LOS	*Line-of-Sight*
LTE	*Long Term Evolution*
LTE-A	*Long Term Evolution - Advanced*
MAC	*Medium Access Control*
MBMS	*Multimedia Broadcast/Multicast Service*
MCCH	*Multicast Control Channel*
MCH	*Multicast Channel*
MCS	*Modulation and Coding Scheme*
MIMO	*Multiple-Input Multiple-Output*
MTCH	*Multicast Traffic Channel*
MUD	*Multi-User Detection*
NLOS	*Non-Line-of-Sight*
NMT	*Nordic Mobile Telephony*
OFDM	*Orthogonal Frequency Division Modulation*
OFDMA	*Orthogonal Frequency Division Multiple Access*
OPEX	*Operational Expenditure*
PAPR	*Peak to Average Power Ratio*
PC	*Power Control*
PCCH	*Paging Control Channel*
PCH	*Paging Channel*
PDCP	*Packet Data Convergence Protocol*
PHY	*Physical Layer*
PRB	*Physical Resource Block*
PSD	*Power Spectral Density*
QAM	*Quadrature Amplitude Modulation*
QoS	*Quality of Service*
RA	*Resource Allocation*
RAN	*Radio Access Network*
RAP	*Radio Access Point*
REC	*Relay Enhanced Cell*
RLC	*Radio Link Control*
RN	*Relay Node*
RR	*Round Robin*
RRM	*Radio Resource Management*
SAE	*System Architecture Evolution*
SC-FDMA	*Single Carrier Frequency Division Multiple Access*
SDMA	*Spatial Division Multiple Access*
SGSN	*Serving Gateway Support Node*

SINR	*Signal to Interference plus Noise Ratio*
SON	*Self Organizing Network*
TCH	*Transport Channels*
TDD	*Time Division Duplex*
TDMA	*Time Division Multiple Access*
TFS	*Transport Format Set*
TIA	*Telecommunications Industry Association*
TS	*Time Slots*
TTI	*Transmission Time Interval*
UE	*User Equipment*
UL	*Uplink*
UL-SCH	*Uplink Shared Channel*
UMTS	*Universal Mobile Telecommunications System*
WCDMA	*Wideband Code Division Multiple Access*
WiMAX	*Worldwide Inter-operability for Microwave Access*
WLAN	*Wireless Local Area Network*

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Dedicated

to

My Beloved Parents and Family Members

Chapter 1

Introduction

The *International Telecommunications Union - Radiocommunications* (ITU-R) defines the requirements for the *International Mobile Telephony - Advanced* (IMT-A) , in order to enable the standardization process for 4th generation wireless cellular technologies. These technologies promise to achieve high spectral efficiency with improved peak data rates and enable an enhanced network coverage with good throughput both in downlink and uplink. In the *3rd Generation Partnership Project* (3GPP) community, the *Long Term Evolution - Advanced* (Release 10) (LTE-A) compliant networks are termed as to fulfill the IMT-A requirements. The standards of LTE-A propose several enhancement techniques to provide a quality-of-service (QoS) to the mobile users with low deployment constraints including *Carrier Aggregation* (CA), *Extended-Multiple-Input-Multiple-Output* (E-MIMO), *Coordinated Multi-point Transmission* (CoMP), *Relaying* and so on.

The communication link between the user equipment (UE) and the base station experiences interferences due to several environmental factors such as distant-dependent path loss, shadowing and multipath fadings, which degrade the network performance to provide high quality mobile services. The expected solutions are to increase the base station transmit power or decrease the UE-infrastructure distance by increasing base station density in the existing network. However, a network operator would reluctant to deploy more base stations due to implementation and maintenance costs. To that end, relaying is emerging as one of the promising radio access techniques, which provides a cost effective solution as well as decreases the UE-Infrastructure distance by deploying low-power base stations known as Relay node (RN), with the macro network, . It ensures to provide coverage gain and improved quality of service in cell edge and indoor environments. Moreover, nomadic relaying being semi-static in nature, provides a temporary RN deployment in desired locations.

The continued developments in the field of telecommunication, enable a desire to exploit the relaying technology for *Public Safety Communication* (PSC) purposes. Emergency telemedicine could be one of practical envisaged scenario, where the *Emergency Medical Services* (EMS) providers (hospitals, paramedics, etc) use the relaying technology to ensure a rapid and coordinated medical care to patients at emergency sites. This typically enables emergency use cases, such as, setting up a communication link for field paramedics with expert opinion from physicians at a remote hospital or trauma center, thus enabling better-informed diagnosis or medical interventions by the EMS responder. In addition, a high-speed link may enable sharing of large amounts of patient measurements or images prior to transfer to relevant trauma center.

The objective of this thesis is to analyze the performance of RN in the macro-overlaid networks by carrying out the system level simulations. This work aims to show the relaying technology benefits of a *Relay Enhanced Cellular* (REC) network from the perspective of the indoor emergency telemedicine use case. To that end, we perform a comparative study of the REC network performance (in terms of data rates and outage probability) against that of the conventional macrocellular connectivity used in existing mobile networks. The results have been also submitted to 3rd International conference on wireless mobile communication and healthcare [1].

The rest of the thesis is organized as follows:

- Chapter 2 describes the architectural overview of 3GPP LTE technology. It also briefly discussed the different transmission schemes used both in uplink and downlink.

- Chapter 3 investigates the principles of *Relay Enhanced Cellular* (REC) networks as well as the challenges to existing macro-cellular networks.

- Chapter 4 summaries the exploitation of several communication technologies for different aspects of public safety communication in emergency and disaster events.

- Chapter 5 provides a general overview of the proposed system level simulator, system parameters and propagation models for the current work. Similarly, it also provide a comparative overview of simulation results for the proposed resource scheduling technique in the assumed emergency scenario.

- Chapter 6 concludes the thesis report and yields the guidelines for the future work.

Chapter 2

3GPP Long Term Evolution

2.1 Background

Mobile communications has been developed tremendously in the last decade. The number of mobile subscribers have been growing day by day. The first billion landmark was passed in 2002, the second billion in 2005, the third billion 2007, the fourth billion by the end of 2008 and the fifth billion in the middle of 2010 [2]. The reason for this rapid growth is provision of cheap services with improved network coverage and capacity by mobile network operators.

To understand the today's mobile communication systems, an extensive study required to know the steps involved in the cellular system evolution. These evolutionary steps include the experiments performed by Guglielmo Marconi till today's advanced broadband mobile telephony, which is one of the great technological explorations of the last century. The *Nordic Mobile Telephony* (NMT) system was the first international mobile communication system introduced by the Nordic countries in 1981. Meanwhile, the analogue *Advanced Mobile Phone Service* (AMPS) was introduced in North America. These systems collectively named as the *1st Generation* (1G) communication systems supporting voice communication and supplementary services.

During the 1980's, the inventions of digital communications techniques give rise to a need to develop the *2nd Generation* (2G) mobile communication systems which enable enhanced system capacity with improved quality of service (QoS). In Europe, the *Global System for Mobile Telephony* (GSM) system was initiated using the *Frequency-Time Division Multiple Access* (TDMA/FDMA). The *Conference of Postal and Telecommunications Administrations* (CEPT), later on, renamed as *European Telecommunication Standards Institute* (ETSI), carried out the standardization. In parallel, IS-94 standard was introduced by the *Telecommunication Industry Association* (TIA) in USA, and later on evolved to IS-95 in 1993. Both the IS-94 and 95 are based on the *Code Division Multiple Access* (CDMA). All the aforementioned narrowband technologies were designed to provide low-bandwidth services such as voice traffic.

In 1990s, 2G networks make use of newly invented digital transmission techniques and enable the data services (9.6kbps) which include the text messaging *Short Message Services* (SMS) and circuit-switched emailing. The inclusion of packet data transmission technique, known as *General Packet Radio Service* (GPRS) evolves the 2G GSM system to 2.5G technology. Subsequently, the *International Telecommunication Union* (ITU) standardized the *Universal Mobile Telecommunication Systems* (UMTS) as 3rd Generation (3G) mobile communication systems in order to achieve high data rate mobile services. These systems are based on the *Wideband Code Division Multiple Access* (WCDMA) which was, then evolved to 3.5G *High Speed Packet Access* (HSPA) systems to enable a faster network connectivity and efficiency.

Since 1998, most of the standard developing organizations grouped into 3GPP, in order to coordinate the development of the mobile telecommunication standards. The 3GPP technologies like GSM/EDGE and Wideband CDMA (WCDMA)/HSPA have currently captured nearly 90% of global mobile subscribers. While in parallel, the targets from 3GPP LTE-Advanced systems have been also identified. The driving factors for 3GPP LTE-Advanced development were to realize the 4G mobile communication systems as mentioned in IMT-Advanced requirements. Figure 2.1 explains the 3GPP family technology evolution.

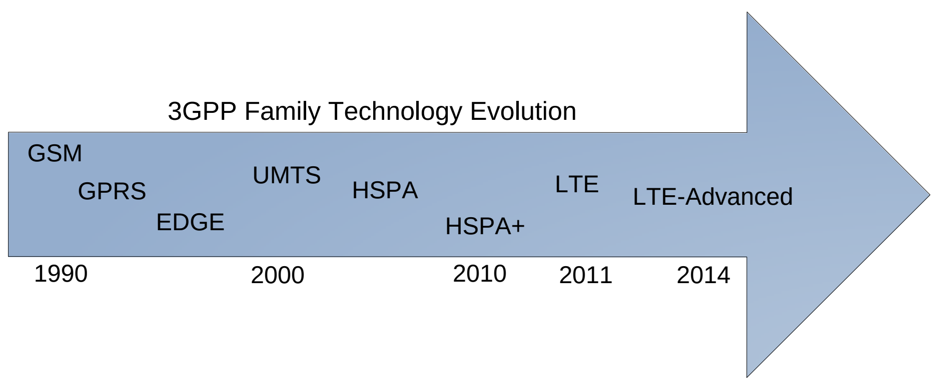


Figure 2.1: 3GPP Technology Evolution.

2.2 LTE System Requirements

The concept of LTE is a step towards 4G communication technologies, ensuring the competitive advantage of 3G technologies for future. The LTE system needs to provide long term efficient solutions comparatively to its predecessors technologies, in order to enable improved network coverage and capacity. The LTE system requirements are enlisted as follow [3]:

1. **System capability**

    - Peak data rates

      The LTE system aims to provide instantaneous peak data rates of 5 *Mbps* (with spectral efficiency of 2.5 *bps/Hz*) and 100 *Mbps* (with spectral efficiency of 5 *bps/Hz*) in uplink (UL) and downlink (DL) respectively, within a 20 *MHz* spectrum allocation.

    - Latency

      The reduction of the system latency (in terms of control-plane and user plane latencies), is also included in LTE main targets. The former refers to the time required for transition from non-active states to active state. The non-active states comprised of camped-state and dormant state and transition should be less than 100 ms and 50 ms respectively. The user-plane latency is defined as the required one-way transmit time for *Internet Protocol* (IP) packet from UE to Radio Access Network (RAN) edge node or vice versa.

2. **System performance**

    - Throughput

      The LTE systems seeks to enable a uniform user experience over the cell area, by improving the cell edge performance. Comparatively, it provides 2 to 3 times of HSDPA Release 6 cell-edge user throughput in DL while 2 to 3 times of HSUPA in UL. In terms of averaged user throughput, it is 3 to 4 times of HSDPA Release 6 in DL while 2 to 3 times of HSUPA in UL.

    - Spectrum efficiency

      In DL case, LTE aims to achieve 3 to 4 times the spectrum efficiency of HSDPA Release 6, with 2 Tx and Rx antennas at the Node B and UE, respectively. While for UL, it is 2 to 3 times of Release HSUPA 6. It has the ability to co-exist with the earlier 3GPP technologies.

    - Mobility

      The LTE allow the user mobility across cellular network. It needs to provides best performance with good quality of service at low speed (0-15 km/h) as well as at high speed (15 to 20 km/h) mobility.

    - Coverage

      The LTE system should attain the performance targets for 5 km of cell radius in terms of throughput, spectral efficiency and mobility. However, there might be a minor degradation in throughput and spectral efficiency for 30 km cell range.

    - Enhanced MBMS

      The LTE system should allow the simultaneous provisioning of voice calls and *Multimedia Broadcast/Multicast Services* (MBMS). The MBMS enables the multicast/broadcast services in the mobile cellular networks.

3. **Spectrum allocation**

   The LTE system support the inter-system handover with the existing deployed GSM and UMTS networks under the constraint of acceptable impact on terminal complexity. Moreover, it should operates in both, paired and unpaired spectrum, i.e. *Frequency Division Duplexing* (FDD) and *Time Division Duplexing* (TDD). It also provides bandwidth scalability to operate at different frequency bandwidth i.e. 1.25, 1.6, 2.5, 5, 10, 15, 20 MHz.

4. **Architecture**

   Though having all IP based architecture, LTE system also needs to support real-time and conversational class traffic. Comparatively, LTE reduces the number of network interfaces exiting in other technologies, such as, *Evolved Node B* (eNB) is the only radio interface between the UE and *Core Network* (CN), which acts as base station reducing the network signalling and jitters.

5. **Cost**

   The *Self-organizing Network* (SON) features will enable the LTE systems of doing the self-configuration and self-optimization of its network which will reduce the network planning and optimization cost.

2.3 LTE Physical Layer

The LTE aims to enable the 3G services with high transmission rates and spectral efficiency, both in UL and DL. Hence, it brings several technological changes to network architecture, such as Hybrid-Automatic Repeat Request (HARQ), multi-carrier and multi-antenna transmission techniques.

2.3.1 OFDM and OFDMA

The physical layer of LTE exploits multi-carrier transmission scheme known as *Orthogonal Frequency-Division Multiplexing* (OFDM) instead of conventional single-carrier modulation. The reason is that, OFDM avoids the *Inter-Symbol Interference* (ISI) with simple receiver design by using a guard period at the beginning of each OFDM symbol known as *Cyclic Prefix* (CP). There are two kinds of CP namely as *normal* CP with seven OFDM symbols per slot and *extended* CP with six OFDM symbols per slot [4].

In OFDM, the frequency-selective wideband channel is subdivided into non-frequency selective narrowband orthogonal subcarriers, thus modulating the data symbols on these subcarriers. The subcarrier spacing is 15kHz. For efficient spectrum utilization and avoiding the *Inter-Carrier Interference* (ICI), the peak of each subcarrier spectrum coincides with nulls of the spectra of remaining subcarriers as shown in Figure 2.2.

However, the OFDM transmitter have a drawback of high *Peak to Average Power Ratio* (PAPR). The practical *Power Amplifier* (PA) of RF transmitters are linear only within a limited dynamic range. In PAPR, PA starts operating in nonlinear region, which leads to significant spectral spreading and in-band distortion. Thus to operate linearly, PA need to use *Power Back Off* technique. Here the PA output power handling is over-design such that the power amplifier can meet the linearity specification at a reduced power level, but at the cost of low power efficiency. Hence, this results in expensive transmitter equipment and reduce the users terminal battery life. These disadvantages suggest that OFDM is suitable to use in DL, because the eNB transmitter has no issue with power consumption.

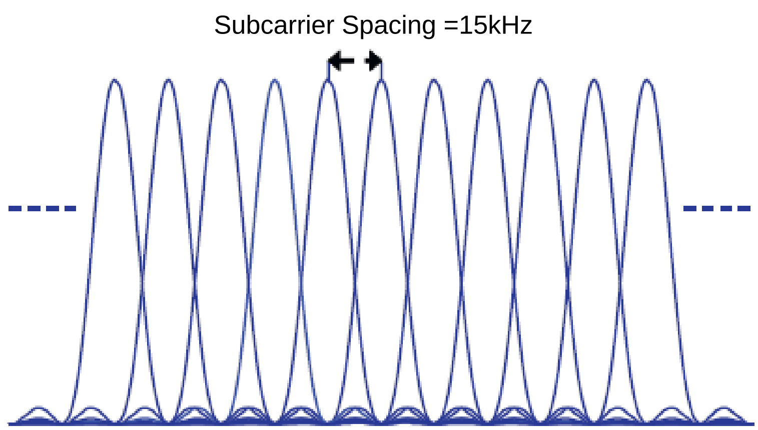


Figure 2.2: OFDM Subcarrier Spacing [4]

Moreover, *Orthogonal Frequency Division Multiple Access* (OFDMA) is a multiple access technique, exploiting the OFDM characteristics. OFDM allows only one user to use the system bandwidth for a given time. While OFDMA is multi-user OFDM, that enables the orthogonal subcarriers scheduling among multiple users at the same time, in order to efficiently utilize the radio resources. It can co-exist with *Time Division Multiple Access* (TDMA) technique, where each user is allocated time-frequency slot known as *Resource Block* (RB).

2.3.2 SC-FDMA

The LTE system exploits the *Single Carrier-Frequency Division Multiple Access* (SC-FDMA) for UL transmission due to high PAPR in OFDMA. Here the subcarrier mapping can be done in two different ways namely as localized or distributed. In the former case, mapping is enabled on the consecutive subcarriers, while in the later case, it performs on regular spaced subcarriers. The distributed SC-FDMA can exploits the frequency diversity but at the cost of system complexity. Hence, the localized SC-FDMA has been adopted for UL transmission while the frequency diversity is derived with *Channel Dependent Scheduling* (CDS) or *Frequency Hopping* scheme. Figure 2.3 present a comparative block overview of OFDMA/SC-FDMA transmitter and receiver.

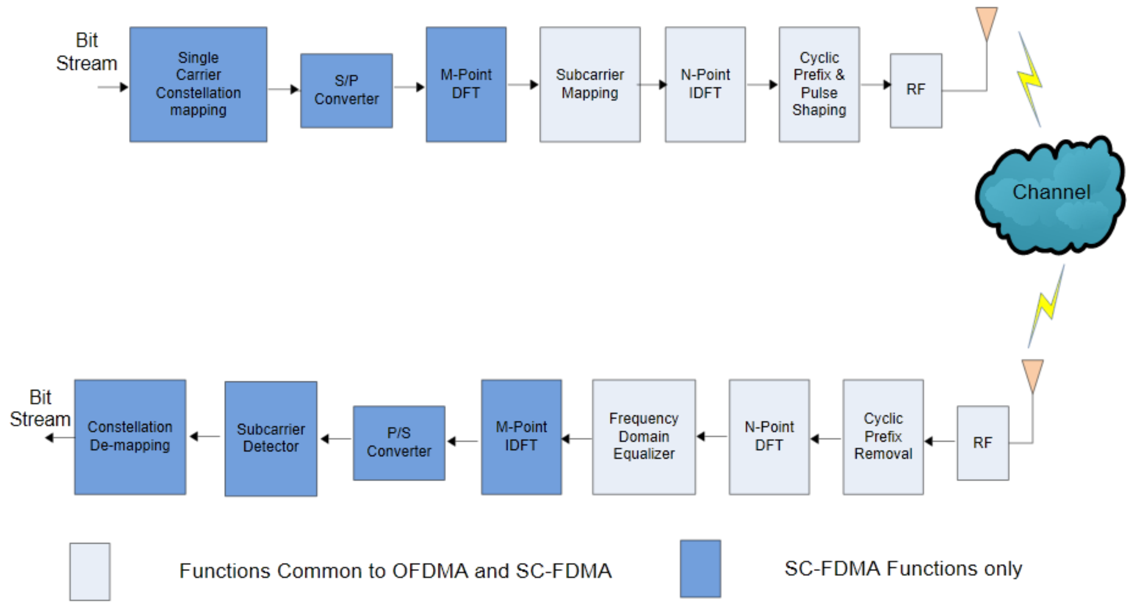


Figure 2.3: OFDMA and SC-FDMA Transmitter-Receiver Block Diagram.

2.3.3 LTE Transmission Resource

The LTE adopts a similar radio frame structure for both UL and DL transmission schemes.

- Frame Structure

  In 3GPP LTE, six possible channel bandwidths have been allocated for signal transmissions, ranging from 1 to 20MHz [4]. LTE DL transmission are segmented into frames, where each frame consists of 10 sub-frames and a sub-frame is formed by two slots of duration of 0.5 ms. Each slot consists of 6 or 7 OFDM symbols as shown in Figure 2.4.

- Physical Resource Block

  In LTE systems, *Physical Resource Block* (PRB) is the smallest element of transmission resource allocation to the physical channels. It consists of 12 consecutive subcarriers with duration of 0.5 ms in the frequency and time domain respectively, as shown in figure 2.5. Hence, in normal CP it consist of 7*12 = 84 resource elements while in extended CP, it consists of 6*12=72 resource elements. It has a total bandwidth of 12*15 kHz = 180 kHz. A physical channel may consists of one or more contiguous resource blocks with multiple of 180 kHz bandwidth.

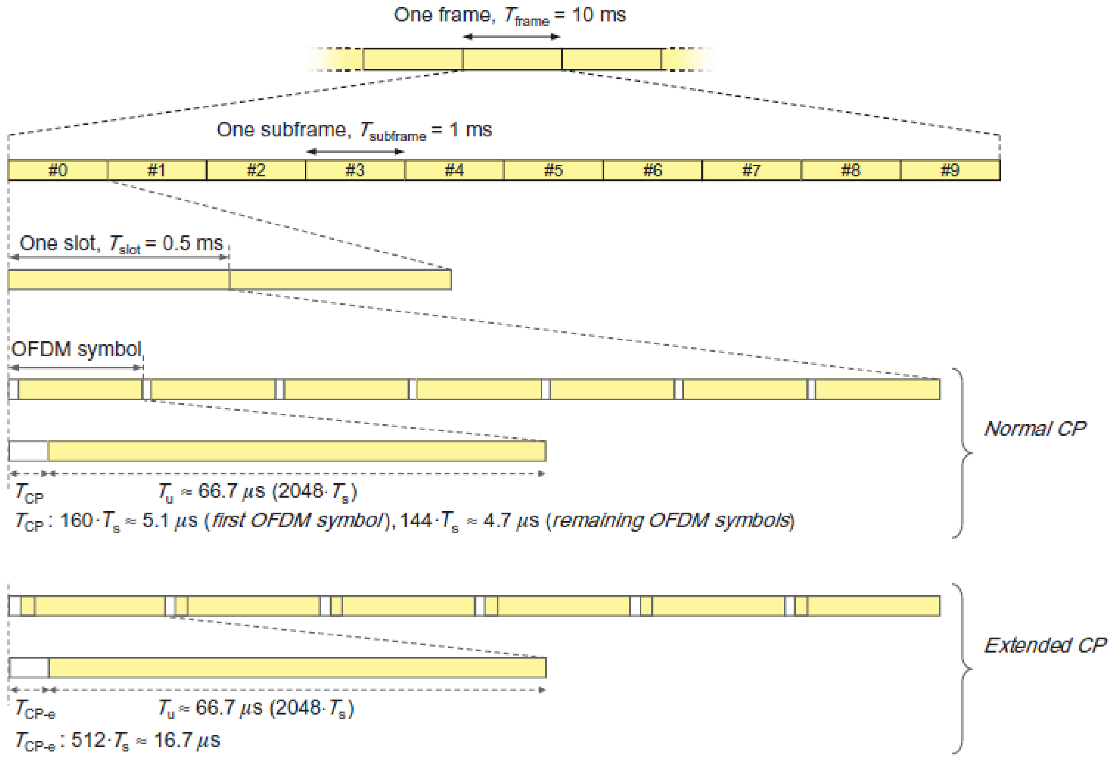


Figure 2.4: LTE Frame Structure [4]

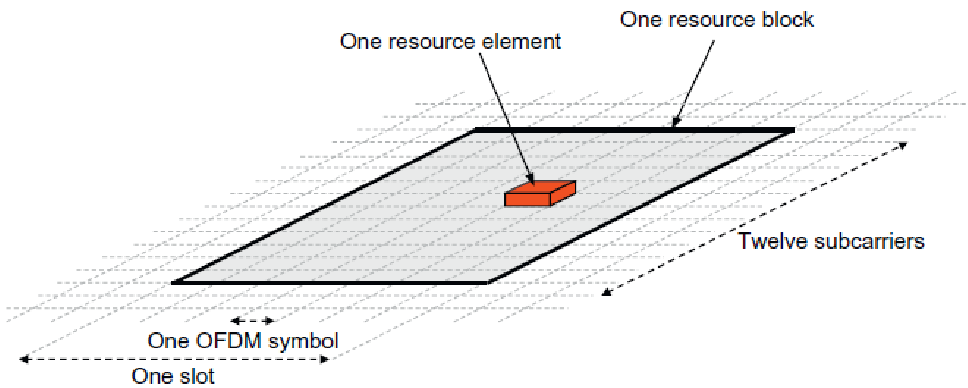


Figure 2.5: Physical Resource Block [4]

2.3.4 Downlink Resource Scheduling

Scheduling is a process to efficiently utilize the network radio resources among the multiple UEs. In dynamic scheduling the radio resources are assigned to UEs per *Transmission Time Interval* (TTI). Due to multipath fading, the UE radio link may experience rapid instantaneous variations [4]. Hence, *Channel-Dependent Scheduling* and *Link Adaptation*

(LA) enable the efficient utilization of network resources among the users. The former deals with rapid adaptation to varying radio-link conditions, while the later deals with the transmission parameter settings and radio-link quality.

Channel Quality Indicator (CQI) is a parameter which is a UE feedback on the basis of downlink reference signal from eNB. It enables the eNB to exploit an appropriate modulation and coding scheme for specific downlink channel conditions. It also informs the eNB about the UE's receiver characteristics. The CQI is calculated for each codeword on either the full transmission bandwidth configuration (Wideband CQI) or on groups of resource blocks known as sub-bands. It can be also used to calculate the wideband Signal-to-Interference plus Noise-Ratio (SINR) [2]. Figure 2.6 gives an overview for CQI procedure between UE and eNB.

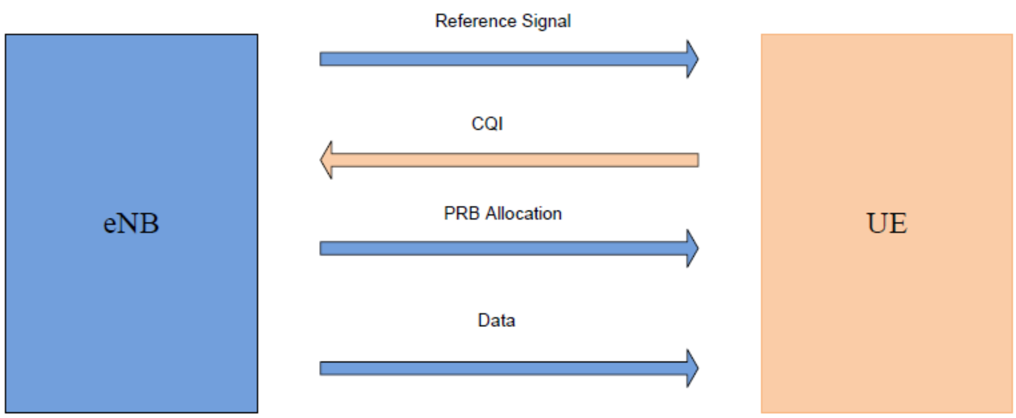


Figure 2.6: Downlink Scheduling Procedure

2.4 LTE System Architecture

3GPP LTE system are designed to ensure a seamless *Internet Protocol* (IP) based connectivity between UE and core network. The main component of LTE system architecture includes UE, *Radio-Access Network* (RAN), *Evolved Packet Core* (EPC), while the combination of LTE RAN and EPC is known as *Evolved Packet System* (EPS) as shown in figure 2.7.

1. **Core Network**

   EPC is the evolution of GSM and WCDMA core network. Its flat architecture enables high throughput services with lower latency level. The EPC consists of different logical nodes which are briefly described below [4].

   - *Mobility Management Entity* (MME) acting as control plane node of EPC, which is responsible for handling the security keys and control the signalling between the UE and EPC.

- *Serving Gateway* (S-GW) is the user-plane node acting as a mobility anchor point between EPC and LTE RAN. It provides connectivity to other 3GPP technologies such as GSM/GPRS and HSPA.
- *Packet Data Network Gateway* (P-GW) is responsible for connecting EPC to the internet. It also allocates the IP address to UEs. The P-GW is acting an mobility anchor point between EPC and non-3GPP radio-access technologies, such as CDMA2000.
- *Policy and Charging Rules Function* (PCRF) controls the quality-of-service (QoS) and charging.
- *Home Subscriber Service* (HSS) is a database node contains the subscriber related information.
- *Multimedia Broadcast Multicast Services* (MBMS) implants the multicast/broadcast services in cellular systems in parallel with unicast services.

2. **Access Network**

   The LTE radio-access network posses flat architecture, consists of *Evolved NodeB* (eNB). It handles all the radio-related functionalities of cellular network. The eNB uses S1 interface to connect with EPC. It also connects with its neighbouring eNB via X2 interface, to enable seamless active-mode mobility [4]. The EPC uses *SGi* interface to connect with internet.

3. **Radio Protocol Architecture**

   A 3GPP LTE radio-access protocols comprised of a layered architecture offering radio bearers for carrying the IP packets as described below [4].

   - *Packet Data Convergence Protocol* (PDCP) execute the IP header compression, to transmit with less number of bits over the radio interface. It also perform the ciphering and ensures the security of transmitted data. There is one PDCP entity per radio bearer configured for a terminal.
   - *Radio Link Control* (RLC) handles the segmentation/concatenation and retransmission of data. It offers services to the higher layers (PDCP) in the form of radio bearers. There is one RLC entity per radio bearer configured for a terminal.
   - *Medium Access Control* (MAC) controls the multiplexing of logical channels. MAC layer is also responsible for hybrid-ARQ retransmissions and scheduling. It provides services to RLC layer.
   - *Physical Layer* (PHY) is responsible for typical physical layer functions such as coding/decoding, modulation/demodulation etc. It provides services to MAC layer.

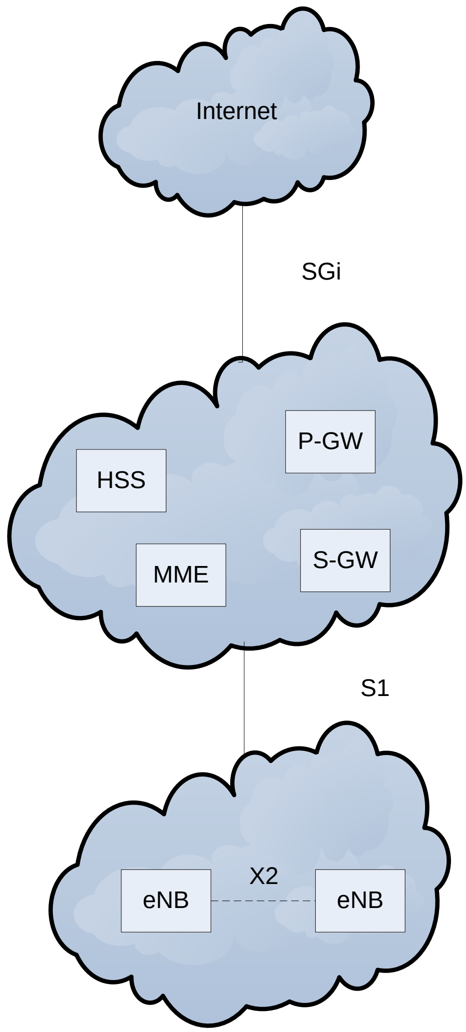


Figure 2.7: General Structure of LTE Architecture

Chapter 3

LTE-Advanced and Relaying

3.1 LTE-Advanced

The LTE-Advanced (Release 10) is an evolution of LTE, which is to compliant with the IMT-Advanced requirements and targets. It aims to provide peak data rates of up to 1 Gbps (for low mobility) and 500 Mbps in DL and UL respectively. LTE-Advanced is required to reduce the user- and control-plane latencies as compared to LTE (Release 8). It targets to achieve peak spectrum efficiency of 30 bps/Hz and 15 bps/Hz in DL and UL respectively. LTE-Advanced enhances the cell edge user throughput (5%-ile user throughput) in order to achieve a homogeneous user experience in cell. It will support the mobility across the cell from 350 km/h to 500 km/h depending on operating frequency band [5].

The LTE-A is backward compatible with existing LTE system and support the existing LTE enabled UEs. LTE-Advanced is expected to be bandwidth scalable and support wider bandwidth upto 100 MHz. It should also support the FDD and TDD duplexing for the existing paired and unpaired band, respectively. It enables network sharing and handover with existing legacy radio-access technologies. LTE-Advanced also considers a low cost infrastructure deployments. It will allow the backhauling using LTE spectrum in order to reduce the cost per bit. Summary of 3GPP LTE-Advanced system performance in comparison with 3GPP LTE is given by table 3.1.

3.1.1 Technology Proposals

3GPP standardization process is constantly promoting the usage of several new technologies in order to cope with the aforementioned requirements as briefly explained below [4].

- *Carrier Aggregation* (CA)

In carrier aggregation, multiple carrier components are aggregated, to provide wider bandwidths for transmission purposes both in DL and UL. It allows the transmission bandwidths upto to 100 MHz, by adding five component carriers of 20MHz bandwidth. CA exploits the fragmented spectrum by aggregating non contiguous component carriers.

Table 3.1: Comparison of LTE and LTE-Advanced requirements

Parameters	**LTE**	**LTE-Advanced**
Peak Data Rates	100 Mbps in DL, 50 Mbps in UL	1 Gbps in DL, 500 Mbps in UL
Spectrum efficiency	5 bps/Hz in DL, 2.5 bps/Hz in UL	30 bps/Hz in DL, 15 bps/Hz in UL
Bandwidth	20 MHz	Upto 100 MHz
Latency	U-plane 5 ms, C-plane $50/100$ ms	Improved, C-plane $10/50$ ms

- *Extended MIMO*

LTE-Advanced (Release 10) brings technological changes to multi-antenna transmission techniques. It supports eight transmission layers in DL while upto four transmission layers in UL.

- *Coordinated multi-point* (CoMP)

In CoMP transmission/reception, multiple geographically separated base station sites coordinate the transmission and reception, in order to achieve good system performance and end-user service quality as shown in figure 3.1. CoMP uses of coordination techniques namely as inter-cell scheduling coordination and joint transmission/reception. The former case deals with the inter-cell interference between multiple base station sites. In later case, the transmitted/received data signals are jointly processed to enhanced the transmission/reception performance. For CoMP, one kind of site deployment is *Centralized RAN* (C-RAN). In such deployment, all the geographically separated cell sites have a common baseband processing unit, located at central office [4].

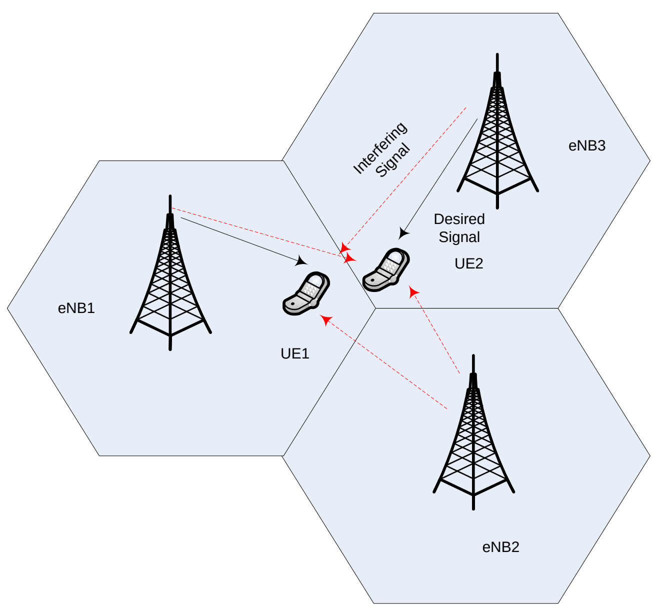


Figure 3.1: Coordinated Multi-point Transmission/Reception

- *Heterogeneous Network*

It is a *multi-layered* network deployment scheme, comprising lower-power nodes, overlaid under the coverage area of a macro-cell. It aims to increase the network capacity as well as achieve peak data rates. Examples are pico base station and home-eNB (femto base stations), relaying as shown in figure 3.2. To that end, relaying is a concept to improve the network cell edge capacity and coverage extension. The following section includes the detailed discussion of relaying concepts.

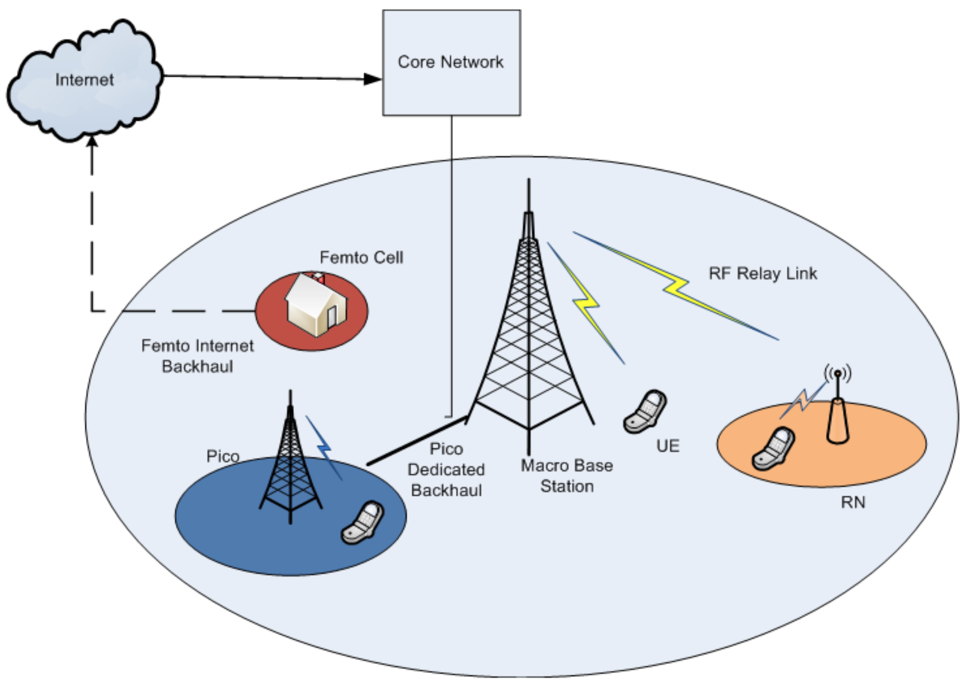


Figure 3.2: Heterogeneous Network

3.2 Relaying in LTE-Advanced

In cellular wireless networks, the communication path between the UE and the network infrastructure are vulnerable to many environmental factors such as path loss, fading and so on. For higher data rates, the network requires a high *Signal-to-Noise Ratio* (SNR) with improved link budget. Thus, one option would be to increase the base station transmission powers to keep the same coverage level, but it will cause the intra-network interference. Another option would be a network with denser infrastructure, which will reduce the UE-to-infrastructure distance. In such deployment scenarios, the UE would experience a good SNR level at the cost of high operation and maintenance expenditures [4].

Relaying being one of the promising deployment scenario, deploys low-power base stations known as RN within the macro-overlaid network. It reduces the UE-Infrastructure distance with a reduced cost. The relay link between RN and *Donor eNB* (DeNB) carries both UEs data traffic as well as control signalling for RNs. It also possess the S1

(Gateway-eNB), X2 (eNB-eNB) and normal LTE air interface (eNB-UE) characteristics [8]. Similarly, the *Direct Link* and *Access Link* refer to DeNB-UE connection and RN-UE connection respectively as shown in figure 3.3.

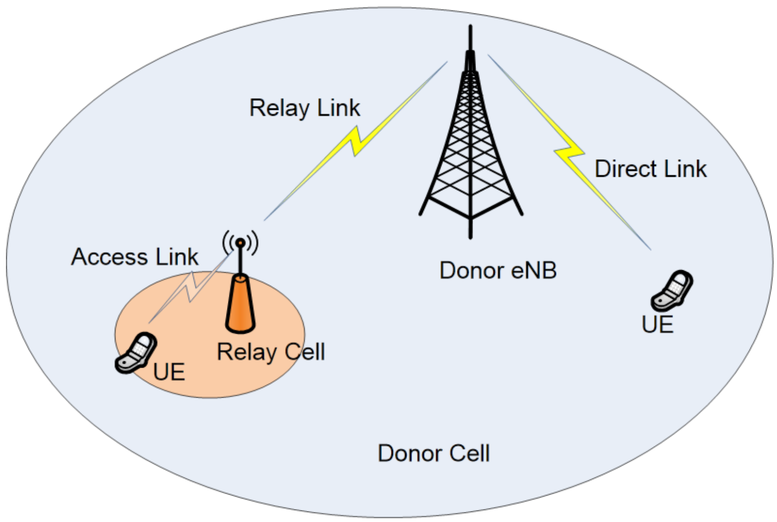


Figure 3.3: Network with Relay Node

3.3 Relays Classification

The RN classification can be done according to different criterion as follow;

1. **Amplify-and-forward and Decode-and-forward Relaying**

   - *Amplify-and-forward Relaying*

     The *Amplify-and-forward* (AF) is a full duplex relaying, amplifying a signal received from the first hop and retransmits to the second hop. AF possess a drawback of amplifying the interference and noise with desired signal which deteriorates the overall SINR level as well as limits the system throughput. In AF relaying, the transmit signal on the access link may leak to relay link receive antenna causing interference known as *Loop Interference* (LI). To minimize LI effect,separate antennas with proper physical isolation are used for transmission and reception purposes. This kind of RN are proposed to deploy in middle of the cell to gain the high spectral efficiency [9].

   - *Decode-and-forward Relaying*

     On the other hand, *Decode-and-forward* (DF) is a relaying technique, where the entire received signal from first hop is decoded and retransmit to second the receiver. It add delay and/or complexity to the system due to encoding/re-encoding of signals. In DF relaying, the throughput over relay and access links can be maximized, if both the links have equal throughputs. Moreover, the access link resources can be reused by multiple RNs within the same macrocell.

DF RNs outperforms the AF RNs both in the cell center as well as at the cell edge [9]. Moreover, DF RNs accomplished better performance then AF RNs for different relay link gains [9].

2. **Infrastructure Based Relaying**

RN can be classified from the deployment perspective, where the coverage is required. During the UE mobility within the network, RN may go through different usage models in network. The UE may move from the indoor to outdoor, provided by indoor RN and outdoor RN respectively. Similarly, it may experience coverage within a bus or train, provided by RN mounted on that moving vehicles [7].

- *Fixed RN*

Fixed RNs are normally deployed to improve the network coverage and capacity at the cell edges, coverage holes due to shadowing as shown in figure 3.4. They are also used to extend the network coverage to users outside the cell area. RN can be easily mounted on towers, poles, tops of buildings or on lamp posts. Antenna heights are kept lowered as compared to macro base station. The network operator can also plan the RN location to attain *Line of Sight* (LOS) channels conditions [7].

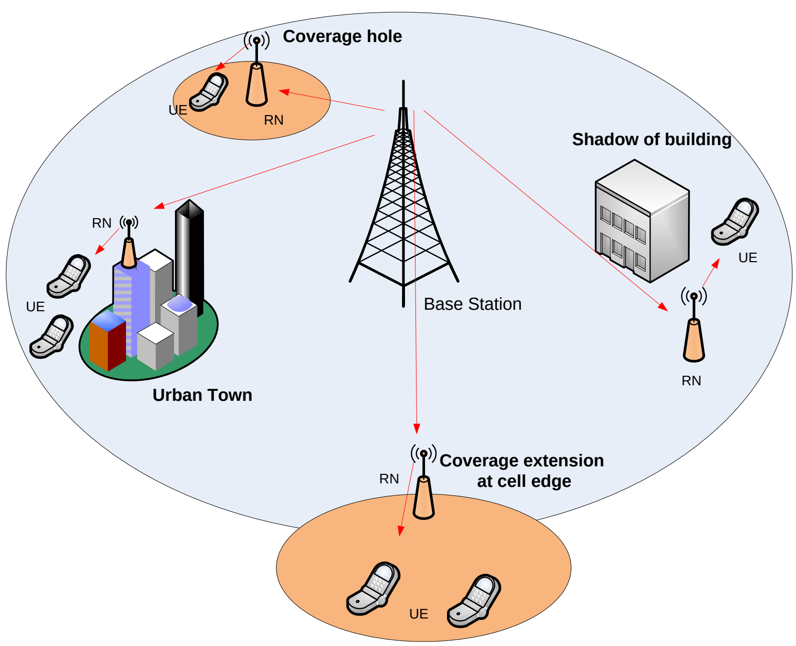


Figure 3.4: Fixed Relay Node

- *Nomadic RN*

  Nomadic RN being semi-static allows temporary RN deployment, in order to provide additional coverage and capacity in the areas where the macro base station (such as eNB) or fixed RN provide bad coverage or experience network congestion as shown in figure 3.5. One examples may be the emergency/disaster recovery where the rescue authorities experience network congestion problem due to excessive calls made by the affected people in the emergency area. The antenna height is comparatively low. The access link may experience both LOS and non-LOS (NLOS) channel conditions. It normally equipped with battery to operate. These RN may have physical structure limitations in order to reduce the weight, size and power usage as compared to traditional RNs [7].

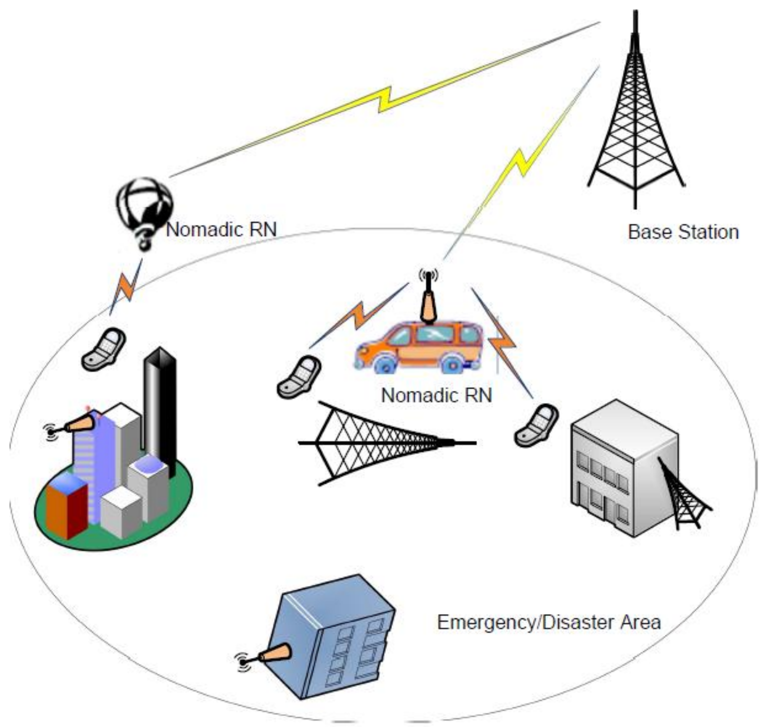


Figure 3.5: Nomadic Relay Node

- *Mobile RN*

  This RN model is usually mounted on the vehicle (e.g. bus, train, etc), which aims to provide the coverage within the moving vehicle, while passing through the network. It connects with the donor base station via mobile relay link while connect to the UEs within the vehicle via access link. The mobile RN's antenna heights are relatively lower, due to vehicle restrictions and operational safety. Figure 3.6 shows a schematic diagram of mobile RN [7].

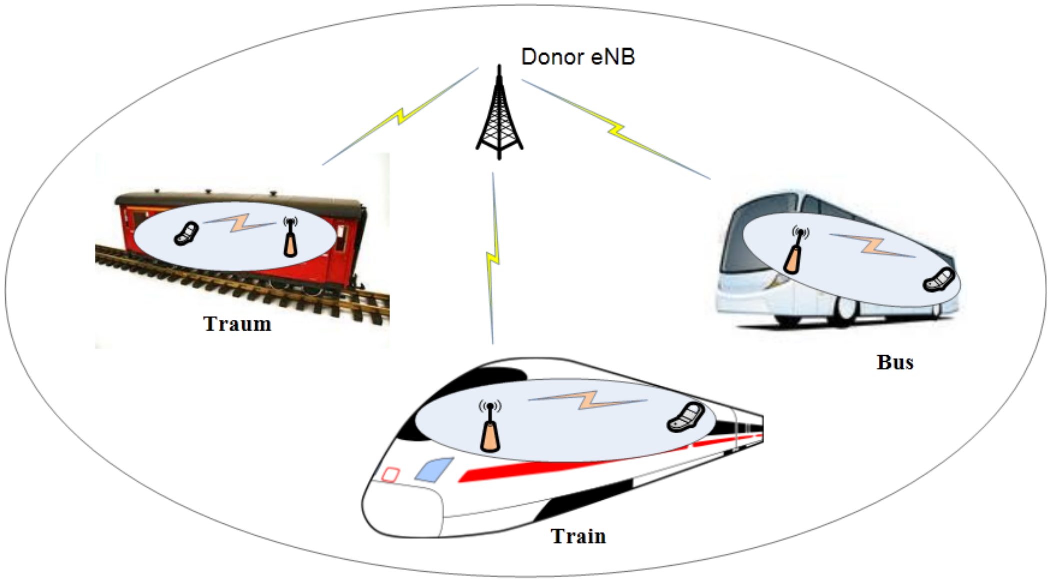


Figure 3.6: Mobile Relay Node

3. **Protocol Based Relaying**

   RNs may also be classified according to the protocol layers used.

   - *Layer 1 RN*

     Layer 1 (L1) RN may be considered as an analogue repeater or booster, possesses part of physical layer functionalities. It simply receives the DeNB signal, amplify it and retransmit to UE. AF full duplex RN can be considered as the L1 RN. It also include a drawback of amplifying the interference and noise components with the desired signal. This put constraint on the overall SINR levels and network throughput. It comprises a high processing time then DeNB, which may cause *Inter-Symbol Interference* (ISI) at UE [10]. Moreover, this type of RN has a power limitation to UE in downlink transmission, due to the amplifier gain.

   - *Layer 2 RN*

     This type of RN incorporates the Layer 2 (L2) functionalities, i.e. medium access control (MAC) layer. It provides a higher link quality in the RN coverage area by decoding the received signals from DeNB, re-encode it and retransmit it to UEs. Comparatively, it achieves good performance level at the cost of system complexity and link delay then L1 RN.

   - *Layer 3 RN*

     A Layer 3 (L3) RN includes all the eNB protocol functionalities. L3 RN use a normal LTE air interface to connect with eNB rather then using an expensive microwave backhaul link. L3 functionalities include, demodulation and decoding of received signal from eNB, process the data by ciphering, combining/dividing and encoding/modulation to retransmit it to UEs. It possess a good system performance, as compared to L1 and L2 RNs, but at the cost of system complexities and user-data processing delay [10].

4. **Resource Usage Based Relaying**

   Relaying can also be classified with respect to network resource usage strategy on the relay and access links, are listed below:

   - *Inband Relaying*

     In this type of relaying, the relay and access links share the same radio resources. It affects the peak data rates achieved by relay users due to the allocation of radio subframes for relay link. Moreover, relay link can be operated with direct link on the same spectrum resources, but will also create an interference towards the non-relay UEs and deteriorating the UE throughput [6].

   - *Outband Relaying*

     In outband relaying, the relay and access links are operated on different carrier frequency spectrum. This type of relaying improves the network capacity at the expense of larger spectrum demand for relay link. Here the relay link can be operated with direct link on the same spectrum resources [6].

5. **UE Knowledge Based Relaying**

   Relays can also be classified according to the UE's knowledge as follow [11];

   - *Transparent RN*

     In transparent relaying, UE is unaware of, whether the communication with eNB is done directly or via a RN, while the UE is present in eNB coverage area as shown in figure 3.7. The UE receives data traffic via RN, while the control signalling received directly from eNB, which cause to increase the relay performance as more resources are available for data traffic. Transparent relay carries the eNB data traffic both in UL and DL. Transparent RN are normally deployed for throughput enhancement purpose.

   - *Non-transparent RN*

     In non-transparent relaying, UE is aware the communication with eNB is carried out via a RN as shown in figure 3.7. In this mode, all UE-eNB related data traffic as well as control signaling are carried out via RN. The non-transparent relay usually deployed at the cell edge, to obtain the network coverage extension. Transparent and non-transparent relays are possible to deploy in the same network.

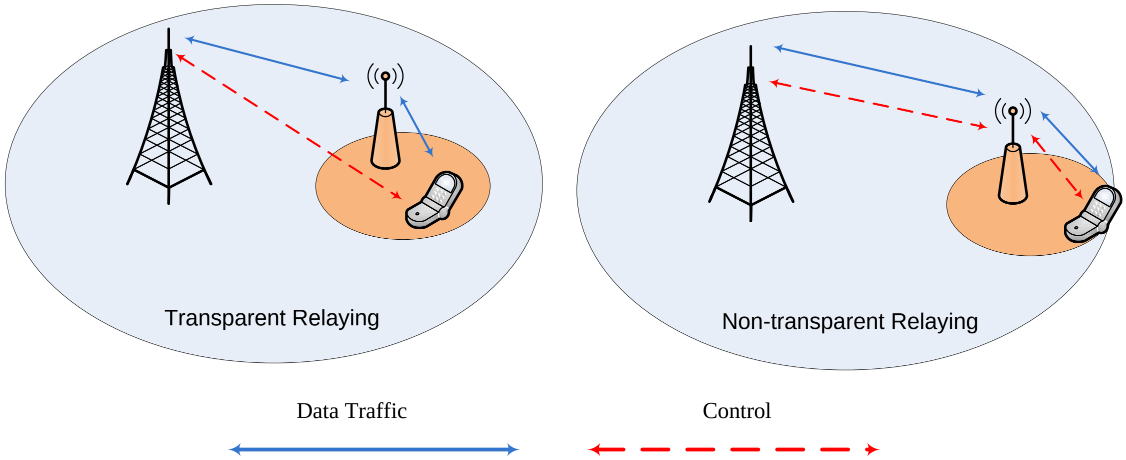


Figure 3.7: Transparent and Non-transparent Relaying

6. **Type 1 and Type 2 Relaying**

   3GPP LTE technical report also classified two RN types namely *Type 1* and *Type 2* RN [6].

   - *Type 1 RN*

     A type 1 RN is basically designed for decentralized network, where the RN is able to conduct independent RRM methods, only based on the local information [12]. It control its own cell as normal eNB, utilizes the same *Radio Resource Management* (RRM) mechanisms. It transmits its own cell identity (ID), synchronization channel, reference signal and control channels to UEs. The only difference with eNB is wireless relay link to connect with core network via DeNB. The relay UEs treat the type 1 RN as eNB by directly receiving the scheduling information and HARQ feedback. The UE is also required to send the control channel information to RN. The type 1 RN need to be backward compatible with LTE REL-8 to support REL-8 UEs. L3 relay is the example of Type 1 RN. Type 1 RN are further classified into Type 1a and Type 1b RN. Both have the Type 1 characteristics with a difference, that former is outband RN while the later is inband RN with enough antenna isolation between relay and access links.

   - *Type 2 RN*

     This type of RN is viewed as part of donor cell having no physical cell identity (ID). Rel-8 UE is unaware of type 2 RN in the cell, means that it is transparent RN. Normally, its deployment means to enhance the eNB signal in the donor cell. Example are the smart repeaters, DF relays and L2 relays.

3.4 Relaying Advantages and Disadvantages

1. Advantages

    - The main purpose of relaying is to provide peak data rates in order to support high data services. Results show that *Relay Enhanced Cell* (REC) network has better downlink performance in terms of UE throughput as compared with single-hop eNB-only network [18].
    - RNs enhance the overall network throughput by efficiently utilizing the network resources. Results have shown that UE experiencing good propagation conditions towards RNs. It invoke the UEs to perform handover towards RNs especially at the cell edge, therefore, increasing the network capacity as well as improve the resource fairness to UEs. It also provides good performance at cell edge by enabling a network coverage extension [13]- [14].
    - RNs being a cost efficient deployment solution, gained the network operator interest. Due to less complex site planning, acquisition, cost-efficient and low power requirements, they can be easily mounted on structures like street lamp posts. Therefore, with low *Capital and Operational* (CAPEX/OPEX) cost, REC networks outperform the eNB-only deployed network [15].
    - RN yields a remarkable SINR gains on the relay link through proper site planning. It also reduces the shadow fading impact by selecting best site location for RN deployment [16].

2. Disadvantages

    - In relaying, the DeNB utilizes the same radio resource pool among three links namely direct, relay and access links. Moreover, in inband relaying, the relay and access link utilize the same radio resources through time-division multiplexing, therefore, limiting the RN performance. It creates high competition for the available radio resources at the DeNB, which requires an efficient and complex resource scheduling techniques [14].
    - RN possess small coverage area due to its low transmit power, low antenna gains and high path-loss exponent. Thus, less number of UEs will be connected to RNs, lead to inefficient utilization of resources as well as load imbalance between RN and macro base station. Moreover, RN-served UEs may also experience interference from high power transmission of macro base station [18]. In addition, it also create interference towards UEs connected to eNB and affects the UE control link.
    - RNs need additional radio resources for relay link, in order to communicate with DeNB. Moreover, the relay link control overhead also effects the overall network performance in terms of throughput, particularly in interference limited scenario [17].
    - RNs causes delay in system due to processing of data before transmission.

Chapter 4

Public Safety Communication

4.1 Background

The concept of Public Safety is referred to protect the public's life and property, during the wide-scale natural disasters (e.g., earth quakes, forest fires, flooding, etc), deadly man-made actions (e.g., nuclear explosion, radiation, etc.) as well as confined emergency situations (e.g., vehicle accident, sudden critical illness, etc.). In all the mentioned scenarios, the public always expecting the government authorities to respond with an immediate and effective action to safeguard the human lives and restoring the services (e.g., roads, electricity, communication, etc.) at emergency site. The term authority refers to emergency first responders (e.g., police, fire-fighters, paramedics, etc.), emergency control centers, public safety access points (PSAP) or any other organizations involved in public safety events.

During the wide-scale emergency events, several different authorities and hundreds of their individuals are involved to provide the medical assistance, fire extinguishing, food, shelter, security and rehabilitation [24]. All the authorities must required to coordinate the activities in order to respond fast and effectively. Moreover, the authorities personals are able to track and assess the problem, as well as, execute an appropriate commands during the events [23]. Therefore, the public safety community must consider the importance of radio communications. Thus, in the absence of other communication means, the *Public Safety Communication* (PSC) systems enables the connectivity among the first responders as well as with concern authorities. This enables the responders to obtain the vital prompt information about emergency venue. For example, the EMS responders need to know the building layouts and other related information about the site. Similarly, this information will ensure, to set up a communication link to provide field paramedics with expert opinion from physicians at a hospital or trauma center, thus enable better-informed diagnosis or medical interventions by the EMS responder. Or then, a high-speed link may enabling sharing of large amounts of patient measurements or images prior to transfer to relevant trauma center.

Finally, rather then emergency events, the PSC authorities required to maintain a communication link in normal situations, to ensure the pubic safety through rapid and coordinated response.

4.2 Emergency Telecommunication (EMTEL)

The *Emergency Telecommunications* is the usage of telecommunication services in emergency events. These events might be range from small scale (e.g., sudden illness, fire in home, etc), to wide-scale disaster events (e.g., earthquakes, floods, etc). It also enables the communication services to other public safety authorities/organization such as fire brigades, police forces, emergency medical service units [25].

The EMTEL related standardizations, always take place in several ETSI technical meetings and partnership projects. ETSI specifies four main emergency telecommunication areas as follow;

4.2.1 Citizen to Authority Communication

In this type of communication, the citizens initiated communication with authorities. It enables the citizens to dial a specified emergency call number (112 for pan-Europe) to reach the authorities via *Public Safety Access Points* (PSAP). The PSAP is required to forward the call to relevant emergency service control center for immediate rescue response as in figure 4.1. The 112 voice call has a drawback of not providing any information about calling user location which may cause to delay/halt the rescue operation. Enhanced 112 (E112)is introduced to automatically provide real time location information to PSAP [26].

Likewise, e-Call is a type of emergency call to PSAP (E-MERGE project). In e-call concept, the call is initiated either, manually by the vehicle occupants or by in-vehicle sensor at the time of accident. It sent a minimum set of data to PSAP which includes the emergency location, driving direction (through GPS) as well as vehicle identification. It also reduces approximately 40%-50% response time of rescue operations [26].

4.2.2 Authority to Citizen Communication

The authority to citizen communication sends warnings/instruction messages to all the affected citizens about the impending high risk disasters to minimize extent of damage. The authorities use different means of communication for ensuring the message delivery by using different mechanisms as point-to-point, point-to-multipoint or broadcast as shown in figure 4.2. Examples are fixed or mobile telephone infrastructures, TV/RADIO Broadcasting, siren systems, speakers, etc. This type of communication also aims to call up the non-government organizations/charities to participate in rescue operations. For such type of communication, an effective emergency notification system is required to distribute an authentic information about the future risks to the targeted citizens. It also

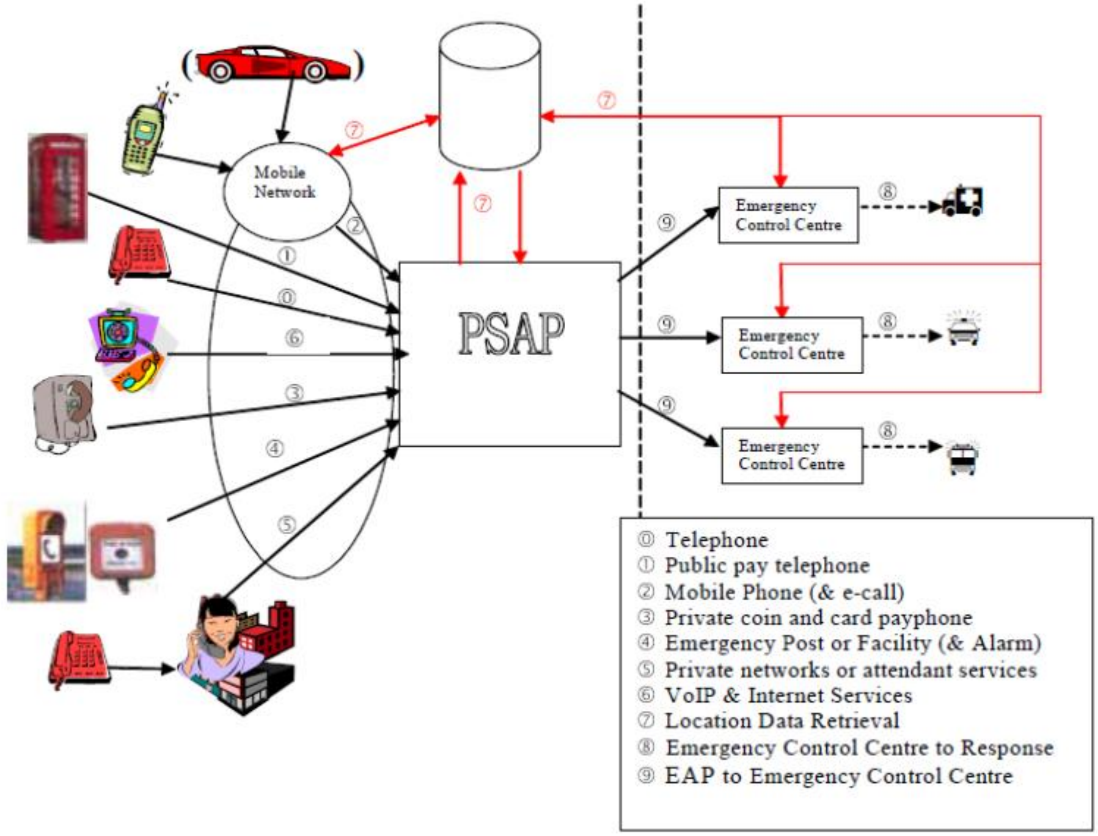


Figure 4.1: Citizen to Authority Communication [26]

needs to ensure the end-to-end reliability and security of message delivery. The message include sufficient information to instruct the public for further safety actions [27].

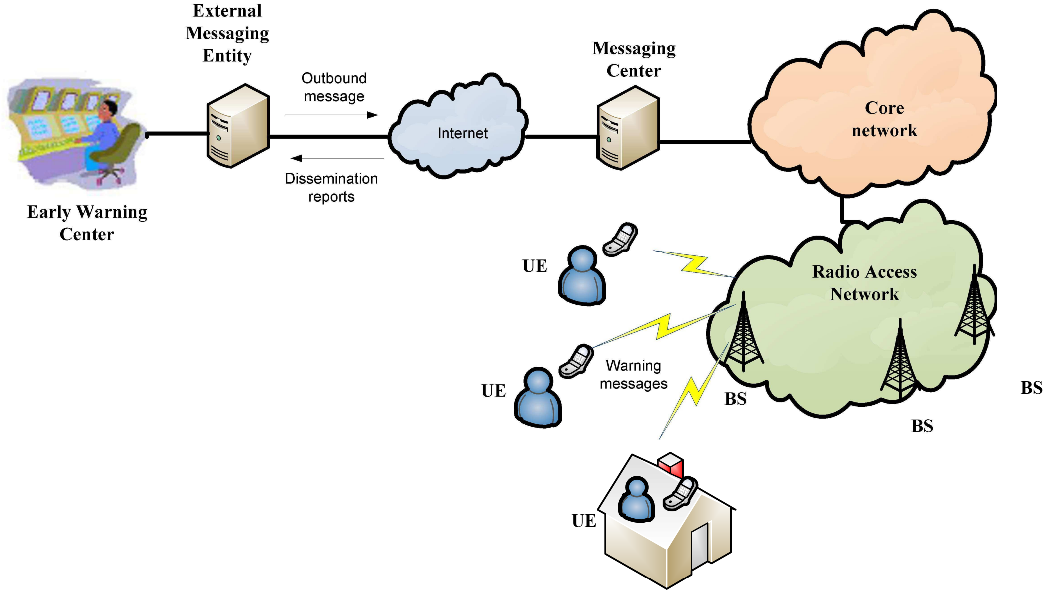


Figure 4.2: Authority to Citizens Communication

4.2.3 Citizen to Citizen Communication

This type of communication enables the communication among individuals (citizens), in order to assure about safety of relative/friends present at emergency site. The individuals present at emergency area, are differentiated as *Involved Individuals* and *Affected Individuals*. The former being hurt directly while the later remain safe during the emergency event. The individual present outside the emergency area is referred as *Concerned Individuals*.

The involved/affected individuals should enable two-way communication with relatives/friends to provide their location information. The authorities are required to have a communication link with individuals particularly, the involved and concerned individuals. Moreover, the PSAP allows to access the relevant and updated information on the emergency place. Thus, coordination is required for citizen to citizen communication, otherwise, it may cause several problems, such as repeated communication attempts to communicate by the individuals, will cause network congestion and put strain on the network resources [28].

4.2.4 Authority to Authority Communication

In this type of communication, the authorities involved in the emergency relief actions, communicate with each other to enable overall management of actions during the emergency crisis. The authorities required to remotely manage and coordinate with the on-field rescue teams. The on-field team members need to communicate with each other as well as to call for additional support. Similarly, it enables the higher authorities to assess the current situation at emergency site and instruct the rescue teams about the priorities of mission. This type of communication helps the authorities to inform the relevant authorities of their need at specific situation (e.g., hospital administrators about arrival of casualties and so on). It aims to facilitate the authorities to mobilize the resources.

This kind of communication requires a radio network with enhanced capabilities, which can be transportable/easily deployable and provide ubiquitous coverage over entire emergency area. It should also ensure the high availability and reliability of services even during the high network congestions. It supports the user mobility as well as enables priority treatment with certain authorized users. The network should be bandwidth scalable. It must support the interconnectivity/interoperability with other networks to ensure a transparent continuation of emergency services [29]. Figure 4.3 shows an schematic overview of authority to authority communication.

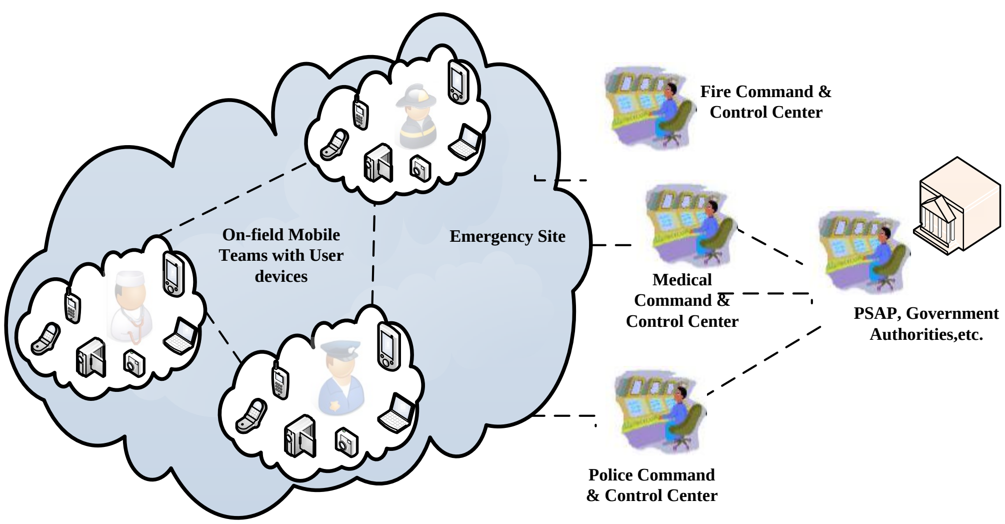


Figure 4.3: Authority to Authority Communication

4.3 Professional Mobile Radio (PMR)

The authorities normally depend on private mobile radio systems for public safety communication (PSC). The *Public Land Mobile Network* (PLMN) is not always a reliable option because the network infrastructure may be damaged during the emergency and/or natural disasters, or may experience network congestion due to repeated call attempts by the affected/concerned individuals.

The PSC requires a communication system ensuring the reliability and availability. The network needs to enable a high degree control, capable to provide access to the involved and/or affected individuals on priority basis with low latency level. It should enable the interoperability with different pubic safety networks as well as cross-border networks [24]. To fulfill the aforementioned requirements, the authorities required a dedicated mobile network for public safety communication purpose known as *Professional Mobile Radio* (PMR). It was generally developed for business users (e.g., Taxi company, etc.) to communicate with each other, normally at short distance from central base stations. PMR systems facilitates the closed user groups with group calls and push-to-talk with low latency. Moreover, many PMR system enables the terminals to directly communicate with each other, located outside of network coverage areas [30]. Hence, with the passage of time, several prominent digital PMR standards have been developed.

4.3.1 Terrestrial Trunked Radio (TETRA)

The *Terrestrial Trunked Radio* (TETRA) is one of the digital PMR technology standardized by ETSI. It exploits the *Trunking* and *Time Division Multiple Access* (TDMA) methods to provide voice and data services with high data throughput. It support low latency group calls. It allows to generate an emergency call in overloaded networks. It also enables *Direct Mode Operation* (DMO), where the users are independent of network to communicate with each other. TETRA introduced sophisticated encryption techniques to ensure the data security [30].

4.3.2 TETRAPOL

TETRAPOL is another digital PMR technology aims to provide communication services to public safety organizations. It possess an integrated voice-data networking. It provide an end-to-end encryption for all voice calls. It has adopted FDMA radio access technique to access the network. The channel bandwidth used by TETRAPOL is 12.5/10 kHz. It also enables the cross-border interoperability with other networks. TETRAPOL networks is providing services in 35 countries with more than 1,850,000 users [31].

4.3.3 APCO - Project 25

Project 25 (P25) is a standard to design and manufacture a public safety communication products, jointly maintained by *Telecommunication Industry Association* (TIA), *Association of Public Safety Communication Officials International* (APCO) and other several

North American's state organizations. This project enables interoperability between different manufacturer's products by introducing an interface known as *Common Air Interface* (CAI). The P25 provide both conventional and trunked media access operations. The former enables direct user-to-user communication without any repeater, while in the later case, users share the radio channels. It also offer an end-to-end security to voice and data communication. The P25 equipments can be operated in VHF, UHF, 700 and 800 MHz frequency bands in 12.5 to 25 kHz channel bandwidths [32].

4.4 PSC Standardization

The importance of public safety communication can be judge by the fact, that most of reputed communication standard development organizations (SDOs) are involved in PSC standardization process, in order to enable a desired system performance during the entire emergency event. Furthermore, the SDOs aims to upgrade the current communication technologies, to effectively meet the future PSC requirements. The current section gives a brief overview of SDOs, involved in PSC-related standardization activities.

- *European Telecommunications Standards Institute (ETSI)* endures many notable contributions to standardization regarding PSC. The *Global System for Mobile Communications* (GSM) standards include specifications of circuit switched emergency call services, which used for citizen-to-authority communications. For authority-to-authority communication, It has specified standard known as Terrestrial Trunk Radio (TETRA). In addition to it, more popular ETSI contributed standards are briefly discussed in section 4.2.

- *International Telecommunications Union (ITU)* is the specialized United Nations (UN) agency deals with information and communication technologies. In 2003, the ITU created *Telecommunications for Disaster Relief and Mitigation - Partnership Co-ordination Panel* (PCP-TDR), which bears the responsibility to coordinate among all the ITU departments (ITU-Radio, ITU-Telecommunication and development sector) involved in PSC standardizations [33].

- The 3GPP takes the responsibility to evolve the GSM standards towards next generation technologies namely as 3G *Universal Mobile Telecommunications System* (UMTS) and coming 4G LTE-Advanced. The 3GPP assigned different tasks to *Technical Specification Groups* (TSGs), among which, the *TSG Service and System Aspects* (SA) deals with PSC requirements for users [34]. The current specified PSC services include, circuit switched Emergency call and Public Warning Systems (PWS). The former used for citizen-to-authority communication purpose [35], while the later, utilize for authority-to-citizen communication by broadcasting the alert messages through 3GPP PLMNs to citizens residing in emergency area.

- The 3GPP2 aims to continue the standardizations for cdma2000 technology. It constitute four TSGs, among which the *TSG Service and System Aspects* (TSG-S) deals with the PSC specifications issues. The 3GPP2 standardization enables call services include Globals Emergency Call Origination and Emergency Service 9-1-1 [36].

- *Internet Engineering Task Force (IETF)* also contributed towards PSC standardizations. The IETF assign a working group (WG), *Emergency Context Resolution with Internet Technologies* (ECRIT), with a task to determine the caller location and call routing solutions for IP-based citizen-to-authority communications [37].

- *Institute of Electrical and Electronics Engineers (IEEE)* has also led effort for the PSC specification, while during the standardization process for IEEE 802.16 *Worldwide Interoperability for Microwave Access* (WiMAX). The collaboration work of WiMAX Forum and IEEE 802.16 WG enables standardizations for citizen-to-authority communications as well as prioritized Emergency Telecommunication Service (ETS) for authority-to-authority communication [38].

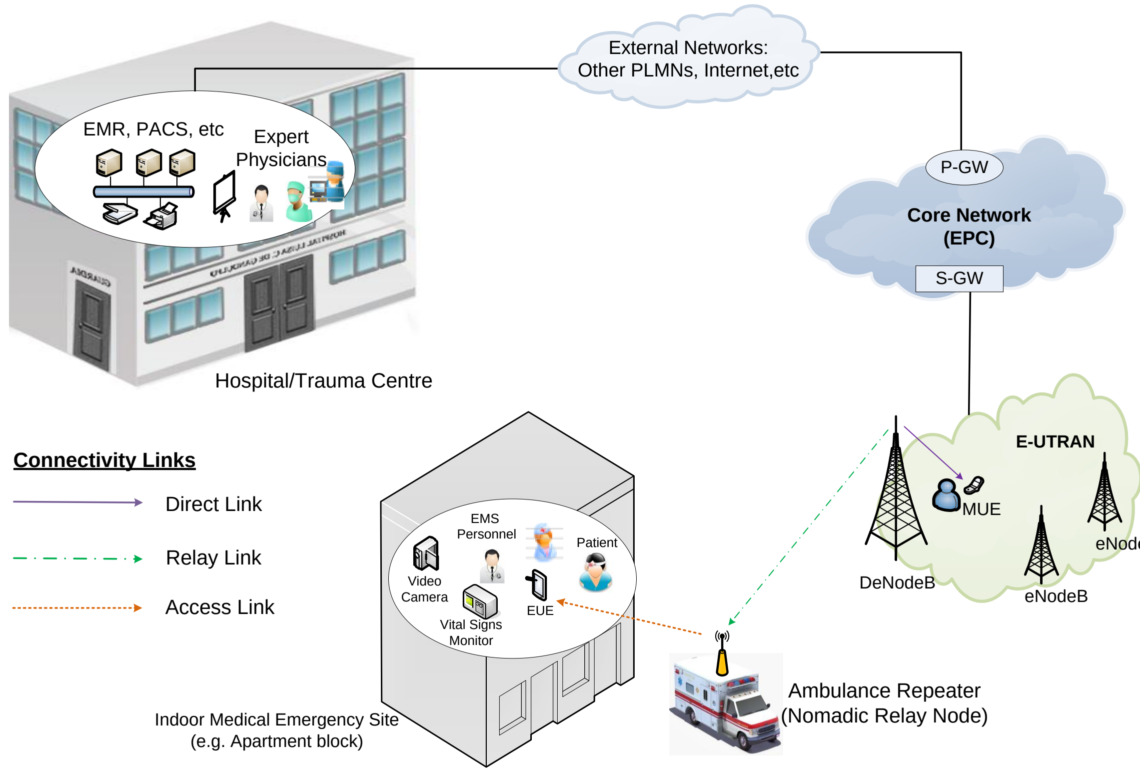
4.5 Relaying in Public Safety Communication

Emergency telemedicine being one of public safety communication applications, is the usage of telecommunication technologies by Emergency Medical Services (EMS) providers (hospitals, paramedics, etc) so as to ensure a rapid and coordinated medical care to patients at emergency sites. Particularly in authority-to-authority communication, a number of wireless networking technologies are considered for use to support indoor emergency telemedicine services [39]. Private WLANs are one of the most common means for subscribers to provide broadband wireless extensions to their residential fixed access lines. However, these WLANs may expose patient data on poorly secured open networks or may be inaccessible to EMS responders due to access controls settings by the WLAN access point (AP) owner. Moreover, lack of centralized management of private APs means that guarantee of services (through admission control, traffic flow prioritization etc.) cannot be provided for emergency telemedicine users [40].

The shortcomings when sharing the commercial networks has prompted the deployment of dedicated *Professional Mobile Radio* (PMR) systems launched, in order to enable a reliable network coverage for the emergency responders (e.g, TETRA, APCO-25) [41]. However, these PMR networks are typically narrowband systems which lack capabilities to support the advanced multimedia emergency telemedicine applications. Broadband satellite communications provides another alternative. However, the satellite terminals cannot be used for high data rate indoor service provision due to bulky terminals, stringent line-of-sight requirements and high latency [39, 40, 42]. As a result mobile broadband networks (and evolutions beyond 3G) provide arguably the most attractive option for emergency telemedicine use cases [39, 42]. This is also previously noted in various experimental telemedicine studies or practical implementations in third generation (3G) mobile networking environments [43,44]. However, these networks employ conventional macrocell deployment for providing coverage in a wide-area. Yet, in many cases they also admit some difficulties for enabling improved services with guaranteed QoS in indoor environments [45].

To that end, multi-hop relaying emerges as a promising deployment scenario, provides an improved network performance gains in the existing macro-overlaid networks. RN being a low-power base station, can be considered as an intermediate access point between UE and LTE-A compliant macro base station, known as Donor Evolved Node B (DeNB) [6]. Likewise, nomadic relaying being semi-static in nature, allows temporary RN deployment in emergency areas, providing additional indoor coverage [7].

Moreover, In authority-to-citizen communication, the RNs can be efficiently utilized instead of macrocellular networks, for PWS service, to broadcast the warning messages to public individuals under risk. The reason for it might be that, the macrocellular networks may experience delays due to network congestion or partly damaged. Furthermore, the individuals located in indoor basement/coverage hole, may unable to receive the alert messages. Hence, the macro-to-RN offloading via wireless relay link, may enable to



DeNodeB = Donor Enhanced Node-B, EMR = Electronic Medical Records, EMS = Emergency Medical Service, EUE = Emergency User Equipment, E-UTRAN = Evolved UMTS Radio Access Network, EPC = Evolved Packet Core, MUE = Macrocellular User Equipment (Common UE), REC = Relay Enhanced Cell, PACS = Picture Archiving and Communications System, P-GW = Packet Data Network Gateway, S-GW = Serving Gateway.

Figure 4.4: Usage of a Nomadic Relay Node to provide improved coverage in Indoor Emergency Areas

reduce the network congestion as well as improve the indoor coverage in low coverage areas.

Figure 4.4 presents a schematic end-to-end overview of relay enhanced cellular (REC) network for emergency telemedicine scenario, comprises a two-hop nomadic RN (N-RN) deployed within the macro-overlaid network. From the network operator perspective, all the emergency telemedicine devices (tablet PC, Smartphone, etc.) would be consider as a UE providing broadband access to the mobile network. The mobile core network can be accessed by EMS responders, either via the DeNB direct link or alternatively, via the two-hop relaying where the UE-RN transmissions are facilitated by the Access link while the RN-DeNB transmission is done via a wireless Relay link.

Chapter 5

Simulator Description and Performance Analysis

A system-level simulator is created to evaluated the LTE-A REC performance. This chapter aims to give an overview of the simulator which examines the REC performance in terms UE data rate improvements. It also enlists all the system parameters including channel models, antenna pattern, fading models as well as throughput equation.

5.1 System Model and Methodology

A LTE-Advanced compliant RN has been proposed to use for the considered emergency communication scenario. The adopted relay operates with the type 1 inband configuration. The REC network performance depends on a resource partitioning strategy between the relay and direct links, along with an effective scheduling technique to allocate relay resources on the access link.

In the downlink, an inband RN quits transmission towards UEs on access link, while during the reception from DeNB via relay link, however, an RN needs to enable a backward compatibility towards Rel-8 UEs by sending cell-specific reference and control signals in all DL subframes. Hence, it facilitates the configuration of Multi-Media Broadcast over Single Frequency Network (MBSFN) subframes in DL, allowing the RN to inform the Rel-8 UEs, not to expect transmission from RN, by sending control signals in the first OFDM symbols of a blank subframe [46]. In this study, three subframes has been reserved as the MBSFN subframes for DL relay link transmissions at the DeNB side. In remaining seven subframes, a simultaneous transmission of eNB and RN enabled on direct and access link respectively, creates an interference to neighbouring cells. Moreover, all the eNB interference towards RN, are avoided, as all the cells use the same frame format. To that end, a *Max-Min Fairness* (MMF) scheduling technique is used to distribute the network resources at eNB on direct link as well as at RN with relay link constraint. From cellular system perspective, this algorithm aims to maximize the minimum user throughput by allocating more network resources to UEs with low SINR, with a condition that all UEs obtain same throughput level. The UE throughput is calculated for given SINR level as

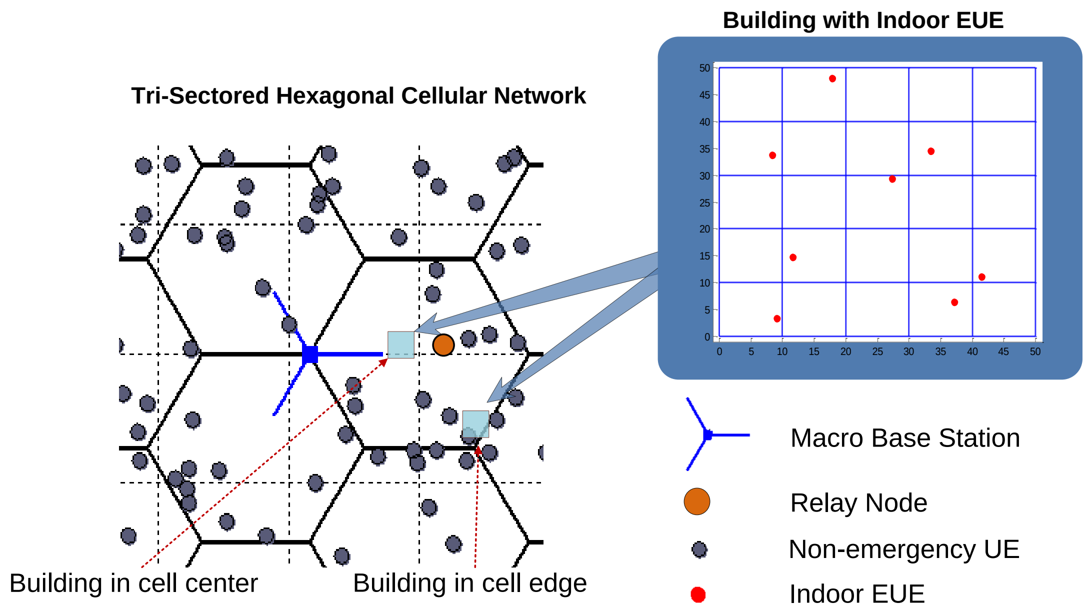


Figure 5.1: Relay Enhanced Cellular (REC) Network

follows [22]:

$$TP_{user} = BW_{PRB}.BW_{eff}.\log_2\left(1 + \left(\frac{SINR}{SINR_{eff}}\right)\right) \tag{5.1}$$

where *Equation* (5.1) represents a modified version of Shannon's capacity formula with parameters known as the bandwidth efficiency (BW_{eff}) and SINR efficiency $(SINR_{eff})$ with values of 0.88 and 1.25 respectively. They presents the performance loss due to the network implementation and signal processing. The parameter BW_{PRB} is bandwidth of one PRB (valued 180 kHz). Moreover, the remaining system parameters are enlisted in table 5.1.

Figure 5.1 shows the simulated network, consists of seven hexagonal cellular eNB sites each possess three sectorized RF antennas to provide coverage to three sectors. Furthermore, it is assumed that there are 10 UEs randomly located in each sector. A $5*5$ grid layout residential building is assumed in central sector at two locations,i.e. cell center or cell edge. The building includes eight EMS responders (each with one emergency UE or EUE) scattered in random locations within the building. A vehicular nomadic RN is located 50 meter away from the building and provides indoor coverage. In simulations, we assumed downlink scenario with 3GPP use case 1 (Urban)and Inter-Site Distance (ISD) of 500m. It represents the typical case, where indoor emergency incident could occur. The baseline scenario with eNB only deployment is used as a reference.

5.2 Path Loss Model

Wireless channel is the most challenging media in communication systems to enable a reliable transmission. A sophisticated system design is needed as the doppler shift, shadowing as well as interference from the other interferer affect the channel performance. Thus, to attained a desired system performance, It requires an extensive study of physical and statistical issues that affecting the radio wave propagation. Moreover, the channel model comprises appropriate precision level as if it evidence similar behaviour for the simulator as well as for real time systems.

This simulator employs the COST231-Walfisch-Ikegami (WI) path loss model, which models both indoor and outdoor radio propagations. The selected channel model accounts for distance-dependent path loss, shadowing as well as indoor penetration loss. To estimate the indoor losses, external and internal walls penetration losses has been explicitly modelled in line with COST 231 report [47].

- **Direct Link**

  $PathLoss_{DirectLink}$ (dB) = 34.938 + 38 * log10 (*R*) + 24.5 * log10 (*f*) + 0.00162 * *f* * log10 (*f*) + *Indoor Loss*

- **Relay Link**

  $PathLoss_{RelayLink}$ (dB) = 26.98 + 38 * log10 (*R*) + 24.5 * log10 (*f*) + 0.00162 * *f* * log10 (*f*)

- **Access Link**

  $PathLoss_{AccessLink}$ (dB) = 42.6 + 26 * log10 (*R*) + 20 * log10 (*f*) + *Indoor Loss*

5.3 Antenna Pattern

Antenna pattern is defined as a 3D graphical representations of antenna radiation properties as function of direction. The isotropic antenna radiation pattern is uniform in all directions while for the directional antenna, the pattern is more focused in one direction. The antenna pattern for MBS is given as [6]:

$$A(\theta) = -\, min \left[12 \left(\frac{\theta}{\theta_{3dB}} \right)^2, A_m \right] \tag{5.2}$$

Where θ_{3dB} = 70^o degrees which is the macro base station (MBS) antenna's main lobe beamwidth. A_m is the MBS antenna front-to-back ratio with value of 25 dB.

Table 5.1: Simulation parameters

Parameters	Values
DeNB Parameters	
Carrier Frequency	800 MHz
Transmission Bandwidth	10 MHz,48 PRBs for data & 2 PRB for signalling
eNB Transmit Power	46 dBm
eNB Elevation Gain	14 dBi
eNB Antenna Configuration	Tx-2, Rx-2
eNB Noise Figure	5 dB
eNB Elevation	25 m
eNB Diversity Gain	3 dB
eNB Antenna Pattern	$A(\theta)$ = - min $\left[12\left(\frac{\theta}{\theta_{3dB}}\right)^2, A_m\right]$ $\theta_{3dB} = 70^\circ$ and A_m = 25 dB
RN Parameters	
RN Transmit Power	30 dBm
RN Antenna Pattern	Omni-directional
RN Antenna Configuration	Tx-2, Rx-2
RN Elevation	5 m
RN-UE Elevation Gain	5 dBi
RN-eNB Elevation Gain	7 dBi
RN Diversity Gain	3 dBi
UE Parameters	
UE Transmit Power (Maximum)	23 dBm
UE Antenna Configuration	Tx-1, Rx-2
UE Noise Figure	9 dB
UE Received Diversity Gain	3 dBi

5.4 Simulator Development

One of the primary objective was to enable the RN deployment in the macro-overlaid network and benchmark the simulator results by citing an IEEE conference paper mentioned in [18]. For the results benchmarking, the system model and simulation parameters mentioned in the citation, has been considered. In simulations, downlink scenario with 3GPP use case 1 (Urban) and Inter-Site Distance (ISD) of 500m has been assumed.

Moreover, it is evident that there is imbalance in coverage of areas of RN and eNB cells due to low RN transmission power as well as low antenna gain as compared to eNB. This enables less number of UEs to handover to RN, creating load imbalance in the network. Thus, one solution is to add random number dB bias to the thresholds used for cell selection and handover in order to connect more UEs to RN [18].

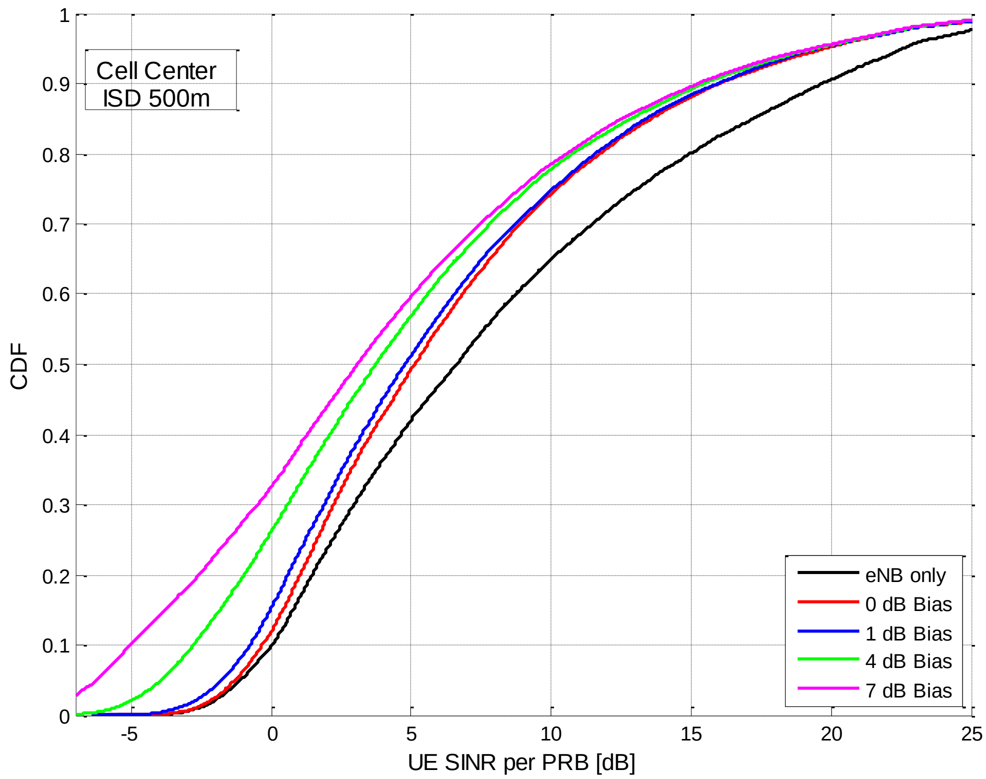


Figure 5.2: CDF of SINR per PRB

Via comprehensive system level simulations, a comparative study of eNB only and REC networks performance is carried out, in terms of CDF of SINR per PRB and UE throughputs. Moreover, the impact of RN transmission on the performance of UEs connected to eNBs, was also examined.

5.4.1 SINR per PRB

Figure 5.2 shows the CDF of SINR per PRB which perform the comparative analysis of eNB only and REC networks as follow.

- Though the RN transmission power is low, but still it creates an interference towards the UEs and hence deteriorates the SINR levels as shown in figure 5.2 from mid to high levels at 0 dB biasing.

- Moreover, the SINR levels further worsens by biasing the cell selection and handover thresholds especially at lower SINR levels, because the UEs make handover to RN, still receiving interference from the high transmission eNB.

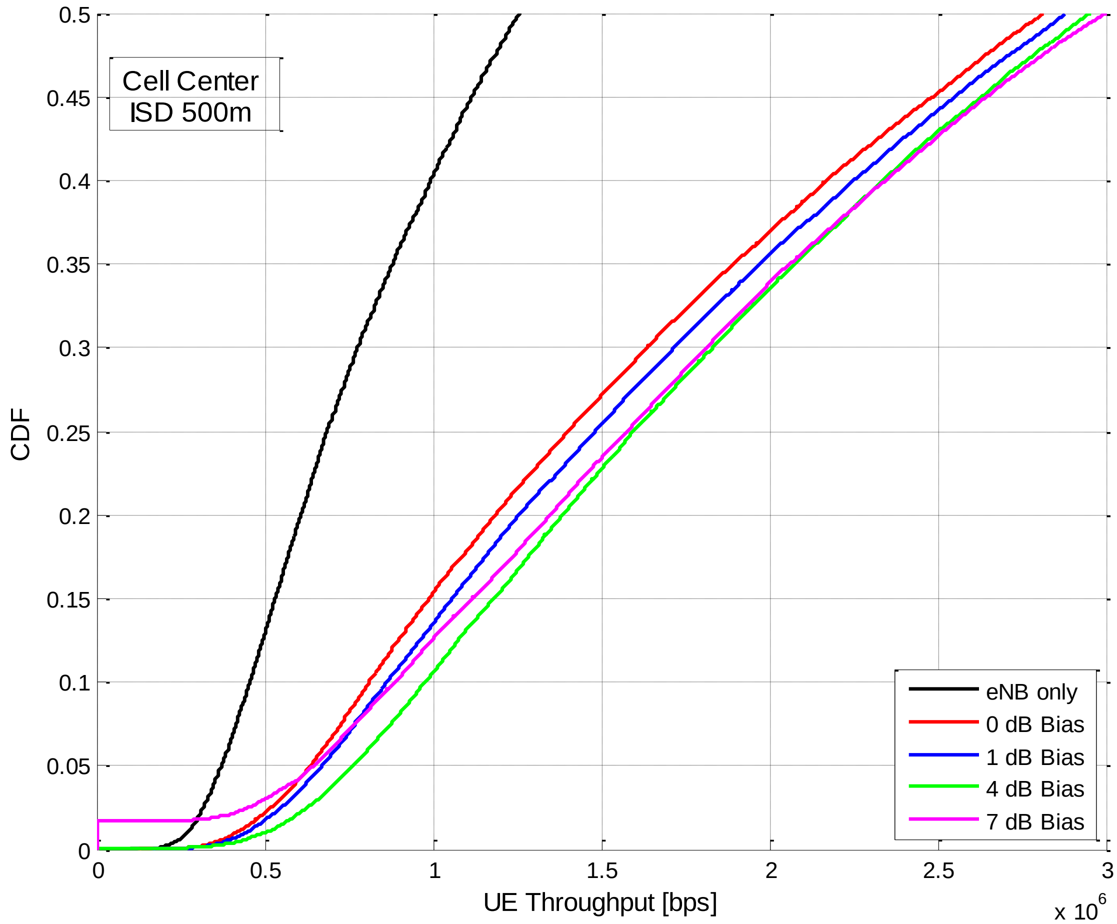


Figure 5.3: CDF of UE Throughput

5.4.2 UE Throughput

Figure 5.3 shows the CDF of UE throughput in order to enable comparative analysis of eNB only and REC networks as follow.

- The RN deployment improves the network performance by achieving considerable UE throughput gain as compared to eNB only scenario, as can be seen at 0 dB biasing level.

- Moreover, biasing the cell selection and handover thresholds, also extend the RN coverage areas. Due to which more UEs make handover to RN and efficiently utilizes the RN resources. Though in RN cell, UEs experience less competition for network resources but still receiving an interference from eNB.

5.5 Emergency Telemedicine Case

This section provides a comparative study of eNB only and REC networks performance. A comprehensive system level simulations has been carried out, in terms of cumulative distribution function (CDF) of indoor EUE data rates. Moreover, we also examine the impact of RN transmission on the performance of non-emergency UEs of only those eNBs, which are serving the indoor EUE.

Though, eight indoor EUE case is rather plausible for more extreme emergencies scenarios, otherwise a routine medical emergency would usually involve only a team of two paramedics with around two EUEs that require mobile broadband connectivity. Additionally, in these routine emergencies the EUEs are likely to located in the same apartment, rather than being randomly scattered in different apartments. e.g. a medical emergency only involving a single person or household. Hence, system level simulations has been generated for different number of indoor EUEs.

5.5.1 Eight Indoor Emergency User Equipments

Figure 5.4 & 5.5 indicate the simulations carried out for cell center and cell edge respectively, with UE performance constraint of 2 Mbps.

- The REC network outperforms the eNB only deployment, with almost 70% indoor EUEs in cell center case and 77% indoor EUEs in cell edge case, achieve a data rate of higher then 6 Mbps (i.e. from mid to high data rate levels) as shown in figures 5.4 (left) & 5.5 (left). This gain is due to the fact that indoor EUE receive good enhanced signal quality from RN as well as experience less competition for radio resources.

- However, in addition to performance constraint of 2 Mbps, the high power eNB creates interference towards the indoor EUE, resulting an outage (2%) in case of cell center scenario shown in figure 5.4 (left) , which is negligible for the cell edge scenario where the eNB interference decays over the long distance as shown in figure 5.5 (left).

- Similarly, figure 5.4 (right) & 5.5 (right) show the CDF plots for outdoor non-emergency UE data rates. The results demonstrate the deterioration impact of RN deployment on the performance of outdoor non-emergency UEs, due to the RN interference power. However, this degradation is insignificant as compared to the indoor coverage provided in emergency events.

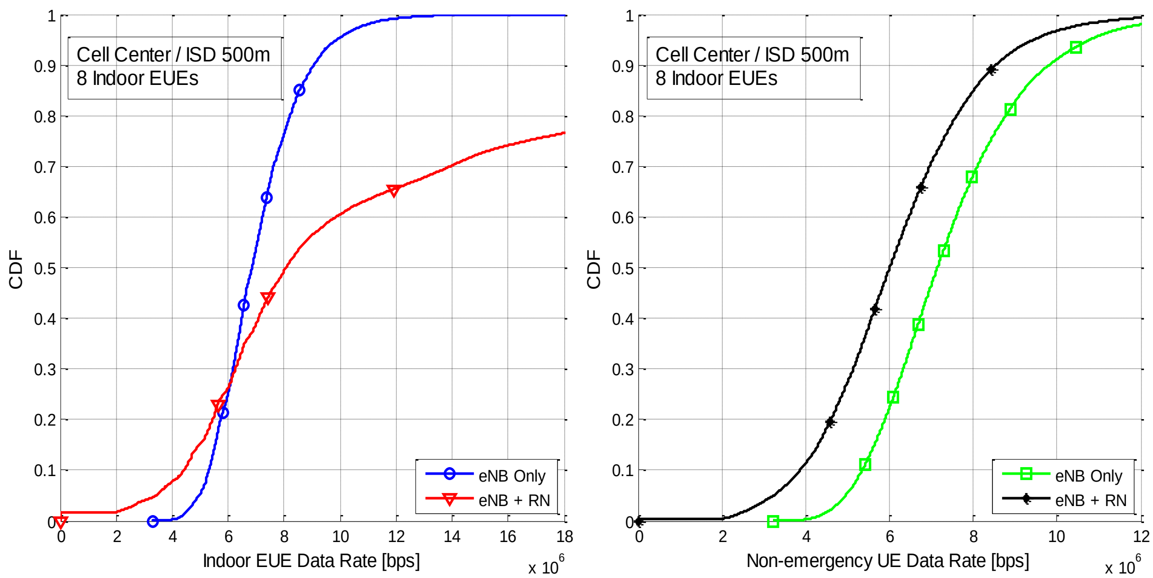


Figure 5.4: CDFs of indoor EUE (left) and non-emergency UE (right) data rates

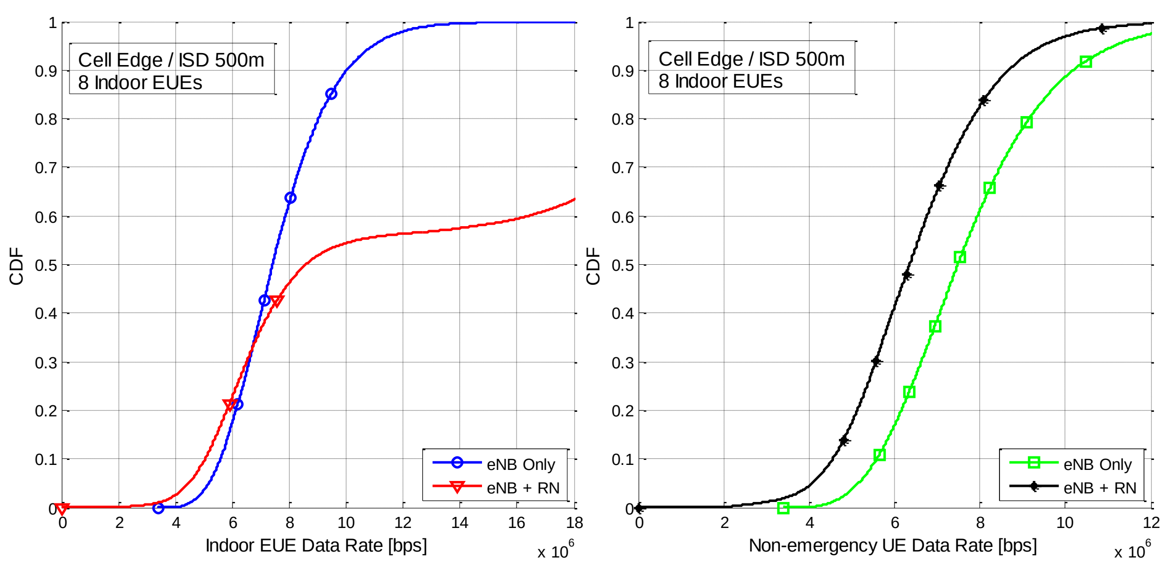


Figure 5.5: CDFs of indoor EUE (left) and non-emergency UE (right) data rates

5.5.2 Four Indoor Emergency User Equipments

This section describes the results generated for the case of four indoor EUEs which indicate the CDF plots of indoor EUE data rates and outdoor non-emergency UEs for cell center and cell edge respectively, with UE performance constraint of 2 Mbps.

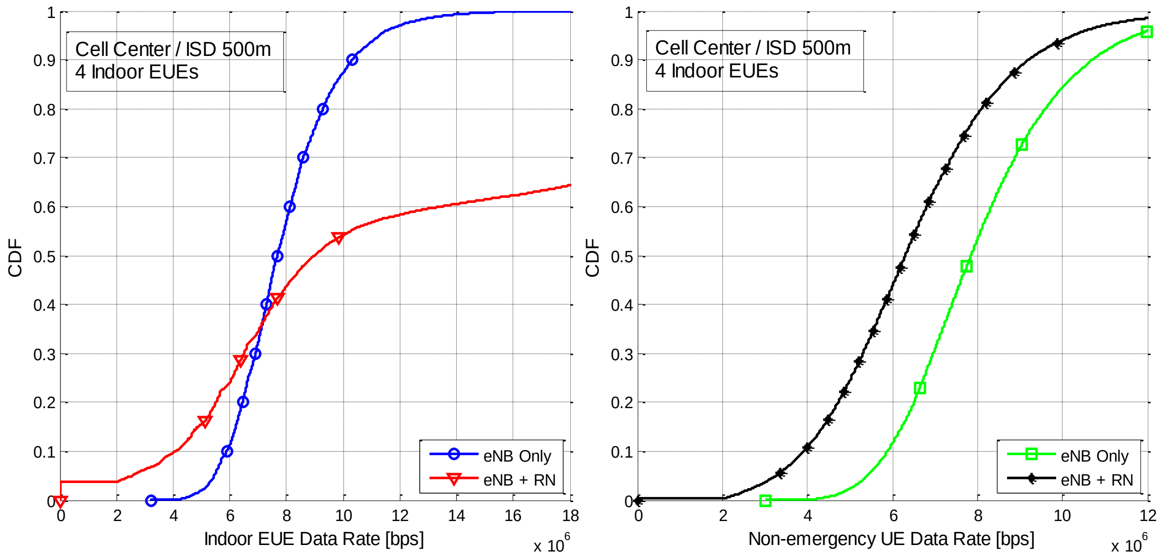


Figure 5.6: CDFs of indoor EUE (left) and non-emergency UE (right) data rates

- Figure 5.6 (left) & 5.7 (left) show the results for the case of four indoor EUEs, where the data rates are comparatively improved inside the building as almost 75% indoor EUEs in cell center case and 85% indoor EUEs in cell edge case, achieve a data rate of higher then 6 Mbps. This improvement is due to the fact that, reducing the number of indoor EUEs ease the competition to acquire more network resources to serving indoor EUEs.

- Moreover, the outdoor non-emergency UEs also obtain considerable amount of network resources which enable improved data rates as shown in figure 5.6 (right) & 5.7 (right).

- Besides the data rate improvements, the outage probability has been comparatively increased. It is due to the reason that, indoor EUEs are randomly distributed inside the building while few of them might experience low RSRP towards RN and/or eNB and need more network resources, which eventually being dropped by the base stations.

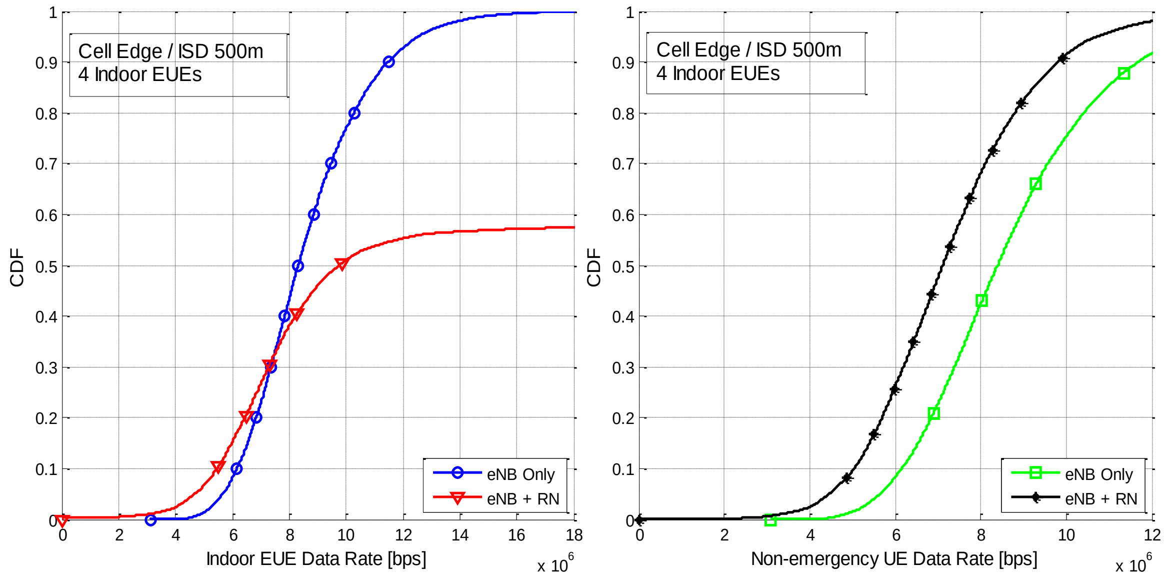


Figure 5.7: CDFs of indoor EUE (left) and non-emergency UE (right) data rates

5.5.3 Two Indoor Emergency User Equipments

This section describes the results for 2 indoor EUEs case which indicate the CDF plots of indoor EUE data rates and outdoor non-emergency UEs for cell center and cell edge respectively.

Figure 5.8 (left) & 5.9 (left) show the results for the case of 2 indoor EUEs, where the data rates are comparatively improved inside the building as almost 75% indoor EUEs in cell center case and 88% indoor EUEs in cell edge case, achieve a data rate of higher then 6 Mbps. This improvement is due to the fact that, less number of indoor EUEs connected will get more network resources as compared to above cases.

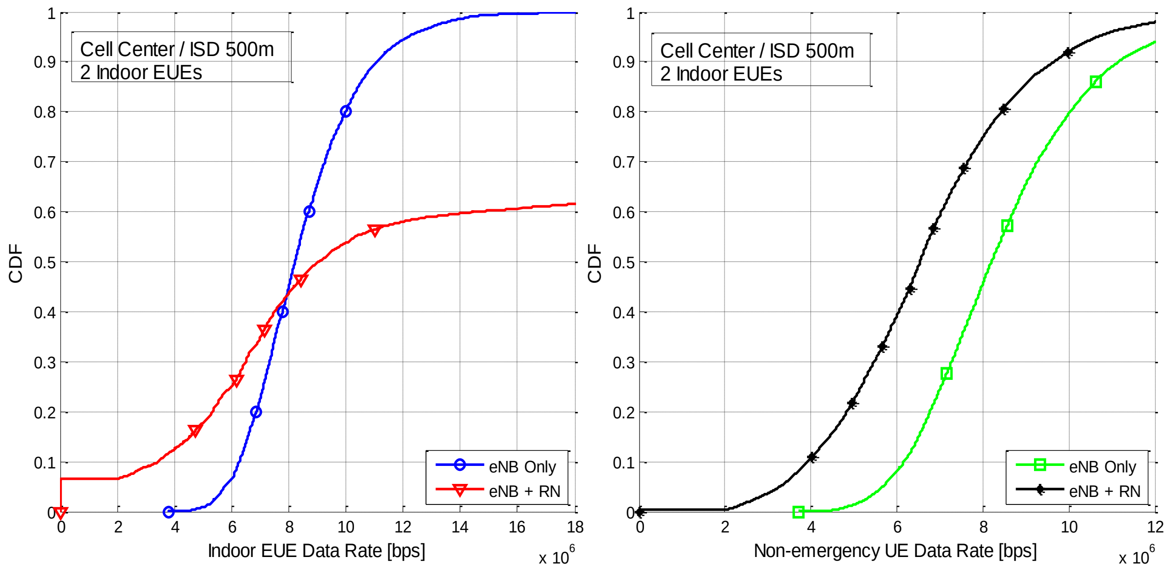


Figure 5.8: CDFs of indoor EUE (left) and non-emergency UE (right) data rates

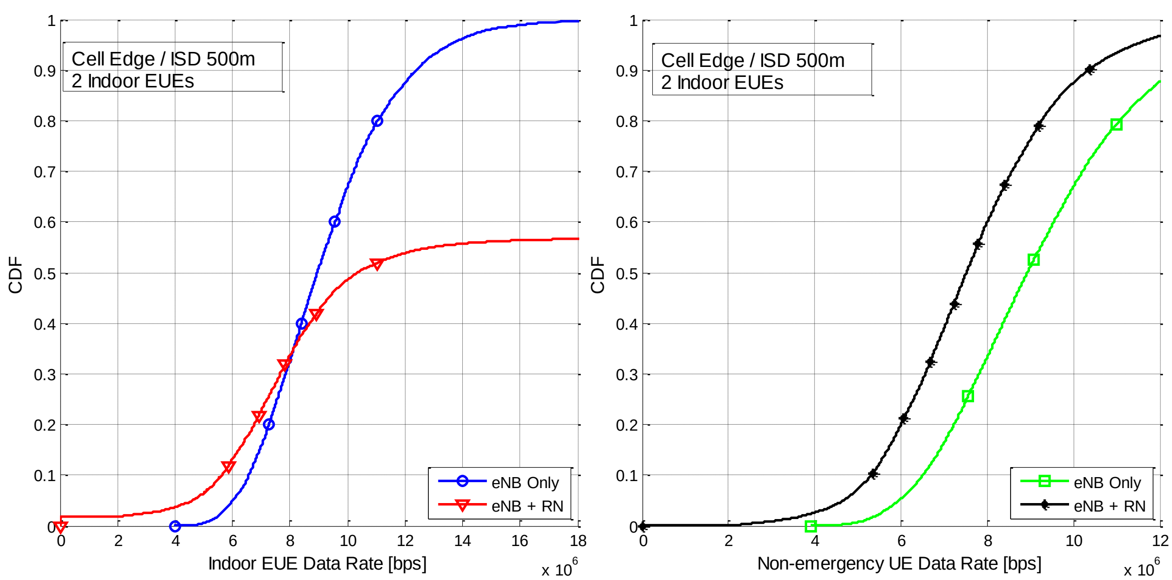


Figure 5.9: CDFs of indoor EUE (left) and non-emergency UE (right) data rates

Chapter 6

Conclusion and Future Work

Conclusions

This thesis work investigated the benefits of REC network deployments in downlink by enabling the comparative analysis with eNB only network. Though in REC networks, the SINR levels deteriorate but still, it has provide significant improvements in coverage extension and capacity enhancement.

Moreover, it also examined the indoor coverages improvements enabled by REC network deployments in emergency telemedicine scenarios. This work also outlined the architectural implementation of REC network as well as yields a comparative analysis of RN deployment to legacy eNB only networks in 3GPP downlink urban scenario.

System level simulation results show that indoor coverage has been significantly improved in relay-based system, with only insignificant performance degradation for outdoor non-emergency UEs. The simulation results also reveals that, decreasing the number of indoor EUEs will also enables the availability of more network resources to these indoor EUEs, in order to achieve high data rates.

Future Work

The future work incorporating multiple tasks to be investigated as follow;

- Currently, the building considered in 5*5 residential apartments with a single floor. Hence, for follow-up simulations, we will consider the scenario whereby the building is a multi-storey building.
- To observe the impact on indoor non-emergency UE.
- The performance of multiple un-coordinated REC used by various PMR organizations. These RNs coexist and operate in the same frequency band, compete for the available radio resources at eNB. Hence, a scheduling mechanism with pre-defined requirement will be needed for optimal RN operations.

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