TAMPEREEN TEKNILLINEN YLIOPISTO
TAMPERE UNIVERSITY OF TECHNOLOGY

DIPESH PAUDEL

# ASSESSMENT OF 3GPP MACRO SENSOR NETWORK IN DISASTER SCENARIOS

Master of Science Thesis

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# ABSTRACT

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The effective and efficient use of communication technologies during the disaster scenarios is vital for the relief and rescue works as well as for the disaster affected people. During the disaster scenarios, links between the Radio Access Network (RAN) and the Core Network (CN) might be broken in the disaster affected areas. If the link between such affected eNodeBs can be established, the data from the user can be transported to the network via node-to-node communication. Thus, this utilization of cellular mobile networks for the communication during such scenarios can be a key technological achievement.

The goal of this thesis is to study the possible realization of the BS of the mobile network as a sensor node during the disaster scenarios for the detection of such scenarios and to study the possible implementation of the node-to-node communication between the BSs for the reliable delivery of the user data to the network. This thesis examines the possibility of this inter-node communication for 3rd Generation Partnership Project (3GPP) Long Term Evolution (LTE). The merits of the LTE technology and its specifications have been deeply studied.

The calculation in the analysis part shows that node-to-node communication is possible in LTE. A probable frequency reuse plan for the node-to-node communication, which is proposed in this thesis, is a result of the bandwidth scalability property of LTE. The result from the theoretical analysis shows that Signal to Interference plus Noise Ratio (SINR) of 5.92 dB can be achieved during such communication. This SINR value can support Quadrature Phase Shift Keying (QPSK) modulation technique with 3/4 or 4/5 code rate for the bandwidth of 2.5 MHz. The Multiple-Input Multiple-Output (MIMO) technology in the LTE specification helps to provide additional increase in the data rates. The simplest communication mode can provide the data rates of 1.86 Mbps whereas 4 x 4 MIMO can provide up to 7.5 Mbps. Further, the proposed framework can be considered as the base for the implementation of node-to-node communication.

This master thesis work has considered LTE as a communication technology for the study of a probable communication technology during the disaster scenarios. The flexibility in the utilization of the bandwidth in LTE provides the possibility for the node-to-node communication. The utilization of frequency band in Global System for Mobile Communication (GSM) also provides the possibility for the node-to-node communication as well. However in Universal Mobile Telecommunication System (UMTS), the frequency band is the limitation for implementing the node-to-node communication. In UMTS, the interference will be very high because of the 5 MHz fixed frequency band implementation.

# PREFACE

This Master of Science Thesis has been written for the completion of Master of Science Degree in Information Technology from the Tampere University of Technology, Tampere, Finland. This thesis work has been carried out in the Department of Electronics and Communications under Radio Network Planning Group during year 2013.

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Finally, I would like to dedicate this thesis to my late grandmother.

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# ABBREVIATIONS

| | |
|---|---|
| 3GPP | 3rd Generation Partnership Project |
| 16QAM | 16 Quadrature Amplitude Modulation |
| AMC | Adaptive Modulation and Coding |
| BS | Base Station |
| BSC | Base Station Controller |
| BTS | Base Transceiver Station |
| BPSK | Binary Phase Shift Keying |
| CN | Core Network |
| CP | Cyclic Prefix |
| CQI | Channel Quality Indicator |
| dB | Decibels |
| DFT | Discrete Fourier Transform |
| E-UTRAN | Evolved-UMTS Terrestrial Radio Access Network |
| EPC | Evolved Packet Core |
| EIRP | Effective Isotropic Radiated Power |
| FFT | Fast Fourier Transform |
| FDD | Frequency Division Duplexing |
| GSM | Global System for Mobile Communication |
| HAPS | High Altitude Platform |
| HSS | Home Subscriber Server |
| HPBW | Half Power Beam Width |
| ITU | International Telecommunication Union |
| ICIC | Inter Cell Interference Coordination |
| ISD | Inter Site Distance |
| ISI | Inter Symbol Interference |
| IDFT | Inverse Discrete Fourier Transform |
| IFFT | Inverse Fast Fourier Transform |
| LTE | Long Term Evolution |
| LOS | Line Of Sight |
| LSR | Link State Routing |
| MIMO | Multiple Input Multiple Output |
| MT | Mobile Terminal |
| MME | Mobility Management Entity |
| MCN | Multi-hop Cellular Network |
| MCS | Modulation and Coding Schemes |
| MISO | Multiple Input Single Output |
| MVDS | Minimum Virtual Dominating Set |
| MPR | Multiple Point Relays |
| OFDM | Orthogonal Frequency Division Multiplexing |

| | |
|---|---|
| OFDMA | Orthogonal Frequency Division Multiple Access |
| OLSR | Optimized Link State Routing |
| PLMN | Public Land Mobile Network |
| P-GW | Packet Data Network Gateway |
| PDRF | Policy and Charging Rules Function |
| QPSK | Quadrature Phase Shift Keying |
| QAM | Quadrature Amplitude Modulation |
| QOS | Quality of Service |
| RAN | Radio Access Network |
| RRM | Radio Resource Management |
| RNL | Radio Network Layer |
| RNC | Radio Network Controller |
| RB | Resource Block |
| RE | Resource Element |
| SINR | Signal to Interference plus Noise Ratio |
| SMS | Short Message Service |
| SIM | Subscriber Identity Module |
| S-GW | Serving gateway |
| SC-FDMA | Single Carrier - Frequency Division Multiple Access |
| SON | Self-Organizing Network |
| SIMO | Single Input Multiple Output |
| STREAM | Sensor Topology Retrieval at Multiple Resolutions |
| SPIN | Sensor Protocol for Information via Negotiation |
| TE | Terminal Equipment |
| TDD | Time Division Duplexing |
| TNL | Transport Network Layer |
| TTI | Transmission Time Interval |
| TBS | Transport Block Size |
| UMTS | Universal Mobile Telecommunication System |
| UN | United Nations |
| UE | User Equipment |
| UICC | Universal Integrated Circuit Card |
| USIM | Universal Subscriber Identity Module |
| WSN | Wireless Sensor Network |

# 1 INTRODUCTION

Communication has played a vital role during the disaster scenarios from its early development to the present day. Communication techniques have been used for providing early information about the scenarios and during the emergency rescue and relief operation for disaster affected people. All the disaster scenarios and crisis situations are frenzied, creating physical, emotional and social disorder. In such kind of crisis events, communication is critical during disaster management. During the events surrounding the sinking of "Titanic" in the night of April 13-14, 1912, the radio communication system was vital communicating with nearby ships "Carpathia", "Virginian", "Baltic" and "Mount Temple", because of which they changed their course for rescue of people [1]. Moreover, the Tsunami of 2004 at Indian Ocean was an alert for the world on efficient communication system during an emergency for disaster management.

When disaster strikes, various communication links might be interrupted and communication networks become unfunctional. Various research and works have been done to re-establish the network and provide a prompt service to the relief workers and the people in disaster affected areas. High Altitude Platform (HAP) system has been proposed for replacing UMTS coverage in disaster scenarios [2]. Number of research has been done in the field of Wireless Sensor Networks (WSN) and Ad hoc Sensor Networks for the rescue operation and disaster survivor detection. The combination of cellular network and the ad hoc network leading to the Multi-hop Cellular Networks (MCN) is proposed in [3] which combine the benefits of fixed infrastructure of cellular networks and the flexibility of ad hoc networks. However, HAP faces the challenge of mechanical phenomena such as the stationary allotment of the station due to wind, the supply of the energy and the consumption as well as the deployment of HAP is costly. MCN does not scale very well and it is difficult to provide uninterrupted high bandwidth connectivity to large number of users with these networks [3].

The joint effort of International Telecommunication Union (ITU), The United Nations (UN), and member countries delivered "The Tampere Convention on Emergency Telecommunications"; the treaty on Telecommunication for Disaster Mitigation and Relief was signed by 30 Countries on 18th June, 1998. Till now, the numbers of countries that have signed the convention have increased to 46. ITU defines this convention as "A Life Saving Treaty" [4].

"*The Tampere Convention calls on States to facilitate the provision of prompt telecommunication assistance to mitigate the impact of a disaster, and covers both the installation and operation of reliable, flexible telecommunication services. Regulatory barriers that impede the use of telecommunication resources for disasters are waived. These barriers include the licensing requirements to use allocated frequencies, restrictions on the import of telecommunication equipment, as well as limitations on the movement of humanitarian teams*."[4]

“Keeping People Connected is Keeping people safe” [5]. Keeping this in mind, Public Land Mobile Network (PLMN) can be used in these disaster scenarios to transfer the data from sensors, establish communication between relief teams or the communication with victims and people in the disaster areas. The Tampere Convention facilitates the use of telecommunication for humanitarian aid, removing regulatory barriers and use of the frequencies. Further, the cost of the implementation of technology for the disaster purpose is also a vital role for telecommunication operators. Thus, realising all these various circumstances, this thesis put forth the framework for the efficient use of telecommunication network during the disaster scenarios.

LTE is the leading mobile technology used for communication in the present context. For this technology, the network is divided into the RAN and the CN. A disaster scenario can be realised, where the link between the RAN and CN is broken. Thus, resulting to the network outage in the disaster areas and this can directly affect the relief work, victims and the people in the disaster zone.

One possible solution for this outage is the realization of mobile antennas as WSN nodes and establishes the relay network between the affected mobile antennas, that is, antenna (node) to antenna (node) communication. The node-to-node communication can be established between the nodes in the disaster affected areas and the fully functional node at the shortest distance from the disaster affected area. This functionality can be turned on in the communication network as a “Safety Mode” and the communication blackout can be eliminated and network can be re-established. Once the link is established, the danger warning message can be sent to the people in the affected areas and limited services such as Short Message Service (SMS) or data services can be provided to the people which results in the proficient and timely relief operation as well as provides the people or victims to communicate.

GSM, UMTS and LTE are the three major technologies representing the 2nd, 3rd and the 4th generation of mobile communication. The GSM and LTE provide the flexibility in the utilization of their frequency bandwidth. The frequency reuse concept and the use of cells were first introduced in GSM. Different frequency bands (Channels) can be used as per the requirement to accommodate the users. Similarly, LTE provides the bandwidth scalability functionality which offers the flexibility in the utilization of its 20 MHz bandwidth. But UMTS technology is designed to use nominal 5 MHz bandwidth. During disaster scenarios, the basic requirement for node-to-node communication is that the node should communicate with the users as well as with the neighbour node. Thus, the preliminary investigation for node-to-node communication in UMTS shows that due to frequency limitation, the interference is very high at the receiver and thus the communication is unlikely to be feasible. But the communication can be possible in GSM and LTE.

As LTE is an emerging technology with packet based network, this Master of Science thesis discusses the feasibility of the “Safety Mode” operation in LTE networks and proposes a framework for the realization of this “Safety Mode” operation during the disaster scenarios. The special focus in this thesis is on the utilization of the frequency bandwidth efficiently, analysis of the interference during node-to-node communication and the capacity analysis during “Safety Mode” operation. And at the end, an operational framework is proposed which includes the flow chart stating the possible mechanism for the operation of the “Safety Mode”.

This thesis is the assessment of the macro sensor network for the 3GPP technologies to provide the communication mechanism during the disaster scenarios. As the nature and the timing of the disaster cannot be predicted and the effects of these disasters can lead to the blackout of the communication mechanisms, this thesis can be considered as a new approach to indulge the communication mechanism during the disasters. The holistic view of 3GPP communication technologies as probable macro sensor network realization in this thesis is probably the first of its kind.

# 2 INTRODUCTION TO 3GPP LTE

A rapid increase in the usage of mobile data services and development of new applications such as multimedia applications, live streaming and many other applications motivated the 3GPP to put forth the fourth generation mobile communication system, also known as LTE. LTE is the first cellular communication system enhanced to support packet switched data services with packetized voice communication. Developed as fully IP oriented packet based network, LTE can bring high performance improvement and much better spectral efficiency to cellular networks. The efficient mechanisms for the operation and maintenance of the network using the self-optimization functionality are also introduced in LTE. The first specification for the LTE is in 3GPP Release 8 [6]. The network architecture is simplified as compared to UMTS and earlier releases. This section of the thesis provides the overview of the LTE network architecture.

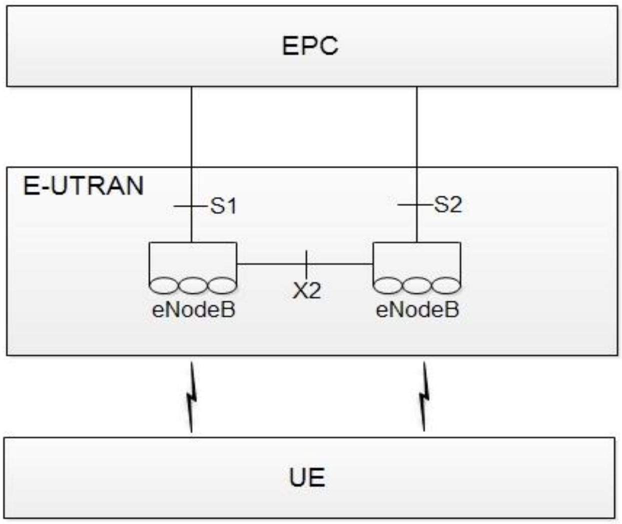


*Figure 2.1. LTE Architecture [7].*

The Figure 2.1 shows the overall architecture of LTE network. This network architecture comprised of following three main components:

1) The User Equipment (UE)
2) The Evolved UMTS Terrestrial Radio Access Network (E-UTRAN)
3) The Evolved Packet Core (EPC)

Each of these Network Elements will be covered in the following sections.

## 2.1 LTE Radio Network Architecture

LTE Radio Network Architecture aggregates the two major parts, the UE and the E-UTRA. The main goal of E-UTRA is to provide high data rates, low latency and packet optimized radio access technology supporting flexible bandwidth deployments. Thus, the focus of LTE is in the services provided from the PS-domain. LTE Radio Network focuses on the different areas including the means to support flexible transmission bandwidth up to 20 MHz, signalling optimization and the architectural and the functional split between RAN nodes. The target of this focus area is to increase the peak data rate, improve spectral efficiency, and support inter-working with existing systems. The most important feature of LTE Radio Access Network is the scalability of bandwidth. LTE supports the scalable bandwidth of 5 MHz, 10 MHz and 20 MHz with possibility at 15 MHz. 1.25 MHz, 1.6 MHz, and 2.5 MHz allows the flexibility in narrow spectral allocations where the system can be installed if needed.

### 2.1.1 The User Equipment

The internal architecture of the LTE UE is similar with the UMTS and GSM Mobile Equipment. The UE comprised of mainly the Mobile Termination (MT) which handles all the communication functions, Terminal Equipment (TE) which terminates the data streams and Universal Integrated Circuit Card (UICC) which is also known as the Subscriber Identity Module (SIM) card for LTE UE. Figure 2.2 shows the basic architecture of the UE. UICC runs an application known as Universal Subscriber Identity Module (USIM) [9].

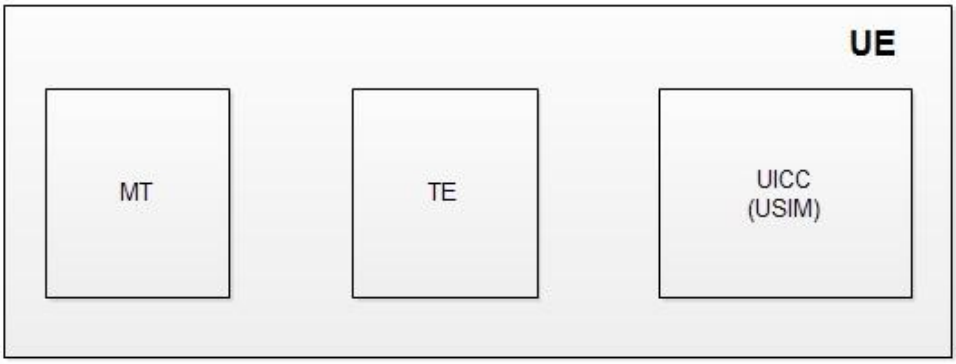


*Figure 2.2. Architecture of UE.*

UE communicates with eNodeB in the air interface. LTE system has been designed to support a set of five UE categories, varying from the simplest, low cost terminals with low data rate support to the high capability terminals with peak data rate support. Thus LTE supports different range of categories of UE to satisfy the demand of different market segments.

### 2.1.2 E-UTRAN

E-UTRAN architecture is packet based architecture and it handles the communication between the UE and the EPC. E-UTRAN consists of group of eNodeBs and each eNodeB controls the UE in one or more coverage area. eNodeB is the Base Station (BS) of LTE and it sends and receives the radio transmissions to the UE, that is, it is the part of LTE air interface. It also controls the low level operation of UE and communicates with them using signalling messages. eNodeB performs the Radio Resource Management (RRM) tasks such as call admission control, handover control, bearer management and the activation and termination of radio interface protocols used for communication with UE. eNodeB can support Frequency Division Duplexing (FDD), Time Division Duplexing (TDD) or both of them to communicate with the UE.

E-UTRAN is layered into Radio Network Layer (RNL) and Transport Network Layer (TNL) [8]. RNL includes the logical nodes (eNodeB) and interfaces between them (X2 and S1). LTE radio access network is configured with eNodeB base station and is connected to EPC via S1 interface. The neighbouring eNodeBs are connected via X2 interface. For each interface TNL protocol is defined. TNL provides the services for user plane and signalling transport. Figure 2.3 shows the architecture of E-UTRAN with X2 and S1 interface.

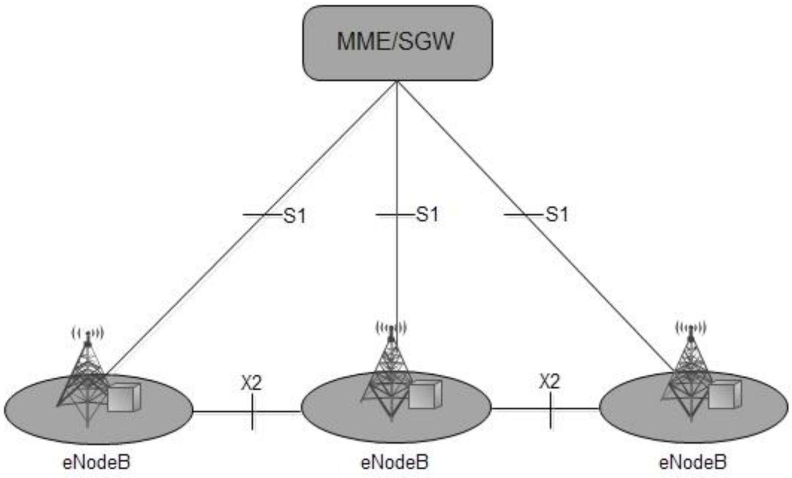


*Figure 2.3. E-UTRAN Architecture.*

This architecture of Radio Network reduces the processing for each packet in the Radio Access Network and also reduces the number of control signals. This is because the higher level node such as Base Station Controller (BSC) in GSM and Radio Network Controller (RNC) in UMTS is eliminated in LTE system. As a result, the packet delays and control delays in call connection is reduced. Since the higher level node is removed in LTE Radio Network, the functionality in the eNodeB is increased as compared with Base Transceiver Station (BTS) and NodeB. eNodeB has the same functionality as the NodeB in UMTS and in addition to this it has most of the RNC functionality added into it. Thus, eNodeB controls the radio resources in its coverage area, takes decisions regarding the handovers and also makes the scheduling decisions for the uplink and downlink. There is no centralized controller in E-UTRAN, and hence E-UTRAN has the flat architecture.

## 2.2 LTE EPC

EPC was first introduced by 3GPP in its Release 8 of the standard. It is responsible for the overall control of the UE and the establishment of bearers. EPC is based on flat all-IP architecture for high data rates, low latency, and support for multiple radio access technology in the interests of seamless mobility and to increase the capacity of LTE System [10]. The control and the bearer part are separated in the design of EPC. Figure 2.4 shows the basic architecture of EPC with the interface between the nodes.

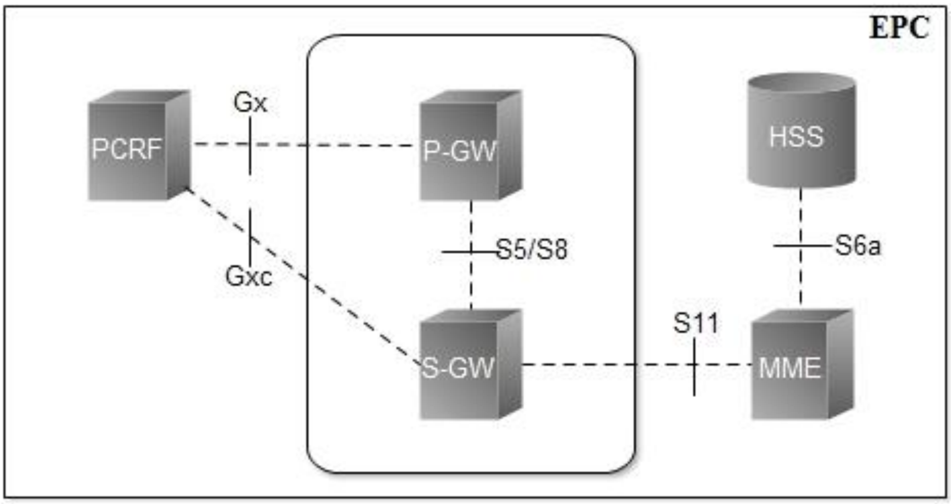


*Figure 2.4. EPC Architecture [11].*

As shown in the above figure, to achieve the flat architecture, EPC is divided into five network elements, the Mobility Management Entity (MME), Serving Gateway (S-GW), Packet Data Network Gateway (P-GW), Home Subscriber Server (HSS) and Policy and Charging Rules Function (PCRF) [11].

MME handles the signalling associated with mobility and the security of E-UTRAN Access. It is also responsible for the paging and authentication of UE. It keeps the location information at the tracking area level for each UE. MME connects to eNodeB through S1-MME interface and connects to S-GW through S11 interface.

S-GW is the point of interconnection between Radio Network side and EPC. It deals with the user plane and it works as a router. Its main role is to forward IP data traffic between E-UTRAN and P-GW. PCRF is responsible for defining the policy and managing the charging according to the service used by the UE. HSS is the database server which stores the information of each subscriber.

## 2.3 Interfaces of LTE Radio Network

As stated in section 2.1.2, the LTE Radio Network is the network of eNodeBs which results in its flat architecture. There is no centralized controller in LTE as there was in case of GSM and UMTS. This results in the speediness of the connection setup and reduces the handover time. The speedy connection setup is important in case of real time data session such as online gaming and the handover time plays a vital role during real time services. To meet this requirement, two major interfaces are introduced in LTE. Each eNodeB is connected to the EPC through S1 interface and neighbouring eNodeBs are interconnected through the X2 interface [8]. Figure 2.1 shows the LTE architecture with these interfaces.

### 2.3.1 S1 Interface

The S1 interface is defined at the boundary between the E-UTRAN and the EPC. eNodeB is the access point of E-UTRAN. For the EPC, the access point can be either the control plane MME or the user plane S-GW. Thus, two types of S1 interfaces are possible depending upon the access point of the EPC, S1-MME and the S1-U [8]. Thus, depending upon the number of eNodeB, there can be several numbers of S1 interfaces. It is a logical interface in nature [8]. There can be multiple numbers of S1-MME logical interfaces with the EPC and there can be multiple S1-U logical interfaces towards the EPC from a single eNodeB. Figure 2.5 shows the S1 interface with S1-MME and S1-U interface.

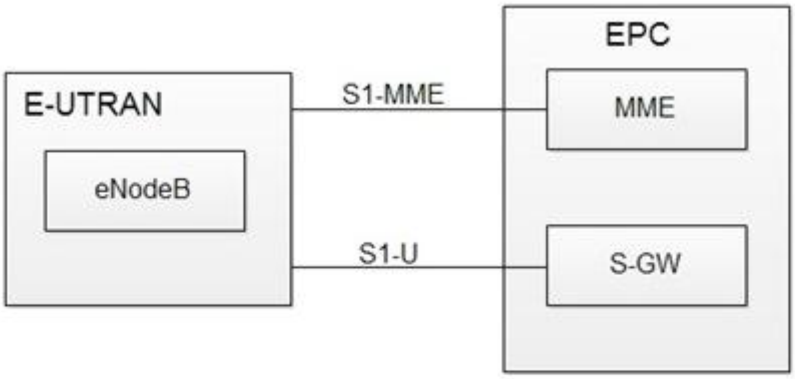


*Figure 2.5. S1 Interface [8].*

As shown in the figure, S1-MME is the interface between the MME and the E-UTRAN. This interface is responsible for the management of the S1 interface. It also provides the path for paging message delivery to the UEs. S1-MME interface manages the bearers to be setup for the UE.

S1-U is the interface between S-GW and E-UTRAN. This interface is used for transmitting user IP packets between the eNodeB and the S-GW. Thus, S1-U user planes are transport tunnels based on IP and the end users' IP packets are put into the S1-U IP tunnel by S-GW or the eNodeB and recovered at the other end. The selection of the S1-U interface is done inside the EPC and is signalled to eNodeB by MME.

This thesis supposes the case when this S1 interface is down for one or several eNodeBs during the disaster scenarios. Thus, a framework has been proposed to establish the hop to hop communication between the eNodeB to establish a communication path to EPC via eNodeB with working S1 interface.

### 2.3.2 X2 Interface

The interface which allows the interconnection of eNodeBs with each other is referred to as X2 interface. It is a point-to-point interface between two eNodeBs and it is not mandatory to have a direct physical connection between two eNodeBs [12]. It is an open interface and it supports the exchange of signalling information between the eNodeBs. This interface also supports the forwarding of Packet Data Units (PDU) to the respective tunnel endpoints. The occurrence of X2 interface can be seen in Figure 2.1.

During the handovers between the eNodeBs, the source and the target eNodeBs can use X2 interface to directly exchange the handover request and response messages. X2 interface is responsible for the intra LTE mobility of the UE, Load Management in the eNodeB, Inter Cell Interference Coordination (ICIC) and for signal tracing to detect the fault [12].

This thesis proposes a framework for the communication between two eNodeBs during the disaster scenarios. For this communication, certain functionality of eNodeB is inactivated and certain functionality is activated. This will be dealt in the following chapters. Thus, this thesis is not the extension of X2 interface but it put forth the framework for the communication between two eNodeBs only in disaster scenarios. The mode of communication is radio wave and it is the direct communication between eNodeBs.

## 2.4 Radio Access Technology in LTE

LTE is designed for higher data rates and faster connection time with the UE. Since LTE is based on shared and broadcast channels, it does not contain dedicated channels that carry data to the designated UE. This increases the efficiency of the air interface, as the network no longer have to assign fixed resource to each UE but is able to allocate resource according to the real time demand of UE [13]. Thus, Orthogonal Frequency Division Multiple Access (OFDMA) technique was agreed for downlink transmission in the air interface. Similarly, Single Carrier–Frequency Division Multiple Access (SC-FDMA) technique for uplink transmission was agreed for the air interface. SC-FDMA is technically similar to OFDMA but it is good for hand held devices because it is less demanding on battery power [13]. Both of these schemes in the frequency domain led to the flexibility in the system. This flexibility results in the fractional frequency reuse and interference coordination between the cells.

5 MHz channel bandwidth causes limitation in the data rate of WCDMA system. To overcome these limitations in LTE, the higher bandwidths up to 20 MHz is used. The use of higher bandwidths in WCDMA would have caused higher delays problems which would have limited the data rates [13]. LTE removes this limitation by implementing OFDMA technique. OFDMA is a multicarrier technique where the bandwidth is divided into many narrow sub channels. These sub channels are combined together to achieve the total throughput.

### 2.4.1 OFDMA

OFDMA is a multi-user version of Orthogonal Frequency Division Multiplexing (OFDM). OFDM is a multicarrier technology where the available bandwidth is subdivided into several narrowband subcarriers. Figure 2.6 shows the frequency and time domain representation of the OFDM signal. In OFDMA, the subcarriers can be shared between multiple numbers of users. OFDMA is considered as the most ideal technique for high spectral efficiency. In this technique, there are multiple numbers of sub-carriers which can carry the information data. These sub-carriers are orthogonal to each other and a guard time can be added to each symbol to counter the Inter Symbol Interference (ISI) [14].

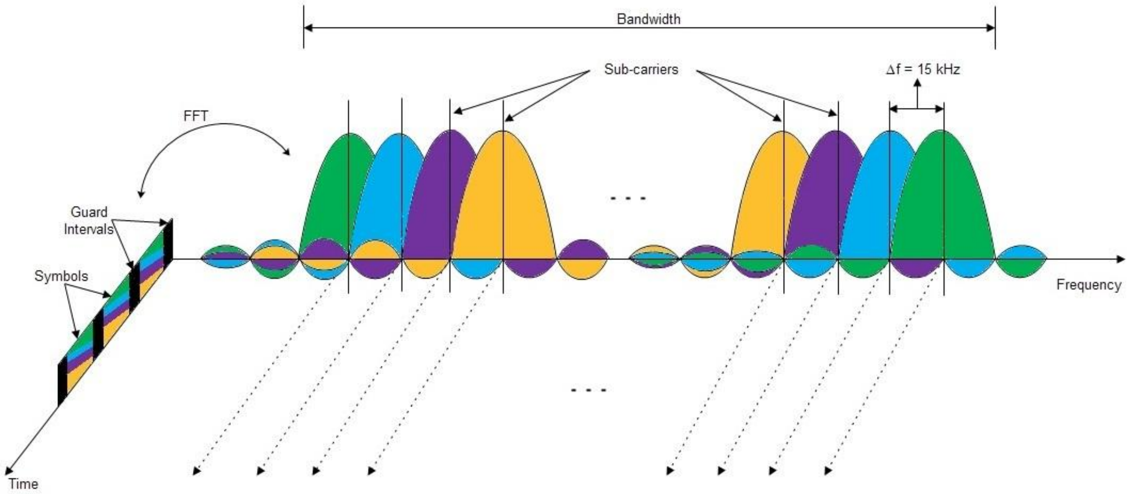


*Figure 2.6. OFDM frequency and time domain representation [15].*

The execution of OFDMA is based on digital technology and it uses Discrete Fourier Transform (DFT) and Inverse Discrete Fourier Transform (IDFT). The practical implementation uses the Fast Fourier Transform (FFT) and Inverse Fast Fourier Transform (IFFT). This results in an OFDMA symbol of duration $T_\mathrm{u}$. The guard interval $T_\mathrm{g}$ is added at the beginning of the OFDMA symbol. Thus, OFDMA yields a frequency structure that divides data over number of sub-carriers with the guard interval called Cyclic Prefix (CP) with total symbol length of $T_s = T_u + T_g$ [16].

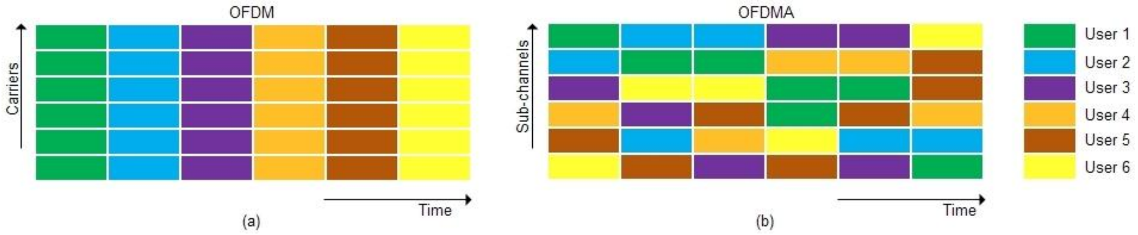


*Figure 2.7. (a) OFDM Representation (b) OFDMA Representation.*

Figure 2.7 (a) shows the OFDM representation of the users in terms of carrier and time and (b) shows the OFDMA representation of the users.

### 2.4.1.1 Physical Layer Structure

In OFDMA, users are allocated a specified number of sub-carriers for a certain amount of time. These are known as resource blocks (RB). RB is the smallest unit of bandwidth that can be allocated by the base station scheduler. Thus, the resource blocks have both time and frequency components. LTE can have both TDD and FDD mode of operation. This thesis considers only the FDD mode of operation. Figure 2.8 shows the OFDM generic frame structure for normal and extended CP.

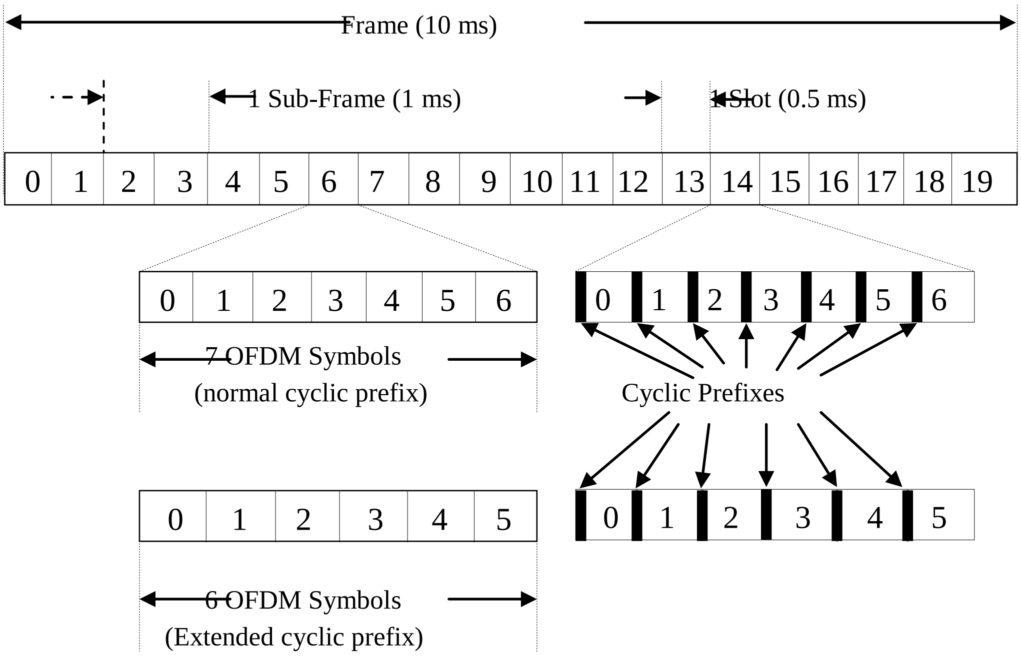


*Figure 2.8. OFDM Generic Frame Structure [17].*

As show in above figure, each LTE frames are 10 ms in duration. They are divided into 10 sub-frames, each sub-frame being 1 ms long. Each sub-frame is further divided into two slots, each of 0.5 ms duration and each slot consists of 7 OFDM symbols in case of normal CP. Extended CP contain 6 OFDM symbols. Thus, there are $12 \cdot 7 = 84$ Resource Elements (RE) in case of normal CP and 72 RE in case of extended CP.

The basic time unit $T_s = 1/30720000$ is defined in LTE to express other time interval as a multiple of this basic time unit [16]. LTE frame is 10 ms in duration, that is, $T_{frame} = 307200 \cdot T_s$. Each sub-frame is 1 ms long, that is, $T_{subframe} = 30720 \cdot T_s$. Each subframe is divided into two slots of size 0.5 ms, that is, $T_{slot} = 15360 \cdot T_s$ .

#### 2.4.1.2 Physical Layer Resources

LTE uses the group of narrow sub-carriers for multi-carrier transmission. The spacing between two sub-carriers in OFDMA is constant at 15 kHz. As discussed in section 2.4.1.1, the number of OFDMA symbols can be 7 or 6 depending upon the type of CP. These symbols are grouped into the RB. Each RB has total size of 180 kHz with 12 sub-carriers in the frequency domain. Thus, a RB consists of 12 sub-carriers in frequency and 14 OFDMA symbols in the time domain. This makes one RB of 180 kHz in frequency and 1 ms in time. This sub-frame is also the minimum transmission time interval (TTI). This short TTI helps to achieve the low latency. The symbol time, with respect to the sub-carrier spacing of 15 kHz is $T_b = 2048 \cdot T_s = 66.68$ µs. Figure 2.9 shows the graphical representation of the physical resource block .

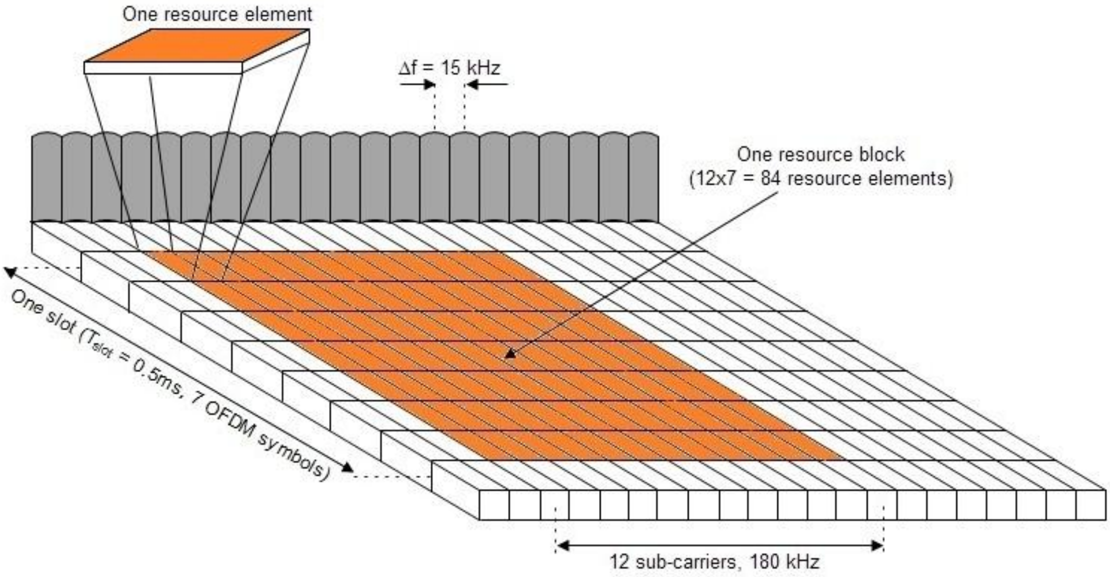


*Figure 2.9. Physical Resource Block Representations [18].*

The major advantage of LTE is its scalability for the frequency. Thus, this flexibility in the bandwidth is provided by allowing different bandwidth options to choose from.

The allowed bandwidths include 1.25, 1.6, 2.5, 5, 10, 15 and 20 MHZ [20]. The guard band uses 10% of total bandwidth. The Table 2.1 shows the requirement of number of resource blocks according to the channel bandwidth.

*Table 2.1. LTE Downlink Resource Block parameter.*

| Bandwidth | 1.25 MHz | 2.5 MHz | 5 MHz | 10 MHz | 15 MHz | 20 MHz |
|---|---|---|---|---|---|---|
| Number of Resource Blocks | 6 | 12 | 25 | 50 | 75 | 100 |

## 2.5 Link Adaptation

Link adaptation in LTE adjusts the data rate of the transmitted information dynamically so that it can match the capacity for each service to the user. This data rate of the information depends on the modulation technique and channel coding. The quality of the signal received by the UE depends on the quality of the channel from the serving cell, the interference from the other cells and the noise level present. Depending on the prediction of the downlink channel quality, eNodeB assigns the modulation technique and channel coding rate. The LTE specifications are designed such that the eNodeB can optimize the link adaptation but the exact methods the eNodeB follows to use this information are left to the manufactures [19].

The Channel Quality Indicator (CQI) transmitted by the UE to the eNodeB is used during the selection of this modulation technique and channel coding rate. The CQI shows the data rate that the channel can support. The SINR and the characteristics of the receiver are taken into account while transmitting the CQI value [19]. When the eNodeB receives the CQI, then it can select either of QPSK, 16 Quadrature Amplitude Modulation (16QAM) or 64QAM techniques and the suitable coding rate.

The link adaptation is based on Adaptive Modulation and Coding (AMC). The AMC consists of Modulation and Coding Schemes (MCS) [19].

- *Modulation Scheme.* The modulation schemes consists of lower order and higher order modulation techniques. Lower order modulation technique such as QPSK is robust and tolerant to higher levels of interference but provides lower data rates. Whereas higher order modulation technique such as 64QAM offers higher data rates but is more sensitive to the errors due to the interference and noise. Thus, these higher order modulations require higher SINR value.
- *Code Rate.* For a given modulation technique, the code rate can be chosen depending on the radio link conditions. A lower code rate can be used in case of poor radio channel and higher code rate can be used in good radio channel conditions.

In LTE, the UE can be configured to report CQIs to assist the eNodeB in selecting an approximate MCS to use for the downlink transmission. This CQI is prepared on the basis of downlink received signal quality and in LTE, CQI is not a direct indication of SINR value. However, this CQI contains the information about the highest MCS that a UE can decode with transport block error rate probability not greater than 10% [19].

## 2.6 Data Rates

The most important part of the end user application performance depends on the available bit rate, latency and the mobility. Thus, E-UTRAN should support the rapid increase in the peak data rates [19]. The supported peak data rate is scaled according to the size of the spectrum allocation. Also, the peak data rates may depend on the capability of the UE. The LTE target for peak data rates was 100 Mbps in downlink and 50 Mbps in uplink.

The large bandwidth of 20 MHz, the higher order modulation such as 64QAM, and multi-stream MIMO transmission supports LTE to provide high peak bit rates. The Binary Phase Shift Keying (BPSK) modulation carries 1 bit per symbol, QPSK modulation carries 2 bit per symbol, 16QAM carries 4 bits and 64QAM carries 6 bits per symbol. The MIMO system further helps to increase this peak bit rate per symbol. The modulation is accompanied by the term called coding rate. Coding Rate describes the efficiency of particular modulation scheme. If we say 16QAM with coding rate of 0.5, it means the modulation has 50% efficiency and it can carry 2 bits out of 4 bits as information bits and rest of the 2 bits for the redundancy of information.
The Peak bit rate can be calculated by the formula:

$$\begin{aligned}&\text{Peak bit rate[Mbps]}\\&\quad=\frac{\text{Number of symbols per subFrame}}{1\text{ms}}\cdot\frac{\text{bits}}{\text{Hz}}\cdot\text{Number of SubCarriers.}\end{aligned}\qquad(2.1)$$

There are number of ways to calculate the throughput. In the first method, throughput is calculated as symbol per second. It can be converted into bits per second depending on how many bits a symbol can carry. For the carrier bandwidth of 20 MHz, there is 100 RB and each RB has 12·7·2 = 168 symbols per ms in case of normal CP. Thus the total number of symbols per ms for 100 RB is 16800. The symbol per second is 16800000 or 16.8 Mbps If the modulation scheme is 64QAM, then throughput is 16.8·6 = 100.8 Mbps. If the system is 4x4 MIMO, then the total throughput is 4·100.8 = 403.2 Mbps. If we assume that 25% of overhead is used for controlling and signalling, so the effective throughput is 302 Mbps.

The second method is the use of 3GPP specification 36.213 for throughput calculation [21]. The combination of the modulation and the coding rate is called MCS. 3GPP technical specification TS 36.213 specifies the MCS and Transport Block Size (TBS) for LTE. Table 7.1.7.1-1 in this specification specifies the mapping between MCS Index, Modulation Order and the TBS Index.  The eNodeB assigns the MCS Index and the RB on the basis of CQI for the downlink transmission. This CQI value depends upon the SINR. Modulation Order describes the type of modulation technique and its value is 2 for QPSK, 4 for 16QAM and 6 for 64QAM. LTE supports 0 to 28 MCS in the downlink. Table 7.1.7.2.1-1 in the same specification specifies the mapping between TBS Index, Number of RB and the corresponding TBS. This TBS value is the number of bits that can be transmitted in a sub-frame per TTI.

For the same case of 20 MHz of channel bandwidth, the MCS Index, by referring to Table 7.1.7.1-1 of specification TS 36.213 is 28. Then, from the same table, the Modulation order is 6 and the TBS Index is 26. Modulation order 6 specifies the 64QAM modulation technique. Then from Table 2.1, for 20 MHz, the number of resource block is 100. From 3GPP specification 36.213, Table 7.1.7.2.1-1, the corresponding TBS is 75376. The duration of 1 sub-frame is 1 ms. So the peak data rate is 75.376 Mbps. If we consider the case for higher 4x4 MIMO system, then the peak data rate is $4 \cdot 75.376 = 301.5$ Mbps.

## 2.7 Self-Organizing Network (SON)

SON is a technology designed to make the configuration, management and healing of the mobile radio network automated. The main aim of SON is to improve the network performance reducing the manual intervention in the network operation [22]. SON concept has been included in the 3GPP specification from release 8 and its range is expanded in the following releases.

The scope of the SON is increasing in each release. Release 8 includes the different aspect of eNodeB self-configuration such as automatic inventory, software download, neighbour relation and physical cell ID assignment. The next release of SON, that is release 9 leads to more maturing networks which include coverage and capacity optimization, mobility optimization, inter-cell interference coordination and load balancing. Release 10 includes the enhancement to existing use cases and defines new use cases such as self-healing functions, energy savings and most importantly the cell outage detection and compensation [22].

Cell outage detection and compensation function of SON can be very helpful during the disaster scenarios and it can play a role to detect and initiate the role to establish the links between eNodeBs for the communication during disaster.

# 3 FREQUENCY ALLOCATION AND REUSE

The wireless industry has seen a rapid growth in the voice and data services in recent years. The allocation and usage of radio spectrum, a very finite and valuable resource for the wireless communication, varies widely from region to region and is not enough to satisfy the demand.  Mobile broadband networks will quickly consume current spectrum allocations, since they are offering high level of user experience by providing multimedia applications. Moreover, the mobile industry is rapidly increasing and this is directly benefiting the user and increasing the economic development of the country. The regulation in the spectrum has become flexible allowing the operators to address demand more effectively.

Various new innovations in the wireless technologies, from the service providers and equipment vendors have led to the efficient use of radio spectrum, providing high capacity in a given bandwidth. LTE has emerged as this kind of innovation meeting the requirement of efficient use of spectrum. This section confers about the frequency aspect of the LTE system.

## 3.1 Frequency Allocation in LTE

LTE is defined for the wide range of different frequency bands. The frequency bands are organised according to the FDD or TDD mode of operation respectively. FDD spectrum requires pair band, one for the uplink and another for the downlink whereas TDD requires a single band, as uplink and downlink are time separated in the same frequency. 3GPP has defined the band number for different regional allocation. Table 3.1 shows the detail of the frequency band allocated for LTE respectively with the respective LTE band numbers.

*Table 3.1. Frequency allocation for LTE [23].*

| LTE Band | Uplink (MHz) | | | Downlink (MHz) | | | Duplex Mode |
|---|---|---|---|---|---|---|---|
| 1 | 1920 | - | 1980 | 2110 | - | 2170 | FDD |
| 2 | 1850 | - | 1910 | 1930 | - | 1990 | FDD |
| 3 | 1710 | - | 1785 | 1805 | - | 1880 | FDD |
| 4 | 1710 | - | 1755 | 2110 | - | 2155 | FDD |
| 5 | 824 | - | 849 | 869 | - | 894 | FDD |
| 6 | 830 | - | 840 | 875 | - | 885 | FDD |
| 7 | 2500 | - | 2570 | 2620 | - | 2690 | FDD |
| 8 | 880 | - | 915 | 925 | - | 960 | FDD |
| 9 | 1749.9 | - | 1784.9 | 1844.9 | - | 1879.9 | FDD |
| 10 | 1710 | - | 1770 | 2110 | - | 2170 | FDD |
| 11 | 1427.9 | - | 1447.9 | 1475.9 | - | 1495.9 | FDD |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 12 | 699 | - | 716 | 729 | - | 746 | FDD |
| 13 | 777 | - | 787 | 746 | - | 756 | FDD |
| 14 | 788 | - | 798 | 758 | - | 768 | FDD |
| 15 | 1900 | | 1920 | 2600 | | 2620 | FDD |
| 16 | 2010 | | 2025 | 2585 | | 2600 | FDD |
| 17 | 704 | - | 716 | 734 | - | 746 | FDD |
| 18 | 815 | - | 830 | 860 | - | 875 | FDD |
| 19 | 830 | - | 845 | 875 | - | 890 | FDD |
| 20 | 832 | - | 862 | 791 | - | 821 | FDD |
| 21 | 1447.9 | - | 1462.9 | 1495.9 | - | 1510.9 | FDD |
| 22 | 3410 | - | 3490 | 3510 | - | 3590 | FDD |
| 23 | 2000 | - | 2020 | 2180 | - | 2200 | FDD |
| 24 | 1626.5 | - | 1660.5 | 1525 | - | 1559 | FDD |
| 25 | 1850 | - | 1915 | 1930 | - | 1995 | FDD |
| 26 | 814 | - | 849 | 859 | - | 894 | FDD |
| 27 | 807 | - | 824 | 852 | - | 869 | FDD |
| 28 | 703 | - | 748 | 758 | - | 803 | FDD |
| 29 | - | - | - | 717 | - | 728 | FDD |
| 33 | 1900 | - | 1920 | 1900 | - | 1920 | TDD |
| 34 | 2010 | - | 2025 | 2010 | - | 2025 | TDD |
| 35 | 1850 | - | 1910 | 1850 | - | 1910 | TDD |
| 36 | 1930 | - | 1990 | 1930 | - | 1990 | TDD |
| 37 | 1910 | - | 1930 | 1910 | - | 1930 | TDD |
| 38 | 2570 | - | 2620 | 2570 | - | 2620 | TDD |
| 39 | 1880 | - | 1920 | 1880 | - | 1920 | TDD |
| 40 | 2300 | - | 2400 | 2300 | - | 2400 | TDD |
| 41 | 2496 | - | 2690 | 2496 | - | 2690 | TDD |
| 42 | 3400 | - | 3600 | 3400 | - | 3600 | TDD |
| 43 | 3600 | - | 3800 | 3600 | - | 3800 | TDD |
| 44 | 703 | - | 803 | 703 | - | 803 | TDD |

All of these bands shown in the above table are available in each region of the world. But different regions are using different bands. Different LTE frequency bands are allocated numbers. From the above table, we can see that the LTE band from 1 to 29 is for the paired spectrum and the band from 33 to 44 is for the unpaired spectrum. Table 3.2 illustrates the deployment areas for different FDD bands [23].

*Table 3.2. Region-wise FDD frequency usage.*

| Europe | Asia | Asia (Japan) | America |
|---|---|---|---|
| 1 | 1 | 1 | 2 |
| 3 | 3 | 6 | 4 |
| 7 | 5 | 9 | 5 |

| | | | |
|---|---|---|---|
| 8 | 8 | 11 | 10 |
| 20 | 28 | | 12 |
| 22 | | | 13 |
| | | | 14 |
| | | | 17 |
| | | | 23 |
| | | | 24 |
| | | | 25 |
| | | | 26 |
| | | | 27 |
| | | | 28 |
| | | | 29 |

The 900 MHz band is the most ubiquitous and most harmonized worldwide wireless spectrum band available today [24]. It has the advantage of increased coverage and offers improved building penetration. The deployment cost as compared to the deployments in high frequencies is relatively lower [24]. [26] highlights the need of the frequency band allocation and the importance of LTE deployment for the manufactures and the operators. The deployment of LTE in 800 and 900 MHz band can bring the high capacity benefits and can also provide the greater coverage at much reduced cost. Further, LTE in 900 MHz can bring the additional cost benefits of being able to deploy LTE at existing GSM sited with existing infrastructure. European Parliament on May, 2010 approved the 800MHz band for the mobile broadband [25].

Thus, this thesis considers the 800 MHz band for the LTE and all the realization is done on the basis of LTE 800 MHz band.

## 3.2 Bandwidth Scalability

E-UTRAN should operate in spectrum allocations of different sizes to provide flexible utilization of the bandwidth. This operating bandwidth can be 1.25 MHz, 1.6 MHz, 2.5 MHz, 5 MHz, 10 MHz, 15 MHz and 20 MHz in both uplink and downlink communication. The sub-carrier spacing remains the same for all the above options at 15 kHz, as seen in Table 2.1, it is only the number of sub-carriers that changes. This flexibility in spectrum is the key feature of LTE. In the context of operators, not all operators have been allocated the same amount of frequency band in 900 MHz bands and further, many GSM 900 MHz networks have reached their full capacity with GSM traffic and operators cannot free up the frequency spectrum [24]. In such case, LTE offers a solution and advantage because of its scalable bandwidth.

Although LTE supports a scalable bandwidth, a 20 MHz bandwidth will be needed to achieve its best performance and to deliver expected data traffic. But, scalability of bandwidth introduces the cost effective deployment in lower frequency bands as well.

This thesis has highlighted the use of bandwidth scalability during the disaster scenarios. The usable bandwidth is determined according to the traffic needed.

## 3.3 Frequency Reuse

The frequency bands allocated to the operators are expensive as well as bandwidth limited. Thus, the operators are searching for such a technique that the expensive spectrum is used most efficiently. One way to use spectrum efficiently is the frequency reuse scheme. Frequency reuse is the use of same frequency more than once within a same network to increase the capacity and efficiency. The frequency reuse was first introduced in GSM standards with frequency reuse factor between 3 and 9. Frequency reuse factor is the rate at which the same frequency can be used in the network. For the 3rd generation UMTS systems, frequency reuse of 1 was decided through spreading and scrambling of codes. Frequency reuse is an important part of frequency planning and this frequency reuse of 1 in UMTS leads to the reduction in the burden of frequency planning. For LTE, to improve the cell edge throughput, flexible radio resource reuse scheme has been developed. Frequency Reuse was adopted by 3GPP LTE as ICIC technique.

The effective use of resources in a cellular system can highly enhance the capacity. In a multi-cellular network employing frequency reuse across different cells, inter-cell interference occurs when neighboring cells uses the same frequency bandwidth for communication. To reduce this inter-cell interference, various frequency reuse schemes have been proposed. Soft Frequency Reuse schemes [27] and Flexible Resource Reuse Scheme [28] are some general approaches towards inter-cell interference reduction. Traditional frequency reuse schemes, using a certain reuse factor deployment can significantly reduce the inter-cell interference and increase SINR value.

This thesis focuses on the efficient use of LTE network during the disaster scenarios and it only considers the scenarios for the eNodeB to eNodeB communication and does not consider the case for the communication with the UE. The frequency reuse plan for the LTE network is explored in this thesis to use the available bandwidth efficiently and to reduce the interference during the inter eNodeB communication.

Further, it is assumed that LTE sites are deployed by using 3 sectors. For the normal operation, the reuse pattern is 1x3x1. The first digit 1 means that the frequencies are reused in each site. The second digit 3 is the number of sectors which are deployed in each site. The third digit 1 is the number of channels, distributed by each site. This scheme is supposed to be used only for the communication with UE. During the disaster scenarios, for the eNodeB to eNodeB communication, a different frequency reuse pattern is investigated.

### 3.3.1 Alcatel’s Proposal

Figure 3.1 shows the frequency reuse scheme proposed by Alcatel. The whole band is divided into several subsets with corresponding power levels. A set of frequency F1, F2 and F6 are allocated respectively for the cell-edge users in cell 1 with full power. A reduced power is used for the users in the inner cell.

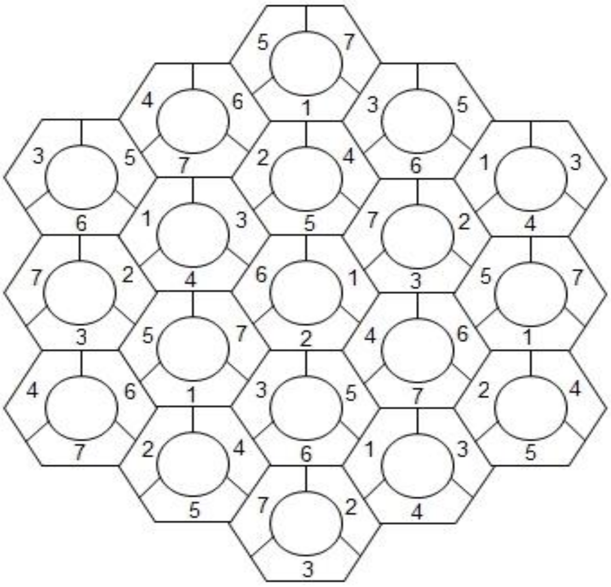


*Figure 3.1. Frequency reuse pattern [29].*

Section 6.2 deals with the detail study about this reuse pattern and put forth the modification for this pattern as this thesis focuses on the node-to-node communication.

### 3.3.2 Radio Interference

Shannon’s Capacity theorem states that the capacity C of a communication channel with bandwidth B and the SINR follows the following relation [30]:

$$C = B \cdot (1 + SINR). \tag{3.1}$$

As shown in Figure 3.2, let a transmitter T1 transmits a signal to its desired receiver R1. At the same time transmitter T2 also transmits a signal. Then, R1 received a signal from T1 as well as the signal from T2. At the receiver R1, the signals from T1 and T2 superimpose and for R1, T2 signal will be interference to it. Higher interference leads to the low SINR value which implies low quality of the wanted signal.

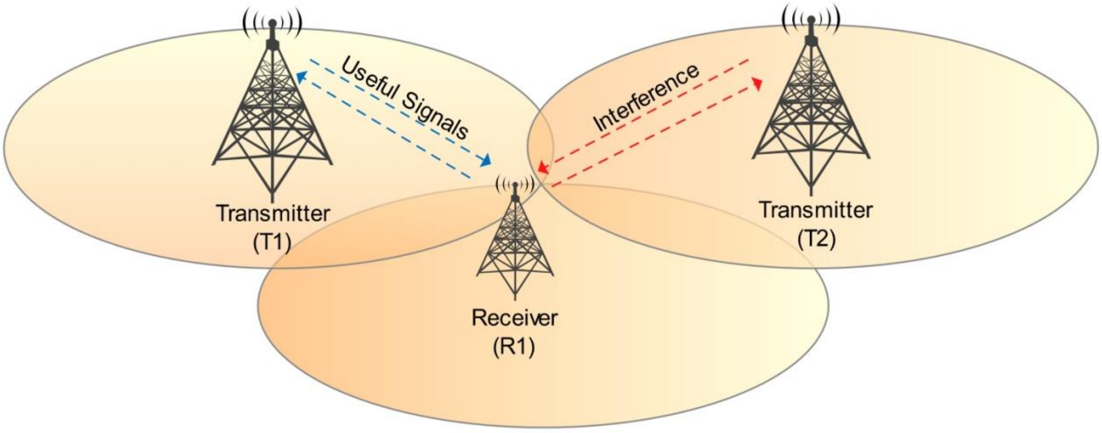


*Figure 3.2 Generic Radio Communication System.*

This thesis assumes that during the disaster scenarios, the frequency will be reused and will result in the interference at the receiver.

The receiver is continuously trying to detect the transmitted signal. The quality of the signal is generally represented with SINR. In a wireless communication system, the SINR is defined as

$$SINR = \frac{P_{\mathrm{r}}}{P_{\mathrm{inter-cell}} + P_{\mathrm{intra-cell}} + P_{\mathrm{n}}}, \tag{3.2}$$

where the $P_r$ is the received power of the signal, the $P_{\text{inter-cell}}$ is the other cell interference power, the $P_{\text{intra-cell}}$ is the inner cell interference power and $P_n$ is the noise power. Intra-cell interference is minimized due to the OFDMA access technology and thus can be neglected. Other-cell interference is the total average power received from other cells in the allocated bandwidth.

The signal power of the desired transmitted signal received by the receiver can be calculated as [31]

$$S = P_{\mathrm{td}} + G_{\mathrm{td}} + G_{\mathrm{r}} - PL, \tag{3.3}$$

where the parameters involved are

- S is the received desired signal power
- $P_{td}$ is the transmit power from the desired transmitter in dBm
- $G_{td}$ is the antenna gain of the desired transmit station in dB
- $G_r$ is the antenna gain of the desired receive station in dB
- PL is the pathloss of the desired path in dB

The interference power received at the same receiver can be calculated as [31]

$$I = P_{\mathrm{ti}} + G_{\mathrm{ti}} + G_{\mathrm{rd}} - PL, \tag{3.4}$$

where the parameters involved are

- I is the received interference power at the desired receiver
- $P_{ti}$ is the transmit power from interfering station in dBm
- $G_{ti}$ is the antenna gain of the interfering transmit station in dB
- $G_{rd}$ is the antenna gain of the desired receiver station in dB measured at the angle of arrival of the interfering station
- PL is the path loss of the desired path in dB

Signal with the lower SINR value is harder to be detected by the receiver correctly. Further, if the SINR of the transmitted signal is below the threshold, then correct detection is not possible. SINR is the main performance indicator for LTE. The throughput of the given node is defined according to the SINR at the receiver. The required SINR depends upon the MCS value and propagation model. Thus, higher the MCS used, higher is the required SINR and vice versa. The range of data rates supported by LTE depends on the suitable SINR. 64QAM requires high SINR condition whereas QPSK needs relatively low SINR. LTE has the ability to vary instantaneous bandwidth to a user, which implies a large number of modes of operation and flexibility during signal handling and the reception of maximum data rate at high SINR and the highest bandwidth. Table 3.3 shows the assumptions for SINR values for different modulation and coding schemes.

*Table 3.3. SINR value for different coding schemes [19].*

| System | Modulation | Code Rate | SINR (dB) | IM (dB) | SINR+IM(dB) |
|---|---|---|---|---|---|
| LTE | QPSK | 1/8 | -5.1 | 2.5 | -2.6 |
| | | 1/5 | -2.9 | | -0.4 |
| | | 1/4 | -1.7 | | 0.8 |
| | | 1/3 | -1 | | 1.5 |
| | | 1/2 | 2 | | 4.5 |
| | | 2/3 | 4.3 | | 6.8 |
| | | 3/4 | 5.5 | | 8.0 |
| | | 4/5 | 6.2 | | 8.7 |
| | 16QAM | 1/2 | 7.9 | 3 | 10.9 |
| | | 2/3 | 11.3 | | 14.3 |
| | | 3/4 | 12.2 | | 15.2 |
| | | 4/5 | 12.8 | | 15.8 |
| | 64QAM | 2/3 | 15.3 | 4 | 19.3 |
| | | 3/4 | 17.5 | | 21.5 |
| | | 4/5 | 18.6 | | 22.6 |

In the above table, implementation margin is included to account for the difference in SINR requirement between theory and practical application. For QPSK, 2.5 dB implementation margin has been defined and the value increases for higher order modulation scheme.

Thus, the focus of this thesis is on the interference analysis and the calculation of the SINR to investigate the best possible modulation technique applicable for the inter node communication during the disaster scenarios.

# 4 RADIO PROPAGATION

The concept of radio propagation covers the radio wave propagation between transmitting and receiving antenna. Radio wave can propagate between two points depending upon the nature of the medium. It can either travel in free space or can travel by being guided through a medium such as coaxial cable, waveguide or optical fibre. This thesis considers only the case for the propagation in free space.

## 4.1 Propagation Environments

The propagation in space depends on the propagation environment. The free space propagation is prone to the interference and noise from other sources depending upon the propagation environment. The radio propagation environment can be classified as shown in Figure 4.1.

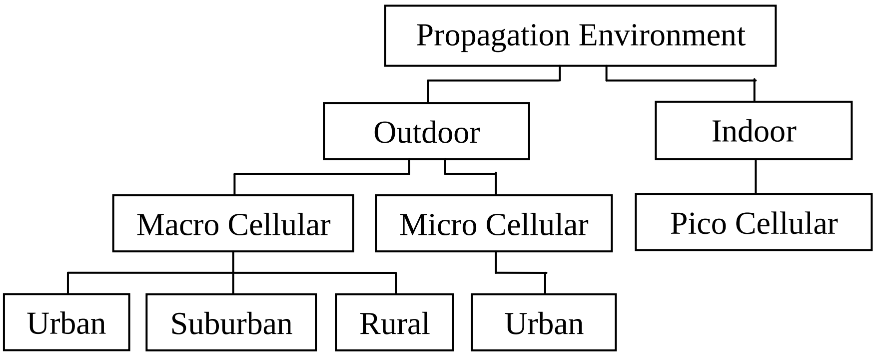


*Figure 4.1. Radio Propagation Environment [32].*

According to above figure, the radio propagation is characterised by the antenna environment of the transmitting and the receiving station. This characterization is based on the following parameters:

- *Morphography Type.* This includes the urban, suburban and rural areas. These areas are categorized according to the size and the density of the obstacles located in the surrounding environment of the transmitting and the receiving station antennas. The obstacles can be human constructed buildings or natural obstacles such as trees.
- *Antenna Location.* This parameter differentiates the environment according to the height of the antenna of transmitting and receiving station. If the height of the antenna array is above the average height of buildings, then it is said to be macro cellular environment. If the height of antenna array is below the average height of the building, then it is micro cellular environment.

These macro and micro cellular environments are the outdoor environments and for indoor environments, there can be pico cellular environment.

- *Receiving station location.* This can be either indoor or the outdoor environment depending upon the location of the receiving station antenna.

## 4.2 Propagation Mechanisms

Radio wave can propagate from the source to the destination in many ways. The most important mechanisms of propagation used can be categorised according to the decreasing order of frequency as below [33]:

- *Propagation along a Line-of-Sight (LOS) path*. This propagation mechanism resembles the propagation in free space. The LOS path may be accompanied by diffraction and reflection from the buildings and ground as well as by propagation through vegetation and building walls.
- *Scattering from inhomogeneities of atmosphere*. This propagation mechanism is applicable for the frequency range of 300 MHz to 10 GHz.
- *Propagation via the ionosphere*. The ionosphere which extends from about 60 km to 1000 km from the earth surface may reflect the radio wave at frequencies below 30 MHz. Radio wave may also reflect multiple times between the ionosphere and ground resulting in the propagation around the world.
- *Ground-wave propagation.* The attenuation of the ground wave rapidly increases according to the frequency. This phenomenon is important for the waves at the frequencies below 10 MHz.

## 4.3 Antenna Theory

Antenna is an independent and an integral component of any wireless communication system which transmits and receives radio waves. Thus, antennas are the vital part of the wireless communication system. An ideal antenna radiates the entire power which is incident from the transmission line feeding the antenna. It radiates to or it receives from the desired direction, which means it has a pre-defined radiation designs. In other way, antenna is a way of converting the guided waves from transmission line into radiating waves travelling in free space or vice-versa. Thus, a good antenna is the one which is radiating the power from the transmitter towards the direction of the intended receiver. Antennas are needed in almost all applications of wireless communication systems. They are reciprocal devices, meaning the properties of an antenna are similar both in transmitting and receiving mode. If an antenna radiates to certain direction, then it can receive from those directions only. The reciprocity does not apply if non-reciprocity components are added into the antenna. The space covered by the antenna radiation can be divided into following three regions [33]:

- *Reactive near-field region.* It is closest to the antenna.
- *Radiating near-field region or Fresnel region.* In this region, the shape of the normalized radiation pattern depends on time.
- *Far-field region or Fraunhofer region.* The normalized radiation pattern is practically independent of the distance.

### 4.3.1 Radiation Pattern

The radiation pattern of an antenna is the graph of its far-field radiation from the antenna which describes the relative distribution of electromagnetic energy in space. The radiation pattern is determined in the far-field region as there is no change in pattern with distance. Figure 4.3 illustrates a radiation pattern plot for a generic directional antenna.

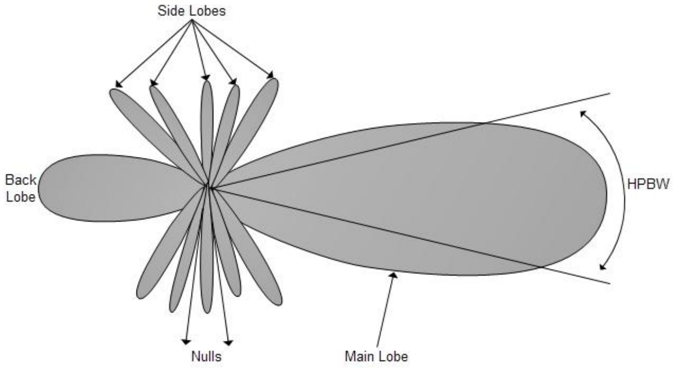


*Figure 4.3 Radiation pattern of directional antenna [34].*

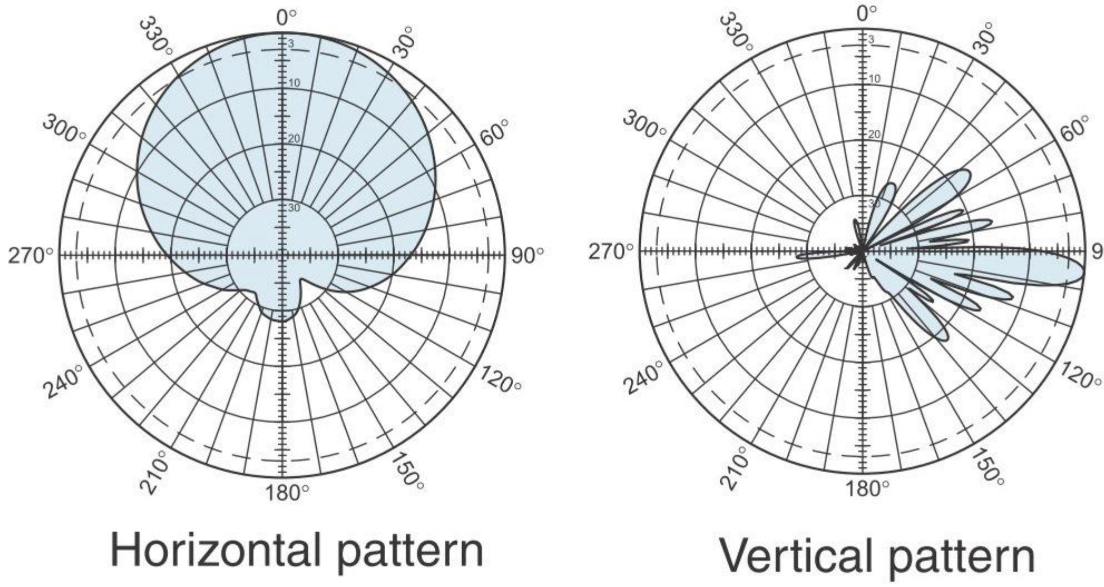
The main lobe of the radiation pattern, as shown in the figure, includes the direction of maximum radiation. Back lobe of radiation is at opposite of the main lobe and several other side lobes can be seen in the figure. Side lobes are separated by nulls where there is no radiation. The Half Power Beam Width (HPBW) is the angular width of the main lobe within which the radiation intensity is one half the maximum value of beam.

### 4.3.2 Directivity and Power Gain

Directivity indicates how well the radiated power is concentrated into a particular direction. It is the ratio of maximum radiation intensity to the averaged radiation intensity over all directions. The directivity of an antenna depends on the size of the main lobe of the antenna radiation pattern. The narrower the main lobe, the larger is the directivity of the antenna.

The gain of an antenna is closely related with the directivity. The power gain of an antenna is the ratio of its radiation intensity in a given direction to the radiation intensity of an isotropic antenna, which is radiating the same power as accepted by real antenna

[34]. This gain may be expressed in dB for easier use. dBi is use to emphasise the use of the isotropic antenna as reference.


Horizontal pattern

Vertical pattern

*Figure 4.4. Radiation pattern with gain at different angles [Annex 1].*

Figure 4.4 shows the horizontal and vertical radiation pattern for the 65° single band panel antenna developed by Kathrein. The specification of this antenna can be found at Appendix 1.

In this thesis the radiation pattern with the gain at different angle is estimated from this specification and this gain is one of the parameter used for the calculation of interference level from the neighbouring eNodeB during the eNodeB (node) to eNodeB (node) communication.

### 4.3.3 Multiple Antenna Techniques

Multiple antenna technique is a method which utilizes the multiple numbers of antennas at the receiver and/or at the transmitter side. The use of multiple antenna technique improves the system performance which includes the throughput, signal quality and availability. Depending on the availability of multiple antennas at the transmitter and/or the receiver, the multiple antenna techniques can be classified as Single-Input Multiple-Output (SIMO), Multiple-Input Single-Output (MISO) or MIMO. The use of multiple antenna techniques in LTE is the first mobile system designed to utilize the multiple antenna techniques as an important part in its specification. The MIMO is LTE’s major technological innovation used to increase the performance of the system.

MIMO is used in LTE to improved signal performance as well as the higher data rates above that obtained by the use of OFDM. Due to this property, MIMO has been included as a part of LTE system. The MIMO techniques introduced in LTE are the spatial multiplexing, transmit diversity and the beamforming [35]. The MIMO technology was included in Release 8 of 3GPP.

The use of the multimedia communication has significantly increased the demand for the high data rates. MIMO technology has been developed to meet the demand for this high data rate and better coverage without increasing the average transmit power or the frequency bandwidth [35]. The MIMO utilizes the multipath signal propagation to provide the higher data rates. It uses multiple antennas on the receiver and the transmitter to utilize the multi-path effects which exist to transmit the additional amount of data rather than the interference.

The beamforming sends the same symbol over each transmit antenna with a different scale factor. At the receiver, all the received signals are coherently combined using a different scale factor. Thus it increases the received signal gain by combining the signals from different antennas constructively and reducing the multipath fading effect. In LOS propagation, beamforming results in a well-defined directional pattern.

## 4.4 Radio Propagation Models

To estimate the signal parameters for a communication system, the system’s propagation characteristics through a medium should be considered. The propagation analysis provides a good estimation of the characteristics of the signal. The limitation on the performance of the wireless communication system is due to the different nature of the radio channels. Due to various reasons such as the cost of each site measurement, the propagation models have been developed as a cost effective and convenient alternative. A propagation model predicts the characteristics of the radio signal while propagating from the transmitter to the receiver in the given environment. The propagation environment between the transmitter and the receiver vary from LOS to the one which is obstructed by buildings and mountains. Thus, the prediction of the radio propagation is the basics for the radio communication.

There are two different and independent propagation phenomena. First is the fast fading which causes the rapid fluctuations in the phase and amplitude of the signal due to the change in the propagation environment. The mobility introduces the changes in the radio environment. Second is the slow fading which occurs due to the geometry of the path. The high buildings obstructing the path of the signal station causes the shadowing. The large scale attenuation depends on the nature of the path of the radio link. Large scale attenuation is because of free space path loss, groundwave propagation and diffraction.

In this thesis, large scale propagation models are used to calculate the signal strength over a given transmitter and receiver separation distance.

### 4.4.1 Path Loss

Path loss is a quantity that determines the efficiency of the propagation channel in different environment. It characterizes the alterations in the signal amplitude or the field intensity along a path from the source to the destination within the communication channel. Path loss between the transmitter and the receiver, in linear scale is the ratio of transmitted power from the transmitter to the power received by the receiver. It is usually expressed in decibels (dB) where path loss is the difference between the transmitted power and the received power. The path loss includes all the possible loss elements encountered by the propagation wave. Since there are various losses and gains in the radio communication system, this path loss is difficult to measure directly. Thus, in order to define the path loss correctly, the losses and gains of the system must be considered.

Various kind of path loss models have been proposed for different environments. Depending on the formulation of the models, there are basically three kinds of path loss models [36].

- *Empirical Models.* They are based on measurement data and thus, are simple in nature as they have few parameters. These models are forwarded by the site surveys with lots of measurements. They are not very accurate.
- *Semi-deterministic Models.* They are based on empirical models with deterministic aspects. They are based on electromagnetic wave propagation theories which are close to physical principles as well.
- *Deterministic Models.* They are based on the specific location of the transmitting and receiving station. They require large number of information about the location and thus, are more accurate than the empirical models.

A radio communication system consists of a transmitter, a receiver and a radio link between them. Figure 4.5 shows the elements of a wireless communication system with all the parameters involved.

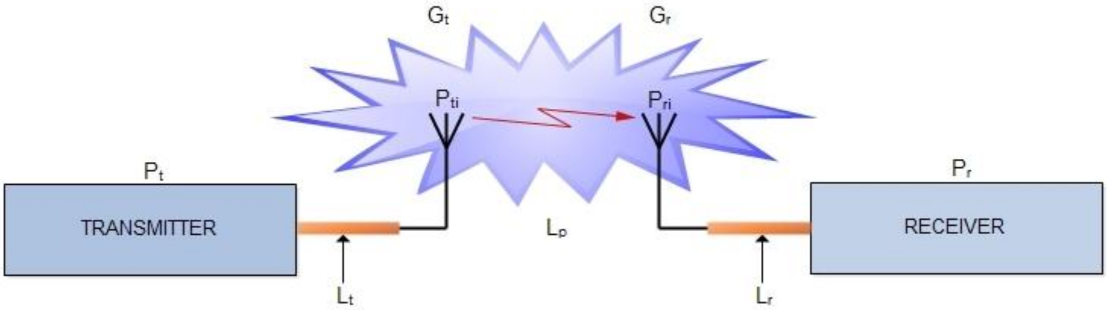


*Figure 4.5. Elements of wireless communication system [34].*

The parameters involved in Figure 4.5 are

- $P_t$ is the transmit power.

- $G_t$ is the gain of the transmitter.
- $L_t$ is the feeder loss in the transmitter side.
- $P_{ti}$ is the effective isotropic transmit power.
- $L_p$ is the path Loss.
- $P_r$ is the receive power.
- $G_r$ is the gain of the receiver.
- $L_r$ is the feeder loss in the receiver side
- $P_{ri}$ is the effective isotropic received power

Gains and losses are the power ratios and thus are unitless quantities and powers are in watts.

The Effective Isotropic Radiated Power (EIRP) from the transmitter can be expressed as

$$EIRP = \frac{P_\mathrm{t} G_\mathrm{t}}{L_\mathrm{t}}. \tag{4.1}$$

In Figure 4.5, EIRP is denoted by $P_{\mathrm{ti}}$. Thus,

$$P_\mathrm{ti} = \frac{P_\mathrm{t} G_\mathrm{t}}{L_\mathrm{t}}. \tag{4.2}$$

The power received at the receiver terminal can be expressed as

$$P_\mathrm{r} = \frac{P_\mathrm{t} G_\mathrm{t} G_\mathrm{r}}{L_\mathrm{t} L_\mathrm{p} L_\mathrm{r}}. \tag{4.3}$$

Similarly, the effective isotropic received power can be expressed as

$$P_\mathrm{ri} = \frac{P_\mathrm{r} L_\mathrm{r}}{G_\mathrm{r}}. \tag{4.4}$$

As the transmitted and received power is expressed in terms of its EIRP and effective isotropic received power, the path loss can be expressed independently of system parameters as

$$L_\mathrm{p} = \frac{P_\mathrm{ti}}{P_\mathrm{ri}}. \tag{4.5}$$

Thus, the propagation loss can be used to describe the propagation medium, independently of the system gains and losses. The main goal of propagation model is to determine the path loss as accurately as possible. This allows the radio system to determine different parameters before installation. The minimum value of received power for which the communication quality is acceptable is known as the receiver sensitivity of that receiver. The value of path loss for the minimum value of acceptable received power is known as maximum acceptable path loss. The path loss is generally expressed in dB as

$$L_\mathrm{p}(dB) = 10 \cdot \log_{10}\left(\frac{P_\mathrm{ti}}{P_\mathrm{ri}}\right). \tag{4.6}$$

There are different path loss models available which are based in different environment conditions such as LOS or non-LOS.

#### 4.4.1.1 Free Space Path Loss Model

Free Space Path loss model is used to predict the signal strength at the receiver when the transmitter and the receiver have a clear LOS. The wireless communication systems with LOS, such as the satellite communication systems or microwave LOS radio links are modelled as free space propagation. A free space model predicts that the received power declines as a function of the distance between the transmitter and the receiver. When a transmitter antenna transmits a signal with certain power to a receiver at a certain distance away from it, Friis Transmission Formula is used to calculate the power received at the receiver. Let the losses considered in Figure 4.5 be 1 which means there are no losses, then the Friis transmission formula can be written as [34]

$$\frac{P_{\mathrm{ri}}}{P_{\mathrm{ti}}} = G_{\mathrm{t}} G_{\mathrm{r}} \left(\frac{\lambda}{4\pi D}\right)^2 , \tag{4.7}$$

where $\lambda$ is the wave length of the frequency used for the transmission and $D$ is the distance between the transmitting and receiving antenna. Rearranging equation 4.7 as equation 4.5, we have

$$L_{\mathrm{p}} = \frac{P_{\mathrm{ti}} G_{\mathrm{t}} G_{\mathrm{r}}}{P_{\mathrm{ri}}} = \left(\frac{4\pi D}{\lambda}\right)^2 = \left(\frac{4\pi D f}{c}\right)^2 , \tag{4.8}$$

where $f$ is the carrier frequency and c is the speed of light which is equal to $3\mathrm{x}10^8$ m/s.

The expression 4.8 defines the free space path loss. This equation shows that the path loss depends on the square of the distance and the frequency. Now expressing equation 4.8 in terms of dB,

$$L_{\mathrm{p}}(\mathrm{dB}) = 32.45 + 20 \cdot \log_{10} D + 20 \cdot \log_{10} f . \tag{4.9}$$

In the above equation, distance $D$ is in kilometres (km) and frequency $f$ in megahertz (MHz). Thus, from the above equation, free space loss increases by 6 dB for each doubling in either frequency or the distance.

#### 4.4.1.2 Okumura-Hata Path Loss Model

Okumura published the number of empirical curves after the measurements which are useful for the radio system planning [34]. Hata put forth the set of empirical formulas for the curves provided by Okumura which are very convenient to use [34]. Okumura-Hata Model is one of the most popular models for the path loss calculation. The basic formula for the Hata path loss is given by [37]

$$L_{\mathrm{Hata}} = 69.55 + 26.16 \cdot \log_{10}(f) - 13.82 \cdot \log_{10}(h_{\mathrm{te}}) - a(h_{\mathrm{re}})$$
$$+\big[44.9 - 6.55 \cdot \log_{10}(h_{\mathrm{te})}\big] \log_{10} d - k\,, \qquad (4.10)$$

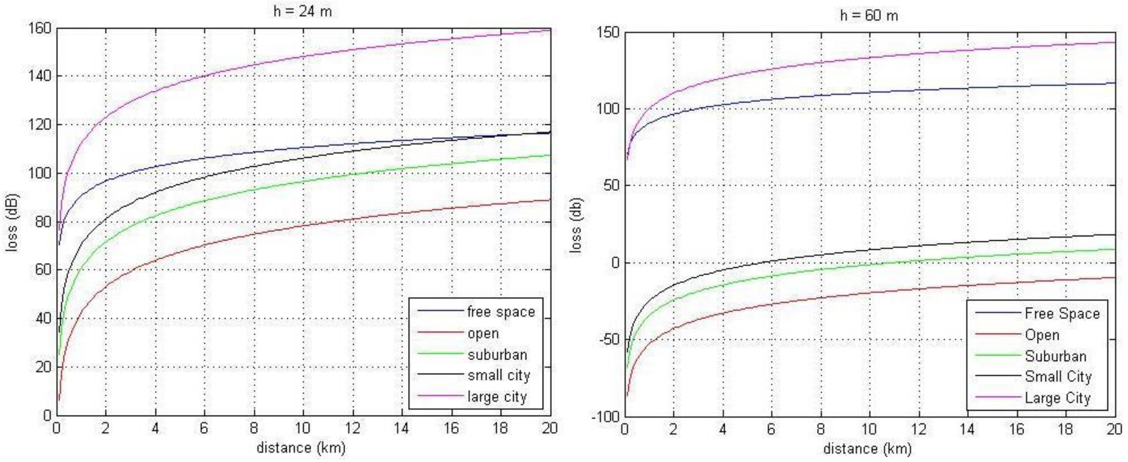
where $h_{\mathrm{te}}$ and $h_{\mathrm{re}}$ are the height of the transmitter and the receiver respectively which are in meters, frequency $f$ is in megahertz and distance $d$ is in kilometres. $a(h_{\mathrm{re}})$ is the receiver antenna height correction factor. $k$ is a factor which depends on the type of propagation environment. The value of $a(h_{\mathrm{re}})$ and $k$ is listed in Table 4.1 below.

*Table 4.1 Values of a($h_{re}$) and k for different environments [37].*

| Type of Area | $a(h_{\mathrm{re}})$ | $k$ |
|---|---|---|
| Open | $[1.1 \cdot \log_{10}(f) - 0.7]h_{\mathrm{re}} - [1.56 \cdot \log_{10}(f) - 0.8]$ | $4.78 \cdot [\log_{10}(f)]^2 - 18.33 \cdot \log_{10}(f) + 40.94$ |
| Suburban | | $2 \cdot \left[\log_{10}\left(\frac{f}{28}\right)\right]^2 + 5.4$ |
| Small City | | 0 |
| Large City | $3.2[\log_{10} \cdot (11.75h_{\mathrm{re}})]^2 - 4.97$ | 0 |

### 4.4.1.3 Use of Path Loss Model

As discussed in section 4.4.1, there are various numbers of path loss models proposed and each models have their own significance. Section 4.4.1.1 and section 4.4.1.2 discusses the widely used two different path loss models namely the free space path loss model and the Okumura-Hata path loss model. Figure 4.6 shows the simulation result of both the path loss models.



(a) (b)

*Figure 4.6. Path loss.*

Figure 4.6 (a) shows the result for loss as a function of distance for the free space path loss and Okumura-Hata model for the transmitter and receiver height of 24 m and

(b) shows the result for the height of 60 m. Frequency parameter for both the results is 800 MHz. From the figure we can see that the loss for higher antenna height is less than the lower one.

## 4.5 Wireless Link and Channels

For any kind of wireless systems, the knowledge of wireless channels is a must for understanding the operation, design and analysis of such systems. Different communication links such as land to air, air to air or land to land can be established as per the requirement. A simplest scheme of such a radio communication link consists of a transmitter, a receiver and a propagation channel. The output of such a link depends upon the condition of the radio propagation in different kind of environments. The design of wireless radio link involves the three major parts. First is the design of the transmitter, second is the modelling and analysis of the propagation properties of the channel that connects transmitting and receiving antennas and third is the design of the operation of the receiver.

The architecture of a generic communication system was originally described by Claude Shannon in his paper ‘A Mathematical Theory of Communication’ in 1948 [30]. Figure 4.7 illustrates the generic architecture.

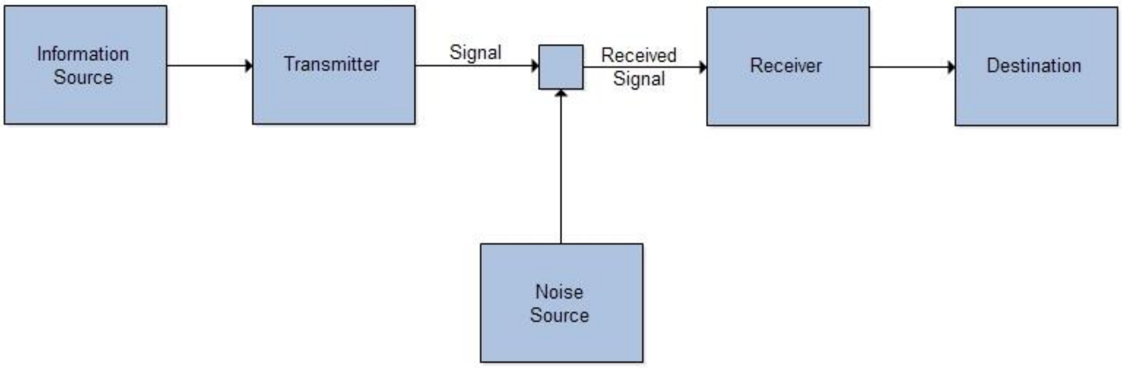


*Figure 4.7. Generic communication system [30].*

In the figure, information source tries to send the information to the destination. The source can be, for example a person speaking or a video camera. The destination can be a person listening or a video display. The data to be sent is transformed into a signal which is appropriate for the transmitter of the source to send. This signal is then sent through the wireless channel and due to the noise and interference in this channel, the signal is altered. Because of this modification in the channel, the receiver is designed to overcome this modification and thus can deliver the information to the destination with as few errors as possible.

This representation applies to all kind of communication systems. The noise in the system must be carefully studied for efficient and effective communication. The noise arises from the passive and active components in the receiver, from the external sources such as atmospheric effects and most importantly, interference from other transmitters.

The effect of the interference must be studied carefully when channels are reused in the system. Thus, this thesis analyses the effect of the interference at the receiver.

# 5 INTRODUCTION TO SENSOR NETWORKS

Wireless communication technology has seen a rapid growth in the research of sensor networks. WSN, typically the one which is ad-hoc in nature has seen a potential growth. The ad-hoc network has the ability for infrastructure less setup, minimum dependence on network planning and the ability of the nodes to self-organize and self-configure without the involvement of the central controller [39]. Because of this feature, WSN is considered to be the helpful technology which can be deployed where there is no existing infrastructure or network setup. During the disaster scenarios when there is an emergency and during the relief operations, the role of WSN can be vital. WSN can be used for object tracking, monitoring and transmitting environmental information and for the detection.

The sensor nodes are deployed in the target environment and each sensor node sends its data to the sink. Sink is also known as fusion centre which is responsible for processing the sensor data and extracting the information from it [38]. The data send to the sink from the sensor node may follow the multi-hop path for the communication. This thesis discusses the before mentioned approach of the WSN functionality to deliver data to the desired destination via multi-hop eNodeB communication. As in this thesis the functionality of WSN is realised at the eNodeB, in macro label, thus the study of WSN in this approach is also in macro level.

## 5.1 Ad hoc Network

Ad hoc network is a technology that enables a wireless network in an environment where there is lack of wired or cellular infrastructure. In ad hoc network, each node participates in routing by forwarding data for other nodes, so, the role of the node for forwarding data is made dynamic on the basis of network connectivity. In ad hoc networks, all the nodes have equal status and are free to associate with any other node in the network. An ad hoc network consists of nodes which are connected by links, and these links can be connected or disconnected at any time. Hence, an operational ad hoc network should cope with the dynamic restructuring of the link. Thus, in ad hoc network, two different nodes can communicate with each other via other intermediate nodes.

Ad hoc network can be established for a special purpose and for a limited period of time. A region strike by a disaster scenario or the battle field can be considered as potential areas for ad hoc network deployment where there is no infrastructure. If there is an infrastructure, then the ad hoc network deployment can be cost effective.

The multi-hopping and self-organization are the two most important characteristics of ad hoc networks [40]. Multihopping refers to the path from source to the destination via several other intermediate nodes in between. Self-Organization refers to the autonomous determination of the configuration parameters including the address, routing, clustering, position identification and power control [40]. Figure 5.1 show a typical ad hoc network structure with communication link between different nodes.

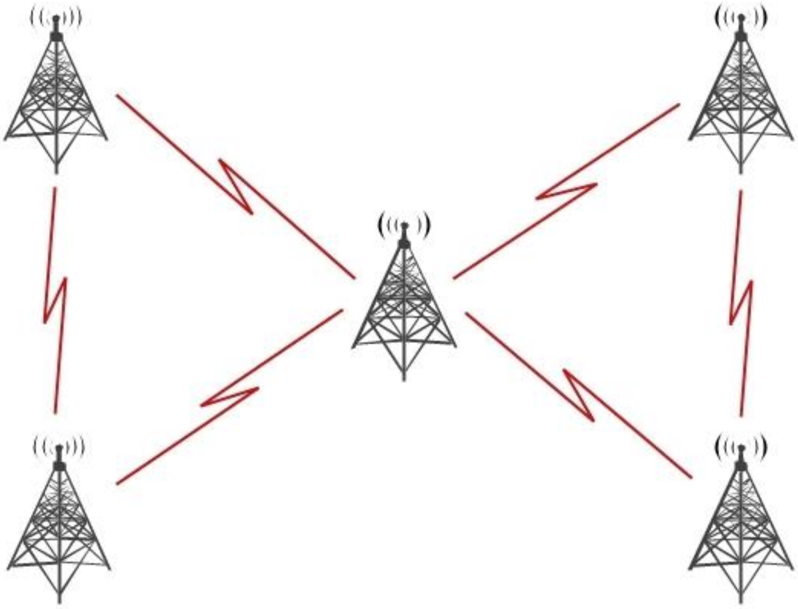


*Figure 5.1. Ad hoc network.*

## 5.2 Topology Management

A constant monitoring is required for any kind of network to ensure reliable and efficient operations. For this monitoring, the knowledge about how the sensor nodes are arranged should be known. This study about how the nodes are arranged in WSN is known as topology management. Topology management is a crucial component for the WSN to maintain the connectivity of the network. It consists of knowing the physical connections and logical relationships among the nodes for the transparent data sharing between the nodes [39].

### 5.2.1 Topology Discovery

Topology discovery includes the network supervising station or simply a base station which determines the topology of the nodes in the network. The physical connectivity or the logical relationship of the nodes in the network is informed to this supervising station which maintains the topology record of the WSN. The supervising station sends the topology discovery request message to all the nodes in the network and in response, all the nodes responds with its information. There are three methods for the topology discovery [39]:

- *Direct Approach.* In this approach, the node upon receiving the discovery message instantly sends a response back to the base station. This response contains the information only about that specific node.
- *Aggregated Approach.* In this approach, the node upon receiving the discovery message does not immediately send the response. Instead, the node waits until it gets a response to the request from other nodes which are connected to it. These nodes are called children nodes. The node then aggregate all the response information received from the children node including its own information and responses back to the base station.
- *Clustered Approach.* In this approach, the nodes are organised in the groups, also called clusters. Each cluster has its own cluster head and only cluster head responds to the discovery request message. The response of cluster head includes the information about all the nodes in the cluster.

The main target of the topology discovery is to keep track of all the nodes in the WSN which helps in effective and efficient management of the network. Different types of algorithms are proposed for the topology discovery process which are discussed in the following section.

#### 5.2.1.1 TopDisc Algorithm

TopDisc is the topology discovery algorithm to determine the topology of the WSN. TopDisc uses the clustered approach to discover the topology and it first creates the clusters and identifies the cluster heads. The algorithm begins by sending the topology request packets to all the nodes in the WSN from the base station. In this process, one of the two different colouring algorithms is used to find the cluster heads while the topology request is propagating through the network [39].

The first colouring algorithm of TopDisc uses a three colour approach. White colour node implies an undiscovered node, a black colour node implies the cluster head and grey colour node implies it has neighbour that is black in colour [39]. The algorithm starts with all node coloured white. If white node receives the topology discovery request from the black node, then the white node becomes grey in colour. If a white node receives the topology discovery request from grey node, then it starts its timer for certain amount of time. If this node receives the topology discovery request from black node before the time expires, it becomes grey but if it does not, then it becomes black. Once a node changes its colour from white to grey or black, then it ignores all the future request packets. Thus, all the black nodes become the cluster heads and then it transfers the topology information to the base station in the response message.

In the second algorithm, TopDisc uses four colour approach. The three colours, white, black and grey are same as in the first algorithm and the fourth colour, dark grey is the new one added. The dark grey node is the discovered node but is not in the range of black colour node. The dark grey nodes are at least two hops away from the black nodes. If the dark grey node receives a request from the grey node, then it starts the timer to become grey node or the black node. If it receives a request from a black node before the timer expires, then it becomes the grey node and it becomes black node if it does not receive a request from another black node. Thus, this four colour pattern has an advantage over the three colour pattern in terms of less overlapping [39]. The cluster formed from four colour pattern has less overlapping than the cluster formed with three colour pattern.

This TopDisk is a distributed algorithm and only the information about the node is exchanged. Since, there is less information transferred between the nodes and from nodes to the station, the required bandwidth and energy is less as well. The problem of this TopDisc is in the distance between the black nodes and these distances are not fixed resulting in the uneven distribution of the black nodes [39]. Thus, the optimal numbers of grey nodes are not covered by the black nodes.

#### 5.2.1.2 Sensor Topology Retrieval at Multiple Resolutions

Sensor Topology Retrieval at Multiple Resolutions (STREAM) is another algorithm for determining the topology of the WSN. This algorithm can determine the network topology according to the type of application of the WSN. Different applications may require different topological information. STREAM creates an approximate topology by neighbourhood lists from a subset of nodes [39]. The minimum set of nodes required to determine appropriate topology is known as Minimum Virtual Dominating Set (MVDS). The MVDS is created by using a message complexity of N, where N denotes the number of nodes in WSN. The MVDS does not increase whether the node density increases or not. The MVDS tree created contains the nodes such that the topology discovery response always travels with minimum number of hops to reach the base station.

STREAM also follows the colouring pattern to find the topology of the network. STREAM uses four colours to determine the topology. White node is an undiscovered node, black is the node in MVDS, red node is the one in the virtual range of black node and blue node is the node within the communication range of black node but is outside the virtual range [39]. The resolution of the topology discovered by STREAM is controlled by its virtual range.

All the nodes are coloured white and the base station sends a topology discovery request to the nodes. If a white node receives the request from a black node and white node is in the virtual range of the black node, then it becomes a red node and forwards the request packet. If the white node is not within the virtual range of the black node, it will become a blue node, and then it starts the timer and forwards the request packet. A blue node, within a virtual range of the black node which receives the topology discovery request from that black node stops the timer and becomes a red node. White node becomes a blue node if it receives the request from a red or a blue node, then starts a timer and forwards a packet. If the timer expires then it becomes a black node. Any black or red nodes does not forward any other topology discover requests it receives.

## 5.3 Routing Protocols for WSN

WSN, realising the scenario in this thesis, is formed by the various numbers of sensor nodes communicating over the wireless links using a fixed network infrastructure. Thus, the routing protocols for this WSN have to ensure reliable multi-hop communication. Routing is a process of sending a data packet from a given source to a given destination, probably using intermediate nodes to reach the destination. In WSN, the data communication between the nodes can be from the sensor node to the supervising node or within the neighbouring nodes or from the supervising node to the sensor node. The communication from the sensor node to the supervising node is used to transfer the sensor data to the monitoring station. Communication between sensor nodes happens when the cooperation between the nodes is required. The communication from the supervising node to the sensor node is used to transfer the information which can be important to the sensor nodes.

Each node of a sensor network has a number of neighbours. The link with these neighbours are wireless in nature resulting in the unreliability of the link. Thus, depending on the location of the neighbouring nodes, the number of hops is determined to reach the destination node. The short hops cause an excessive number of transmissions and hence excessive interference. A longer hop risks the need for a retransmission. Thus, the efficient idea would be to implement the routing through a specific subset of nodes, also called the virtual backbone, to which all the other nodes connect in a single hop. A good virtual backbone can simplify the routing process and can reduce the overall network energy consumption.

The conventional routing protocols follow the flooding technique in which a node stores the data item it receives and then sends a copy of that data item to its neighbours. Thus, these routing protocols have several limitations when used in the WSN, mainly due to the energy controlled nature of these networks. There are two main deficiencies in this approach [46]

- *Implosion.* A node will get a multiple copies of the data if a node is common neighbour to nodes holding the same data. Thus, there is a waste in the resource.
- *Resource Blindness.* The nodes continue with their activities regardless of the energy available to them at a given time. Thus, nodes are not resource-aware.

Hence, the routing protocol designed for WSN should be able to overcome both of the above mentioned deficiencies.

The routing protocols can be divided into proactive and reactive protocols [39]. Proactive protocols maintain the updated routing information between all the nodes by maintaining the routing tables. In reactive protocols, the routes are only created when needed. The routing can be either the source initiated or the destination initiated. The following section discusses the routing protocols which have been proposed for WSN.

### 5.3.1 Sensor Protocol for Information via Negotiation (SPIN)

These protocols aim at distributing information among all the sensor nodes by using information descriptors, known as the meta-data, for negotiation prior to transmission of the data packets [46]. These meta-data are used to remove the transmission of redundant data in the network. In SPIN, each node has its own resource manager that keeps the track of the amount of energy that a node has.

The SPIN family of protocols uses three messages for the communication between the nodes. First is the advertisement (ADV) message containing the meta-data, which is sent to its neighbours when the node has some new data. The second is the request (REQ) message, which is sent when a node wishes to receive some data. The last is the DATA, which are actual data messages with meta-data headers. Different SPIN protocols are discussed in the following sections

#### 5.3.1.1 SPIN-PP

This protocol is designed to perform during the point-to-point communication thus named SPIN-Point to Point. This protocol is a three way handshake protocol in which energy is not considered to be a limitation. When a node has a new data, then it just advertise the ADV message to its neighbours. When the neighbour node receives this advertisement message, it checks the meta-data to see whether this data is already in the node or not. If it does not have it, then it sends the REQ message back to the sender node for the data. When the sender node receives the REQ message, then it starts transmitting DATA messages which contains the data. The main advantage of this mode is that the node only needs the information about its neighbours and not about other nodes in the topology.

#### 5.3.1.2 SPIN-EC

It is a SPIN-Energy Conservation protocol. This protocol is the same as SPIN-PP and it also uses three way handshake structures but this protocol has energy conservation scheme. If the energy of the node is above some threshold value, then it can transmit and receive the messages. But if the energy of the node is below the threshold value, then it does not participate in the communication. If it receives the ADV message, then it transmits REQ only when the energy is above the threshold value.

#### 5.3.1.3 SPIN-BC

It is SPIN-Broadcast protocol. This protocol is designed for the broadcast WSN where nodes uses single communication channel for the communication. A node broadcasts the ADV message which is received by all the other nodes which are in the range of the sender node. A node which receives the ADV message does not immediately respond with the REQ message. It waits for certain amount of time. When a node other than the sender node receives the REQ message, it cancels its own request so that there are no other requests for the same message. When the sender node receives the REQ message, it broadcasts the DATA message only once to all the nodes in its range.

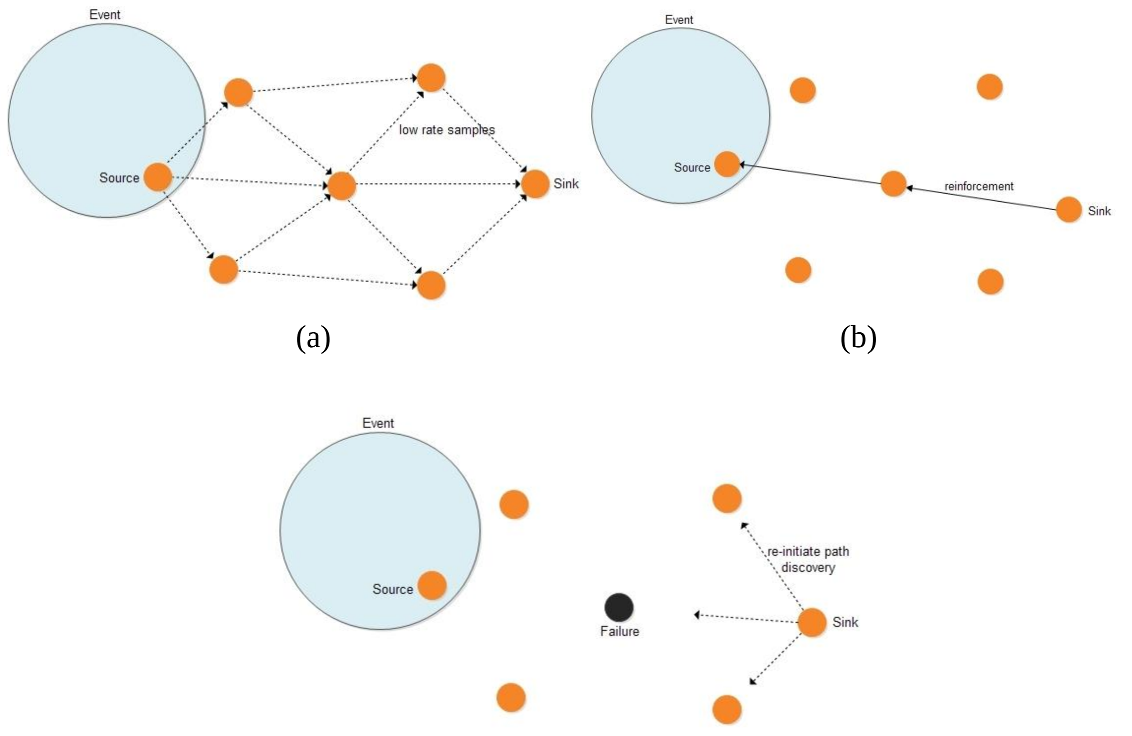
#### 5.3.1.4 SPIN-RL

In this protocol, each node keeps the record of the entire ADV message it receives and the node from which it receives this message. If this node does not receive any requested data within a certain period of time, it sends the request again. The nodes have a limitation on the rate with which they resend the data message. So, after sending a data message, a node waits for certain period of time before it responds to other requests for the same data.

### 5.3.2 Directed Diffusion

Directed Diffusion is a destination-initiated reactive routing technique in which the routes are established when needed. A sensing task or the interest is propagated throughout the network for the named data by the node and data which matches this interest is then sent towards this node. This node is also called a sink in WSN. The propagation of the data and its aggregation at the intermediate nodes, while travelling towards the request originating node are determined by the messages which are exchanged between the neighbour nodes. The data generated by the nodes are called attribute value pairs. A node requests data by sending interests for the named data. Data which matches this interest is then transferred to that node. This node which requests for the data broadcasts its interest message to all of its neighbours. Interest cache is stored in every node and each entry in the interest cache corresponds to distinct interests. The interest is periodically refreshed by the sink node. The sink resends the interest with increasing the timestamp attribute. This timestamp attribute contains the last received matching interest. The interest entry also contains several gradient fields. Each gradient contains a data rate requested by the specified neighbour and also the duration which is received from the timestamp that specifies the lifetime of the interest.

A node can send an interest it receives to its neighbours. For the neighbours, this node appears like an originating node. Thus, in similar fashion, there is diffusion of interest throughout the network. Let a node which detects an event, search for a matching interest entry in its interest cache. If it finds a matching entry, then it sends the event description to all of its neighbour nodes for which this node has gradients. Thus, the sink node starts receiving the events, through a single or multiple paths. The sink node then reinforces a single neighbour which can give better quality of events. Thus, the better quality paths are retained and others are negatively reinforced.



(a) (b)

(c)

*Figure 5.2. Direct Diffusion [41].*

Figure 5.1 shows the simple diagram for Directed Diffusion. A source node periodically broadcasts the events at low rate, where events describe the detection of some incident. When the sink node receives the event message from various nodes, the sink node sends the reinforcement message to a particular node and directs the node to send the event message at higher frequency then to the other nodes. This state is represented by Figure 5.1 (a). This reinforcement message is send to the source node hop by hop. Thus, this message reaches each intermediate node and each intermediate node can decide on its own which propagation path or neighbour should it forward the message to. When this reinforcement message is propagated along the path, the intermediate node(s) set a data path from the sink to the source node. This can be seen in Figure 5.1 (b). If a node on the reinforced path fails, the sink initiates the reinforcement as sink does not receives the event messages and thus can detect the failure. Thus, sink sends the reinforcement message periodically to the source node which can be seen in Figure 5.1 (c).

### 5.3.3 Multipath Routing

The multipath routing is a routing technique which allows multiple number of paths for the information flow between the source and the destination. The multipath routing provides the advantage for the load balancing of the data. In the load balancing, the traffic between the source and the destination can be divided into multiple numbers of disjoint paths. Along with load balancing, the use of multi paths for the data transmission allows the sender node to send the multiple copies of data along different paths. Thus, this prevents the loss due to the failure and increases the probability of the reliable delivery of the data. Both of these advantages of multipath routing can provide a good application in WSN. The load balancing allows the even utilization of energy at the nodes and the multiple copies of data sent through different paths allow the reliability of the communication.

In [41], this multipath routing technique is used to find the alternative paths between the source and the sink or the destination. The best path between the source and the destination is considered as the primary path. During a case of failure of this primary path, a number of alternative paths are required to ensure the data flow. Thus, along with primary path, the alternative paths are also constructed and maintained. When the primary path is established, the alternative paths are also established at the same time where the data is sent at a low rate. This low rate data is only to keep-alive the alternative path. When a failure is detected at the primary path, nodes can quickly reinforce an alternative path without the need of the network to again determine the new path. The failure of both the primary path and the alternative path is rare, but in event of failure of both the paths, the source or the destination can flood the network to find another alternative path.

#### 5.3.3.1 Disjoint Multipath

In this method of routing, the alternative paths along with the primary path are constructed such that the alternative paths are node disjoint to the primary path. Thus, the alternative paths are not affected by the failure in the primary path. In this technique, a primary path is created initially between the source and the sink or the destination. The first alternative path is then created where this path is best path node disjoint to the primary path. The second path is the best path that is node disjoint with the primary and the first alternative path. The number of alternative paths is configured as per the requirement.

This method assumes the global knowledge of the network topology. [41] Proposes a mechanism to realise node disjoint multipath using localized information. Figure 5.2 shows the realization of this disjoint multipath using localized information.

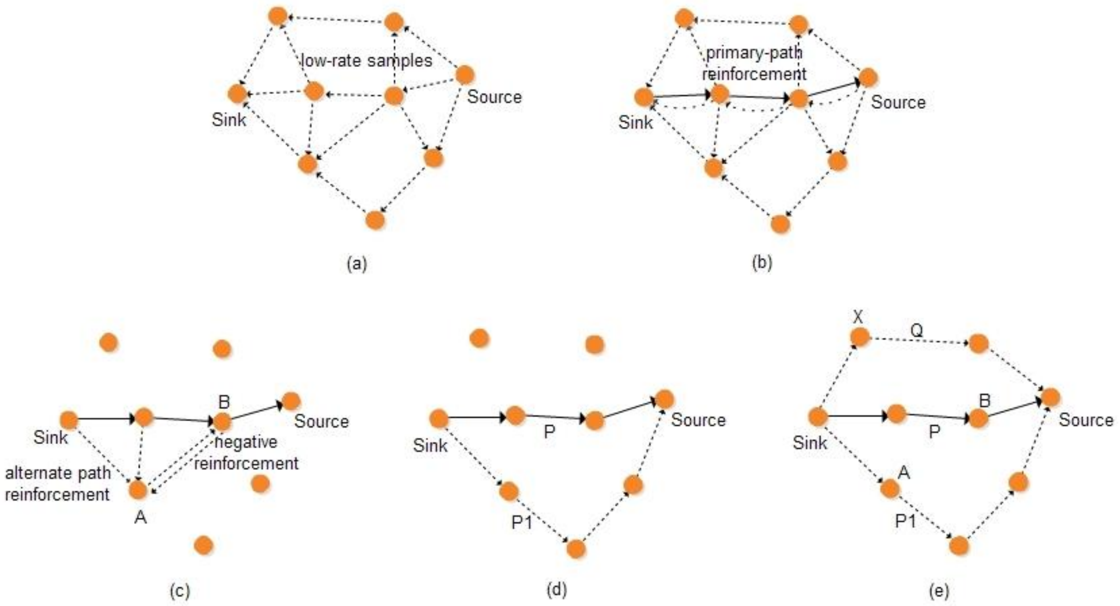


*Figure 5.3. Disjoint Multipaths [41].*

Initially, to find the primary path, the network is flooded with low rate packets. This is shown in Figure 5.2 (a). From this flow of low rate packets, sink can know which neighbour node provides the highest quality of service. The quality is determined by the lowest loss and lowest delay. This node with highest quality is then selected for the primary path and is thus sent a primary path reinforcement message which can be seen in Figure 5.2 (b). Another node in the primary path towards the source is determined locally by this node according to the highest quality of service. Thus a primary path is created from the source to the sink or to the destination. After the primary path reinforcement, the sink sends the alternative path reinforcement to the next most preferred neighbour which then propagates the alternative path reinforcement to its most preferred neighbour node in the direction of the source. If this node is already in the primary path between the source and the sink, it sends the negative reinforcement message to the sending node. This can be seen in Figure 5.2 (c). Then the sending node sends the alternative path reinforcement to next most preferred neighbour node and so on. Thus, an alternative path is created which can be seen in Figure 5.2 (d). These multipath created are called localized disjoint multipath. Figure 5.2 (e) shows the network with number of multipath.

#### 5.3.3.2 Braided Multipath

The disjoint multipath can be sometimes inefficient. Alternative node disjoint paths can be longer and delays can be high. In case of WSN with limited energy, this routing technique can be costly. Thus, [41] proposes another kind of multipath routing technique called Braided Multipath. The braided multipath reduces the requirement for the node disjointedness and the alternative paths are partially disjoint from the primary path.

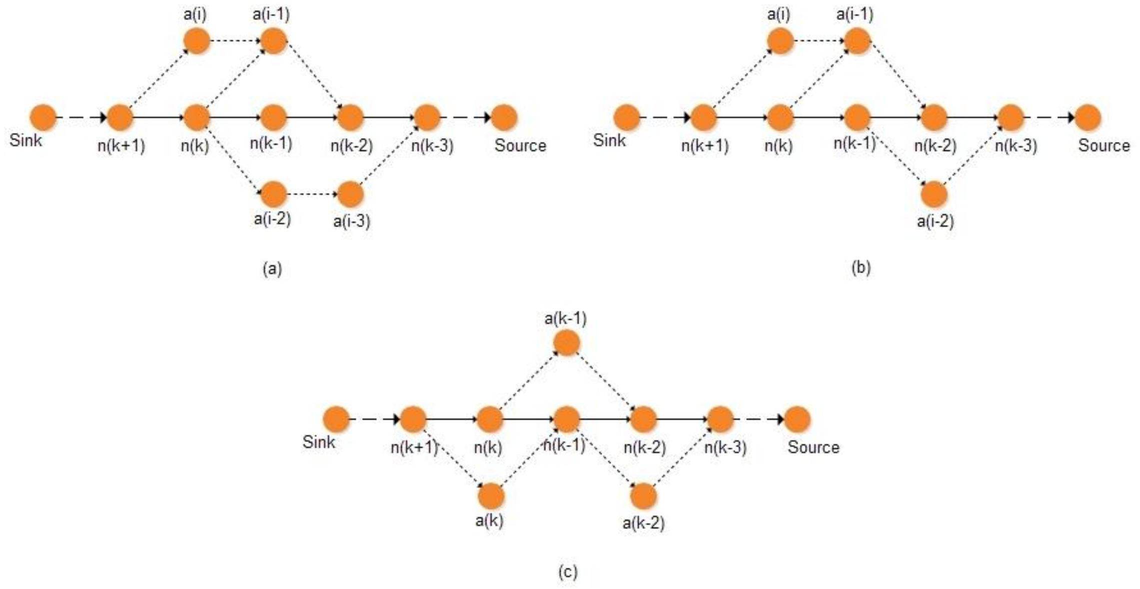


*Figure 5.4. Braided Multipath [41].*

Figure 5.3 (a) is the idealised braided multipath in which for the node on the primary path, the best alternative path to the destination that does not contain this primary node is computed. This alternative path might not be complete node disjoint with the primary node. This is called idealised braided multipath. The nodes denoted by ‘n’ are the primary nodes and the nodes denoted by ‘a’ are the secondary nodes. Figure 5.3 (b) shows the localized braided multipath. Here, the sink sends the primary path reinforcement to its most preferred neighbour node. The sink also sends the alternative path reinforcement to its next preferred neighbour node. Again, as before the most preferred neighbour node again sends the primary path reinforcement to its most preferred node and it continues till it reaches the source node. At the same time, this most preferred node sends the alternative path reinforcement to its next preferred neighbour node as well. When the node that is not on the primary path receives the alternative path reinforcement, it forwards the message to its most preferred neighbour node. When a node already in the primary path receives the alternative path reinforcement, it does not forward the received message any further. Figure 5.3 (b) shows the localized braided obtained by using the above method. But, in practice, this rule does not ensure the perfect detour around a node in the primary path. However, alternative path reinforcement sent by a node can follow any sequence of nodes, which can be complete disjoint from the primary path. The alternative path reinforcement sent by a node may rejoin the primary path as well. Figure 5.3 (c) shows the perfect braided multipath which provides the greater resilience of the braid.

### 5.3.4 Optimized Link State Routing (OLSR)

OLSR is an optimization of pure Link State Routing Protocol (LSRP) which is based on Multi Point Relays (MPR). It is a table driven, proactive routing protocol which updates the information about the path in the network regularly. The nodes exchange this information to establish the route from the source to the destination in the network because of which the routes are immediately available at each node when needed. MPRs are responsible for forwarding control traffic which is diffused in the entire network [42]. Thus, MPR reduces the size of the control messages as nodes communicate only with its neighbours which are selected as MPR and it minimizes the overhead from flooding of control messages. The two major task of OLSR consists of [42]

- *Neighbourhood Discovery.* Each node in the network keeps the information about its one hop and 2 hop neighbours. It sends the Hello message to its neighbours periodically. The node from its 1 hop neighbours, selects the MPR node such that this MPR node can keep the track of its 2 hop neighbours.
- *Topology Dissemination.* The MPRs sends the Topology Control message to other nodes to maintain the topology information about the network. The topology dissemination message is sent periodically to maintain the route from the source to the destination. The routes are available at any point of time and are calculated by Dijkstra's shortest path algorithm which considers the number of hops between the source and the destination.

### 5.3.5 Dynamic Source Routing

Source routing is a routing mechanism in which the sender node determines the set of node through which the data should be forwarded until it reaches the destination. The sender node lists this route in the packet's header which states the address of the next nodes to which the intermediate nodes should transmit until the data packet reaches the destination node. According to this protocol, when a source node needs to send a data to the destination node, the source node dynamically determines the route based on the cached information and the result of the route discovery protocol. Because this dynamic source routing does not have periodic message transmission, it reduces the network bandwidth overhead.

When the source node transmits a packet to another node, it adds the source route in the packet's header. Then the source node transmits the packet to the first hop stated in the source route. When this node receives the packet and if this packet's final destination is not this current node, then this node forwards the packet to another node whose address is stated in the source route. The destination node is referred to as target. Finally, the packet reaches its final destination. Each node in the network maintains the route cache in which it caches source routes it has learned. When one node sends a packet to another node, the source node first checks its route cache for a source route to the destination. If a route is found, then this node uses this route to transmit the packet but if the route is not present then it can use the route discovery protocol. When a source is using any source route, it also monitors the availability of that route. The route maintenance is performed to check for faults in the route. If a problem is detected in a route, then the route discovery protocol can be used to discover a new route.

### 5.3.5.1 Route Discovery

Route Discovery allows any source node in a network to dynamically discover the route to the destination node [43]. The destination node can be directly reachable within the wireless transmission range or reachable through other intermediate nodes. A node which initiates the route discover broadcasts the route request message to all nodes in its range. These route request packet contains the information about the destination node for which the route is requested. When the destination node is identified, the source node receives the route reply message listing the information about the intermediate hops through which it can reach the destination. The route request message also contains the route record which contains the information about the intermediate hops on the way till the destination. Each route request message contains a unique request identification number. The source node address and request identification number is used by the intermediate nodes to take the decision regarding the packet.

When a node receives the route request packet and if the source address and request identification number for a route is found in the list it has for recently seen requests, then it discards the packet. If request node’s address is already listed in the route record in the request then also it discards the packet. If the address and route identification number is not matched in its list, then it appends own address to the route record and rebroadcasts the route request. If the target of the request matches the own address, then the route record of the packet contains the route by which the request reached this node. Then, the node returns a copy of this route in a route reply packet to the source node.

### 5.3.5.2 Route Maintenance

While using the route discovery, periodic messages are not sent from the nodes. When a route is in use, the route maintenance process monitors the operation of the route and in case of any faults, informs the source node. At each intermediate node or hop, the sending node transmitting the data for that node determines if that node in the route is still working or not and thus the route maintenance can be provided. If there is an error which cannot be recovered, then this node sends a route error message to the source node. The route error message contains the address of the node that detects the error and the node to which it was trying to transmit the packet on this hop. When a route error message is received, the error node is removed from the route cache of all nodes.

Instead of hop to hop acknowledgement, route maintenance can also be done by using the end to end acknowledgement. As long as some route between the source and the destination node is available, route maintenance is possible. With hop-to-hop acknowledgement, the hop which is in error is indicated in the route error message. But with the end to end acknowledgement, the source can only assume that the last hop of the route to the destination has error [43].

## 5.4 Acknowledgement Method

In a wireless network, broadcast messages can be used for various purposes such as host discovery, route discovery and network maintenance. When a node broadcasts a routing table for the neighbour nodes or transmits a hello message to determine if nodes are still reachable, the sending node should know if the message is received at receiver node or not.

For the reliability of the data transmission, the link maintenance messages or the other communication messages, the transmitter node should know if the message is successfully delivered or not. Hence, the receiver node should send some kind of message informing the transmitter node that the message is received and can be decoded. If the message is not received at the receiver node, the transmitter node should resend the message.

Thus, when a transmitter node sends some message to the receiver node and if the message is successfully delivered, the receiver node can send an acknowledgement message to the transmitting node. The transmitter node can wait for acknowledgement message for certain period of time and if the acknowledgement message is not received, it can resend the message again. When the receiver sends the acknowledgement message and if the transmitting node does not receive the acknowledgement message, then the transmitting node resends the message which is not acknowledged. However, the receiver node receives the duplicate copy of the received message and the receiver node can discard this message.

# 6 INTER-NODE COMMUNICATION ANALYSIS

The purpose of the inter-node communication analysis is to compute the acceptable parameter values for the effective communication between the two eNodeBs during disaster scenarios. The calculation part includes the proposal for the frequency reuse pattern needed for the communication between the nodes. It is followed by the frequency analysis and the interference and the SINR calculation during a scenario when one eNodeB is communicating with the neighbour eNodeB. The final part includes the analysis of the results.

## 6.1 eNodeB Layout

There are various kinds of layout patterns used for the deployment of the nodes in a communication channel. These nodes are spatially distributed across a geographic area following a specific pattern. These patterns are designed with certain concept for the efficient use of frequency reuse and also to avoid the interference between the neighbour cells [44]. The nodes are deployed with certain tessellation based on the frequency reuse pattern.

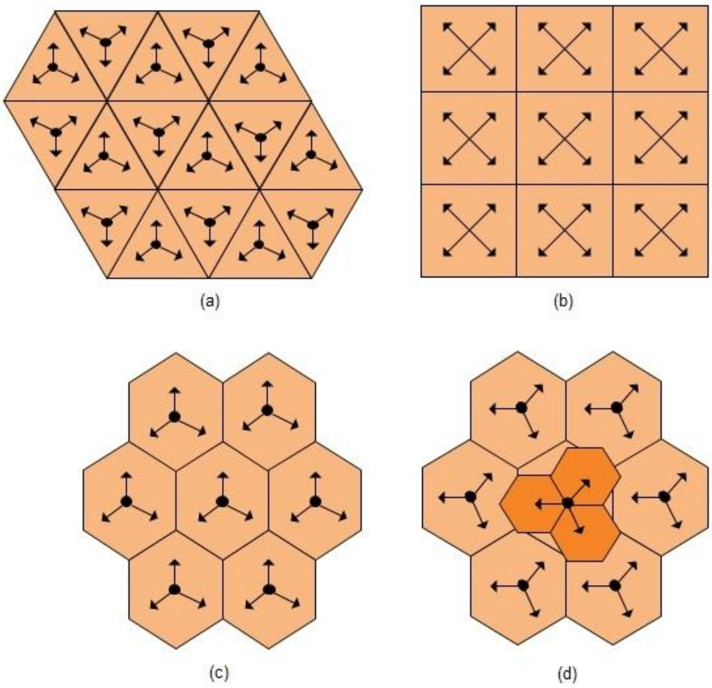


*Figure 6.1. (a) triangle (b) square (c) hexagonal (d) clover-leaf layout [44].*

Figure 6.1 shows the layout diagram for the different patterns in which antennas can be deployed. For three sector sites, clover-leaf layout offers the lowest interference level and thus it can be a good layout for the macro cells [45]. Further, during the inter eNodeB communication, in the clover-leaf approach, the communication between the nodes can be realised in a simple way as each antenna is directly facing to the centre of another antenna. Therefore, this thesis considers the cover-leaf layout of the nodes and all the calculations and the analysis are based upon this consideration.

## 6.2 Frequency Reuse Pattern

Section 3.3.1 shows the frequency reuse scheme proposed for LTE by Alcatel. This frequency reuse involves the use of set of frequency for the cell-edge users and reduced power for the inner cell users. In this thesis, the frequency reuse pattern is used such that the reuse pattern proposed for the cell-edge users is used for the communication between the eNodeBs during the inter eNodeB communication. The frequency reuse patter is shown in Figure 6.2.

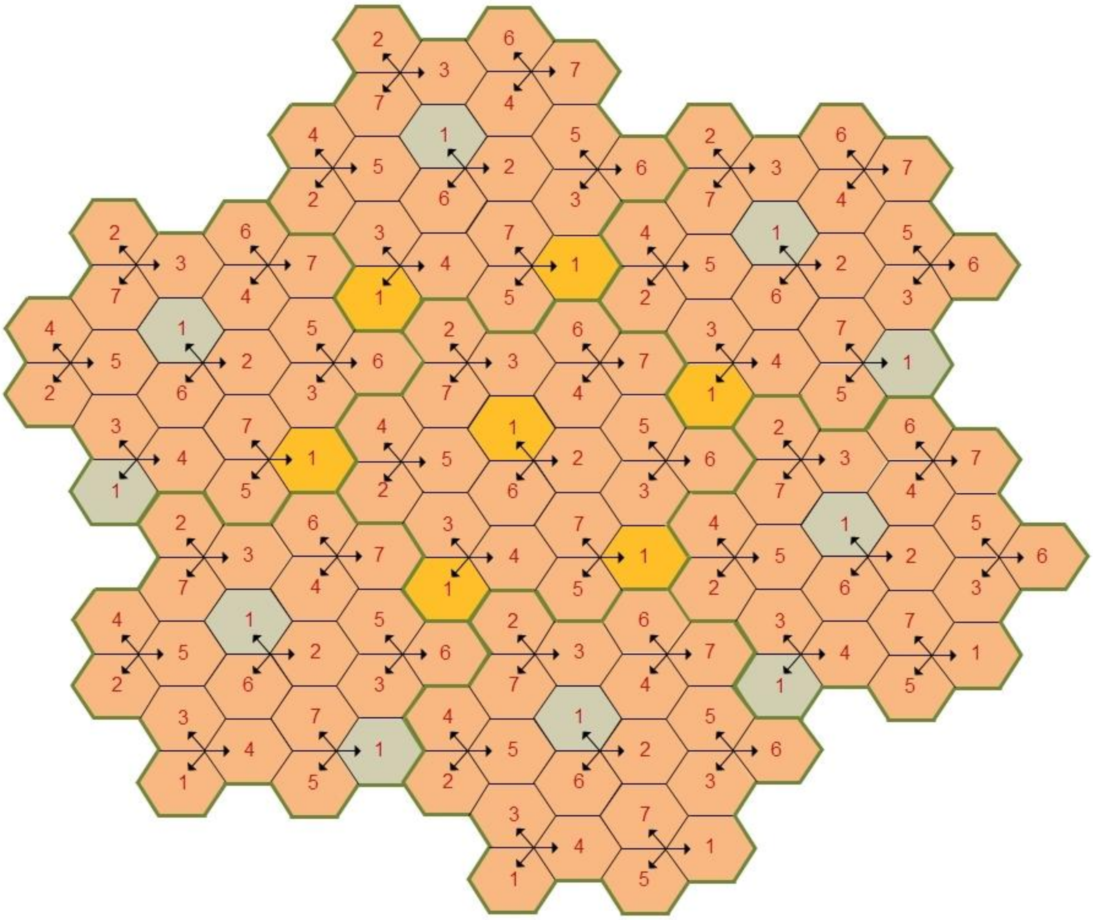


*Figure 6.2. Frequency Reuse Pattern.*

Figure 6.2 shows the proposed frequency reuse pattern. This reuse pattern is only for the inter node communication. First, the cluster of 7 eNodeBs is formed. Thus, there are 21 cells in the cluster. The frequency is reused only at 3 cells in the cluster. These reused cells belong to the 3 different neighbour eNodeBs of the cluster and each antenna of the eNodeBs where this frequency is reused is at an angle of 60° with each other in geometry. It means that, this reused cells' antenna in a cluster are pointing away from each other in a cluster. The reuse cells in different clusters can be visualized as a different cluster of 7 cells which is shown in green colour in Figure 6.2. These reused cells are organised such that the interference from the cells with same frequency is minimized. A group of 7 frequencies are utilized to achieve this reuse pattern. It is assumed that the distances between the nodes in a cluster are the same.

## 6.3 Interference Analysis

This section describes the interference received by the receiver node from the other nodes which are using same frequency as the transmitting node, when the neighbour node is transmitting some information to this receiver.

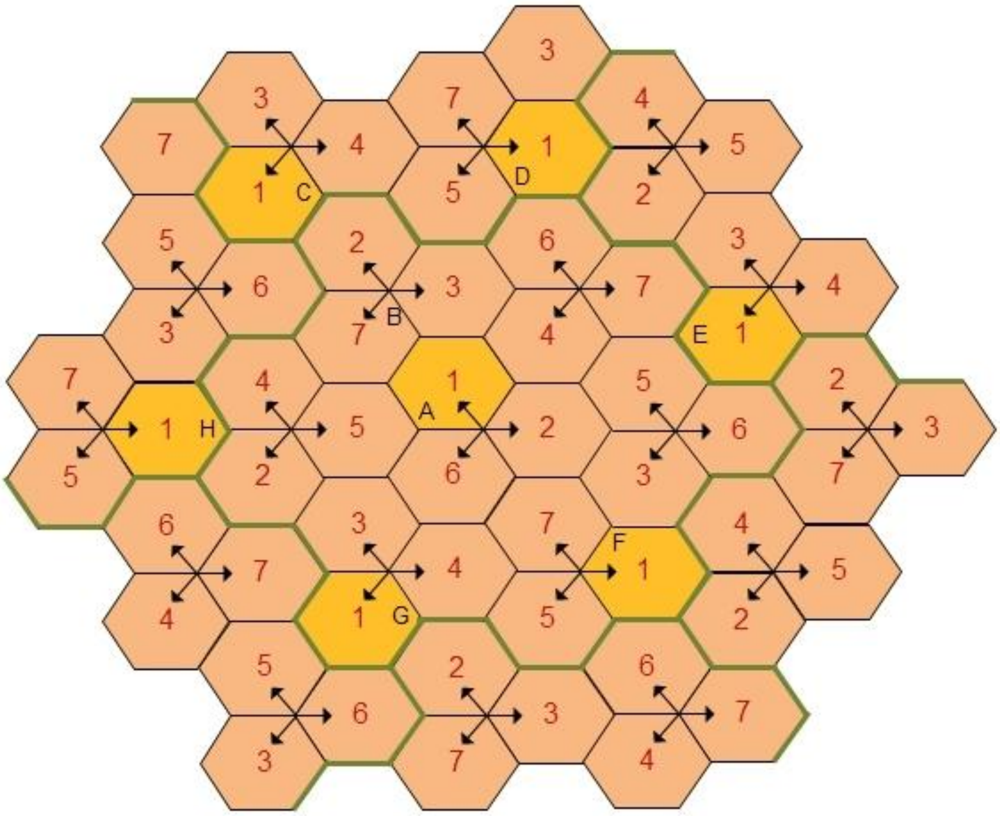


Figure 6.3. Reuse pattern with interfering nodes.

In the Figure 6.3, yellow colour cells show the cells using the same frequency. These cells which are yellow in colour are the first tire cells. Let us suppose that node A is transmitting some information to node B. Let node A transmit with antenna 1 and node B is receive the information through antenna 3 (or 7). Let nodes C, D, E, F, G and

H also communicate with their neighbour nodes using the same frequency as that of node A. Then these nodes C, D, E, F, G and H are the interfering nodes to the node B.

### 6.3.1 Gain Calculation

The gain of the transmitting, receiving and the interfering nodes are calculated in this section. The gain is calculated from the specification sheet of Katherin antenna which is included in Appendix 1. The angle of reception of the signal at the receiving antenna varies according to the location and the transmission from the interfering nodes. Thus, for each interfering nodes C, D, E, F, G and H, the gain is calculated. Figure 6.3 shows the location and the direction of transmission of all the nodes which includes the transmitting node A, receiving node B and interfering nodes C, D, E, F, G and H involved.

*Table 6.1. The Gain of the transmitting and the receiving antenna.*

| | |
|---|---|
| Gain of Transmitting and Receiving antenna (dBi) | 18 |
| Decrease in the gain of receiving antenna at a direction towards the transmitting antenna (dBi) | 9 |
| Gain of receiving antenna at a direction towards the transmitting antenna (dBi) | 9 |

Table 6.1 shows the gain of the transmitting and receiving antenna according to the position of the antenna.

*Table 6.2. Gain of the antennas [From Appendix 1].*

| Node | C | D | E | F | G | H |
|---|---|---|---|---|---|---|
| Gain of transmitting antenna (dBi) | 18 | 18 | 18 | 18 | 18 | 18 |
| Decrease in the gain of interfering antenna at a direction towards the receiving antenna (dBi) | 9 | 27 | 9 | 27 | 35 | 9 |
| Decrease in the gain of receiving antenna at a direction towards the interfering antenna (dBi) | 27 | 9 | 0 | 9 | 17 | 35 |
| Gain of interfering antenna at a direction towards the receiving antenna (dBi) | 9 | -9 | 9 | -9 | -17 | 9 |
| Gain of receiving antenna at a direction towards the interfering antenna (dBi) | -9 | 9 | 18 | 9 | 1 | -17 |

Table 6.2 shows the gain of the respective interfering antennas C, D, E, F, G and H at a particular angle, towards the node B when they are communicating with the neighbour node.

In this thesis, we assume that the total power eNodeB can transmit at a certain bandwidth is 20 watts or 43 dBm.

### 6.3.2 Path Loss Calculation

This thesis discusses the communication between different nodes at macro level. The height of both transmitting and receiving antennas are clearly above the ground level and there is a LOS between the antennas. The height of the receiving antenna in this case is more than the maximum height recommended in Okumura-Hata path loss model, so this thesis uses the free space path loss model to calculate the path loss between the transmitter and the receiver.

Free space path loss is a function of distance and frequency. This thesis uses 800 MHz frequency band for the operation of LTE. From each interfering nodes, the distance is calculated to the receiving node. According to this distance, the path loss is measured from the plot presented in Figure 6.4.

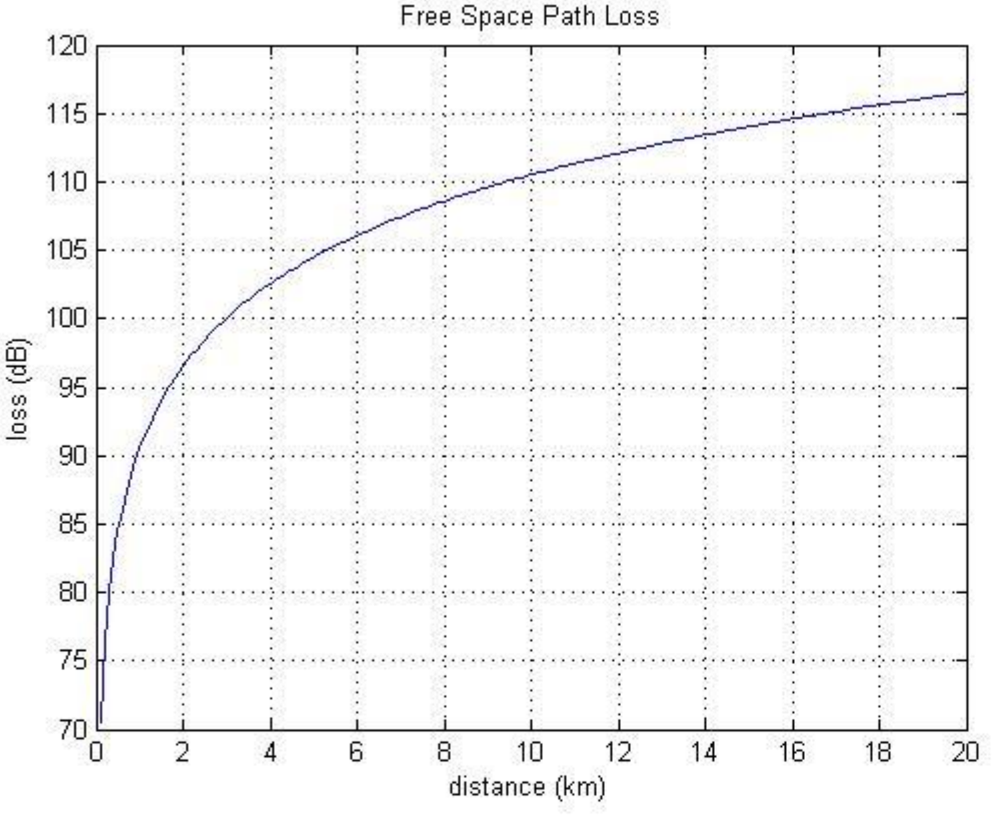


*Figure 6.4. Free Space Path Loss.*

The detailed calculation of the distance and the measurement of the path loss are presented in Appendix 2.

### 6.3.3 Interference and SINR Calculation

The signal power of the desired transmitted signal received by the receiver is calculated using equation 3.3. The interference power received at the same receiver is calculated using equation 3.4. The distance between the transmitter and the receiver is varied and accordingly the path loss is calculated and the received signal is also calculated. The distance between the receiving station and the interfering nodes are also varied in the same ratio as that of the distance variation between the transmitting and the receiving node. Thus, from the signal power and the interference power, SINR is calculated and has a value of 5.92 dB on average. The detailed calculation for signal power, interference power and the SINR is presented in Appendix 2.

## 6.4 Frequency Band and Capacity Analysis

This section describes the optimum use of the bandwidth scalability of the LTE network. The efficient utilization of the 20 MHz bandwidth of the LTE for the user communication as well as for the node to node communication is discussed. The allocation of the bandwidth also plays a vital role in the throughput of the network. Thus, the effective allocation of the frequency band is required for the effective operation of the network.

### 6.4.1 Bandwidth Scalability & Throughput

As discussed in section 2.4, the OFDMA transmission scheme with CP is chosen for the downlink transmission in LTE. OFDM yields a frequency structure that divides the data over a number of sub-carriers. The spacing between two sub-carriers is fixed at 15 kHz. A RB has 12 sub-carriers in frequency and 14 continuous symbols in time. Thus, one RB is 180 kHz in frequency and 1 ms in time.

The scalability in the channel bandwidth is provided by allowing different choices for bandwidth to choose from. This set of allowed bandwidth includes 1.25, 2.5, 5, 10, 15 and 20 MHz. Table 6.3 shows the different parameters associated with different frequency bands.

*Table 6.3. Physical Parameters.*

| Transmission Bandwidth (MHz) | 1.25 | 2.5 | 5 | 10 | 15 | 20 |
|---|---|---|---|---|---|---|
| Sub-frame duration (ms) | 0.5 | | | | | |
| Sub-carrier spacing (kHz) | 15 | | | | | |
| Sampling Frequency (MHz) | 0.5·3.84 | 3.48 | 2·3.84 | 4·3.84 | 6·3.84 | 8·3.84 |
| Number of RB | 6 | 12 | 25 | 50 | 75 | 100 |
| Number of OFDM symbols per sub-frame (Short/Long CP) | 7/6 | | | | | |

If we consider the case for the 2.5 MHz bandwidth, then Table 6.4 shows the values of different peak data rates supported by LTE. The calculations are done with second method described in section 2.6. Different MIMO schemes are also included in the calculations.

*Table 6.4. LTE downlink peak data rate.*

| MIMO Scheme | Modulation Technique | Bits/Symbol | Peak Data Rates (kbps) |
|---|---|---|---|
| 1 x 1 | QPSK | 2 | 1864 |
| 1 x 1 | 16QAM | 4 | 3624 |
| 1 x 1 | 64QAM | 6 | 8760 |
| 2 x 2 | QPSK | 2 | 3728 |
| 2 x 2 | 16QAM | 4 | 7248 |
| 2 x 2 | 64QAM | 6 | 17520 |
| 4 x 4 | QPSK | 2 | 7456 |
| 4 x 4 | 16QAM | 4 | 14496 |
| 4 x 4 | 64QAM | 6 | 35040 |

### 6.4.2 Frequency Band Allocation

This section explores the advantage of bandwidth flexibility in LTE. Figure 6.2 shows the efficient utilization of the frequency band with the reuse scenario. If we realise the cluster in Figure 6.2 as a sensor network, for the communication to occur between eNodeB to eNodeB in a cluster, we need 7 different frequency bands to establish the communication link. The numbering of the frequency is shown in Figure 6.2.

This thesis analyse the use of 2.5 MHz bandwidths allocation out of 20 MHz for the communication between the eNodeBs. Thus, three different frequency bands are allocated to three different antennas of eNodeB for the communication. This thesis considers the LTE FDD mode of operation. FDD mode means 20 MHz for uplink and another 20 MHz for the downlink. Thus, there are two different mechanisms to allocate the frequency to the enodeB.

The first one is to allocate the 2.5 MHZ frequency bands from 20 MHz frequency band directly resulting in the use of 17.5 MHz frequency for the inter node communication and remaining 2.5 MHz for the users. The second one is to allocate 2.5 MHz bands respectively from uplink and downlink band and then use the remaining band for the communication.

If we distribute the frequency bands according to the second method, then the frequency bands can be used more efficiently. 2.5 MHz band is just a consideration in this thesis. If, during the disaster scenarios, large numbers of nodes are affected in the disaster area, then several numbers of hops is used for communication. The traffic in such scenarios can increase. In such situation, the bandwidth for the inter node communication should be increased.

## 6.5 Results Discussion

The assumptions and the calculations for the eNodeB to eNodeB in the macro layer are presented in the above sections. The frequency reuse pattern shown in the section 6.2 provides the base for the utilization of the different frequency band with the minimum interference at the receiver. The gain, path loss and interference calculations are presented in section 6.3. The transmission power of eNodeB is assumed to be 43 dBm. The SINR calculated on the basis of this gain, path loss and the interference was 5.92 dB. Comparing this value with the values presented in Table 3.3, it shows that with this SINR value, we can implement QPSK modulation technique with 3/4 or 4/5 coding rate. The data rates supported by the QPSK and other modulation techniques can be seen in Table 6.4. The utilization of the bandwidth scalability is presented in section 6.4.1 which considers the 2.5 MHz frequency band for the communication between eNodeBs at the macro layer.

# 7 OPERATIONAL FRAMEWORK

This chapter provides the overview of the operational framework proposed for the node-to-node communication during disaster scenarios. The proposed framework includes the flow chat for the different events associated with the node-to-node communication during the disaster scenarios. The events include the detection of the disaster scenarios by the nodes, the functional event that should be enabled from the network side and the events related to the establishment of the path between the nodes.

## 7.1 Disaster Scenarios Detection

When a disaster strikes and there is a communication outage, the first thing the nodes should sense is to detect this disaster situation. In our case, the disaster scenario is the one when the link between the eNodeB and EPC is broken. Figure 7.1 describes the series of events involved with disaster scenario detection.

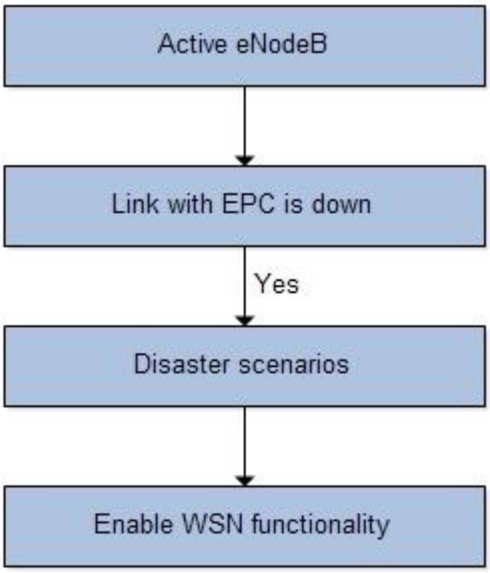


*Figure 7.1. Disaster Scenario Detection.*

Figure 7.1 shows the flow chart for the detection of the disaster scenarios. When the disaster strikes, then there is a possibility that the link between the eNodeB and the EPC is broken. When this link is down, then the eNodeB can detect this event and then can switch its functionality to the macro sensor node. As a macro sensor node, eNodeB can work with LTE functionality along with the sensor network functionality. With the sensor network functionality, this node can detect any kind of disaster events, route establishment with the neighbour node and act as a relay hop.

## 7.2 Events from the EPC

Once the disaster scenario is detected and the macro sensor network functionality is established, the next step is the establishment of the communication path between the nodes such that this communication path provides the delivery of the data, which needs to be transferred from the disaster affected nodes to the EPC. The nodes whose link with EPC is broken can detect the disaster event and can initialize the sensor network functionality. When the link between the nodes is established, the last hop of each route should have a link with the EPC. Thus, the macro sensor network functionality should also be enabled in this last hop. For the sensor network functionality to initialize in this last hop, this thesis proposes that the last hop should be detected and sensor network functionality should be enabled by the EPC. Figure 7.2 shows the flow chart for this event.

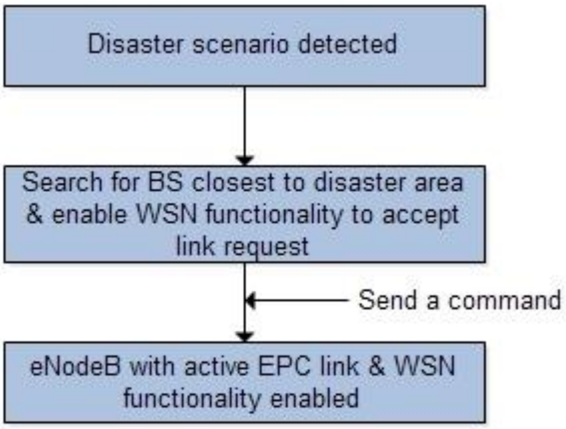


*Figure 7.2. EPC events.*

When the eNodeB in a disaster area is affected, the operation and maintenance entity of the EPC can detect this fault situation and can also locate the nodes in the geographical areas. Once the nodes are located, EPC can send a command to the unaffected nodes which can possibly act as a last hop for the communication. This possible node can be detected according to the closeness to the disaster affected areas. After the nodes are detected, EPC can send a command to these nodes to enable sensor network functionality to these nodes.

## 7.3 Link Establishment Procedure

Once the macro sensor network functionality is enabled in all the nodes, which allows for forming the hop to hop communication, the next step is the link establishment between the most preferred neighbour nodes. The link establishment procedure can use different protocols to establish the link as described in chapter 6. Figure 7.3 shows a flowchart which describes a simple link establishment procedure.

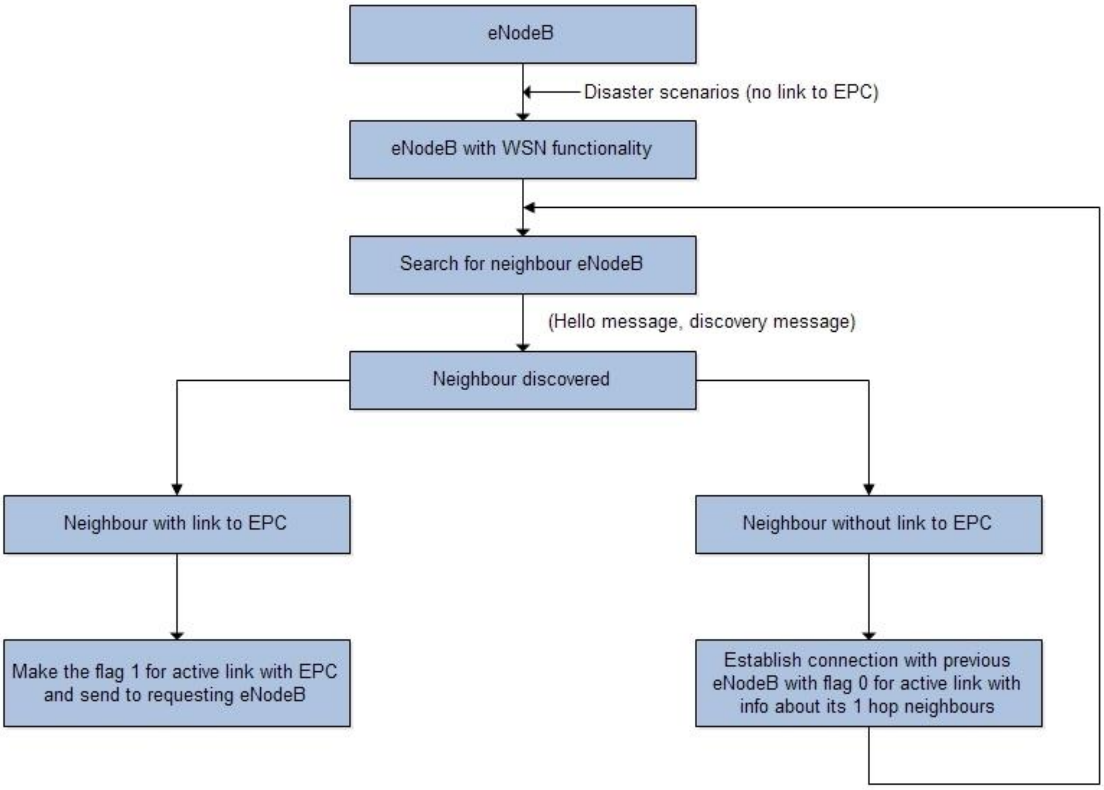


*Figure 7.3. Link Establishment Procedure.*

Once the eNodeB enables the macro sensor network functionality, it can initiate for the communication with the neighbour node to establish the communication link. For this to happen, the node can send the discover message (Hello message) to the neighbour nodes. Then, the receiving neighbour node can reply to the sending node whether it can establish a communication link with the sender node or not. Further, this receiving node can be of two types. First is the node having the active link state with the EPC or the node with the link to the EPC in inactive state. The receiving node can provide this information about the link state in the reply message to the sender using a specific flag. The receiving node can provide the Quality of Service (QOS) information that it can support to the sending node as well.

If the receiving node has the active connection with the EPC, then this node does not need to forward the packet to another node. But if this node does not have an active connection with EPC, then it can search for its neighbour node and provide the information about its 1 hop neighbour to the sender node. All the route informations can be stored in the cache in each node. Following this procedure, the link can be established between the disaster affected nodes and the EPC.

## 7.4 Network Restoration

When a communication link is established between the nodes in the disaster affected region, the temporary communication solution is possible. There can be a limitation in the service offered by the network due to the limitation in the data rates. Even though, if a temporary communication link is established, it will help in the communication between the users, communication for the relief work, and to provide the update about the disaster area.

Along with the node-to-node communication link, the maintenance workers from the operators will start working towards the restoration of the network. Let a node, which is a part of the node to node communication link; re-establish a communication connection with the EPC. Then, it should first check the status of the next hop. The status of the next hop is initially provided in the reply message to its route request message. This node with active EPC state can again ask for the current status of the next hop. If the EPC link state is still inactive, then this node can ask this neighbour node to terminate the communication link with it and this node can act as an end node for the communication with the EPC. Along with the link termination message, this node should send the information to the preceding node about its active link status with the EPC.

Further, once a node with the active link status with the EPC has no role in the node to node communication, it can notify the EPC about this status and can switch back to the normal state.

# 8 CONCLUSION AND FUTURE WORK

This thesis investigates the inter-node communication during the disaster scenarios for the 3GPP LTE technology. LTE specification describes the X2 interface for the indirect inter-node communication for the handover and the inter-cell interference minimization. The realization of the LTE radio network as a macro sensor network to enable the node-to-node communication during the disaster scenarios is the first of its kind. Furthermore, “The Tampere Convention on Emergency Telecommunications” calls on states to facilitate the provision of prompt telecommunication assistant to mitigate the impact of a disaster.

This thesis proposes an operational framework for the possible inter-node communication for LTE at macro level during the disaster scenarios. For this inter-node communication, a specific reuse pattern has been created based on Alcatel’s Proposal. The layout of the node follows the clover-leaf approach. On the basis of this reuse pattern, the interference analysis, SINR analysis and the capacity analysis has been done and the results are presented. Further, an operational flow chart has been proposed which describes the overall procedure of the node-to-node communication during the disaster scenarios for LTE.

From the interference and SINR analysis, the SINR was obtained to be 5.92 dB. Thus, this SINR value can support QPSK modulation scheme in LTE. The code rate can be either 3/4 or 4/5. This thesis explores the bandwidth scalability property of LTE and investigates the use of 2.5 MHz frequency band for the inter-node communication. The use of 2.5 MHz band with QPSK modulation technique can provide a data rate of 1.86 Mbps with simplest mode, 3.73 Mbps with 2 x 2 MIMO and 7.5 Mbps with 4 x 4 MIMO scheme. Thus, the result shows that an inter-node communication can be possible in LTE during the disaster scenarios. Along with the disaster scenarios, this node-to-node communication can be implemented at eNodeB in normal situation when there is a problem in a communication link from eNodeB to EPC. Until the maintenance of this link, a network can be established in such situation. The number of hops for the inter-node communication during this scenario depends on the effect of the delay.

The result presented above is for the 3GPP LTE but the analysis shows that this inter node communication can possibly be implemented in GSM as well. Due to the frequency barrier, this node-to-node communication might not be possible in UMTS. As LTE is the emerging technology and the operators are increasingly moving forward for the rollout, this thesis is focused on the study of inter node communication in LTE. This thesis can be considered as the preliminary step towards the concept of inter-node communication during the disaster scenarios.

As this thesis investigates the possibility of node-to-node communication during the disaster scenarios in LTE, it is probably the first of its kind. Ample research needs to be done in the practical scenarios. Another research can be the implementation of the signalling information to and from the eNodeB. The effect of delay due to the increase in the number of hops also needs to be studied. Further the sensor network functionality can be implemented through the SON technology and it can be an area for the research. The volume of data generated by the users might add some complexity and bottle neck in the smooth functioning of the network, thus a comparative research with respect to the users need to be analysed. Further, the utilization of maximum ratio combining or the switched combining can be studied to receive the signal through two different antennas to provide better SINR can be a new research area. This concept of node-to-node communication should lead to the development of new simulation and analysis tools which can realise eNodeB as a BS for the LTE network as well as the sensor network.

The concept put forth by this thesis opens the door for the reliable and efficient communication during the disaster scenarios.

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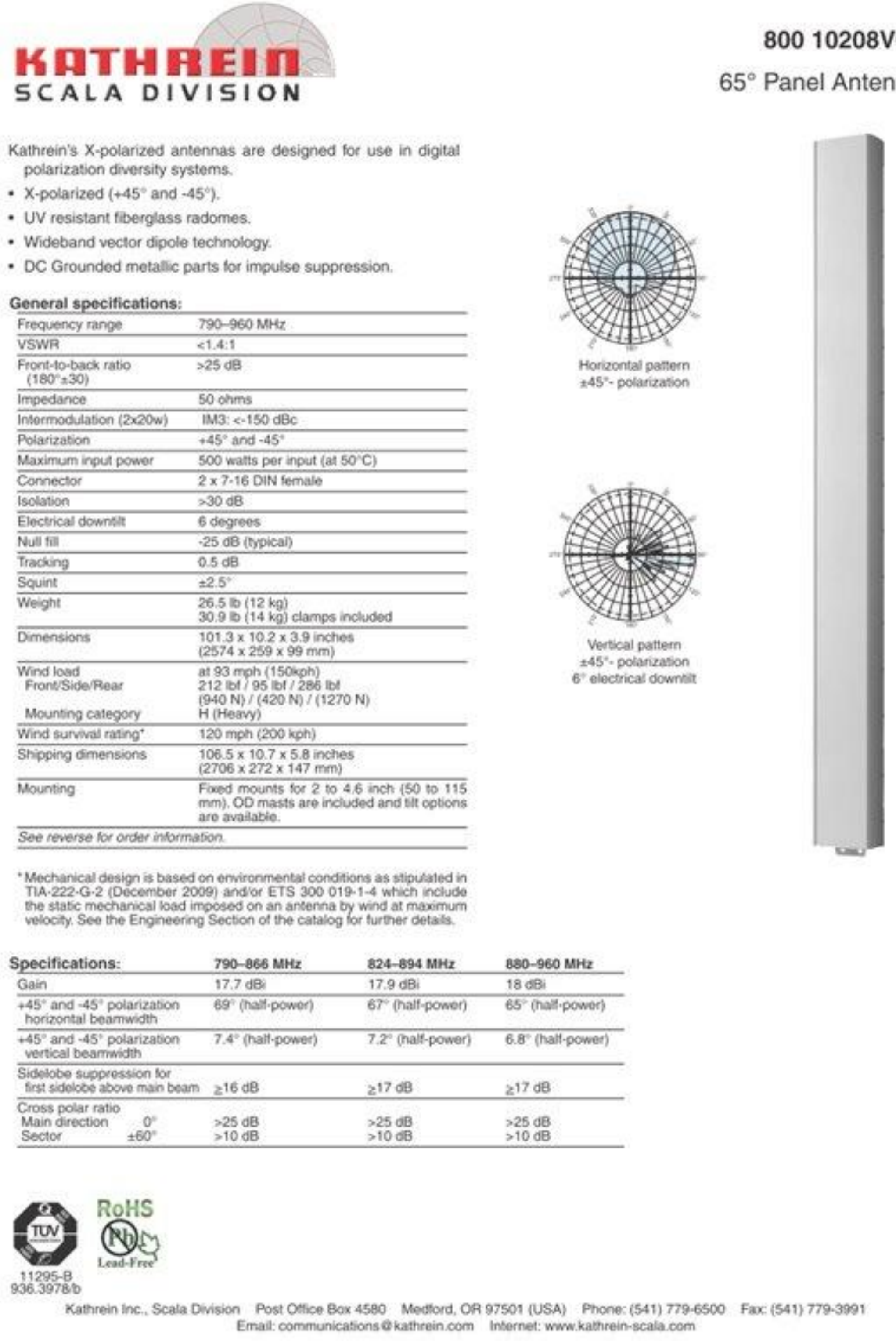
# APPENDIX 1



KATHREIN
SCALA DIVISION

**800 10208V01**

65° Panel Antenna

Kathrein's X-polarized antennas are designed for use in digital polarization diversity systems.

- X-polarized (+45° and -45°).
- UV resistant fiberglass radomes.
- Wideband vector dipole technology.
- DC Grounded metallic parts for impulse suppression.

**General specifications:**

| | |
|---|---|
| Frequency range | 790–960 MHz |
| VSWR | <1.4:1 |
| Front-to-back ratio (180°±30) | >25 dB |
| Impedance | 50 ohms |
| Intermodulation (2x20w) | IM3: <-150 dBc |
| Polarization | +45° and -45° |
| Maximum input power | 500 watts per input (at 50°C) |
| Connector | 2 x 7-16 DIN female |
| Isolation | >30 dB |
| Electrical downtilt | 6 degrees |
| Null fill | -25 dB (typical) |
| Tracking | 0.5 dB |
| Squint | ±2.5° |
| Weight | 26.5 lb (12 kg)<br>30.9 lb (14 kg) clamps included |
| Dimensions | 101.3 x 10.2 x 3.9 inches<br>(2574 x 259 x 99 mm) |
| Wind load<br>Front/Side/Rear | at 93 mph (150kph)<br>212 lbf / 95 lbf / 286 lbf<br>(940 N) / (420 N) / (1270 N) |
| Mounting category | H (Heavy) |
| Wind survival rating* | 120 mph (200 kph) |
| Shipping dimensions | 106.5 x 10.7 x 5.8 inches<br>(2706 x 272 x 147 mm) |
| Mounting | Fixed mounts for 2 to 4.6 inch (50 to 115 mm). OD masts are included and tilt options are available. |

*See reverse for order information.*

Horizontal pattern
±45°- polarization

Vertical pattern
±45°- polarization
6° electrical downtilt

* Mechanical design is based on environmental conditions as stipulated in TIA-222-G-2 (December 2009) and/or ETS 300 019-1-4 which include the static mechanical load imposed on an antenna by wind at maximum velocity. See the Engineering Section of the catalog for further details.

| **Specifications:** | **790–866 MHz** | **824–894 MHz** | **880–960 MHz** |
|---|---|---|---|
| Gain | 17.7 dBi | 17.9 dBi | 18 dBi |
| +45° and -45° polarization horizontal beamwidth | 69° (half-power) | 67° (half-power) | 65° (half-power) |
| +45° and -45° polarization vertical beamwidth | 7.4° (half-power) | 7.2° (half-power) | 6.8° (half-power) |
| Sidelobe suppression for first sidelobe above main beam | ≥16 dB | ≥17 dB | ≥17 dB |
| Cross polar ratio<br>Main direction 0°<br>Sector ±60° | <br>>25 dB<br>>10 dB | <br>>25 dB<br>>10 dB | <br>>25 dB<br>>10 dB |

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RoHS
Lead-Free

11295-B
936.3978/b

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Email: communications@kathrein.com Internet: www.kathrein-scala.com

# APPENDIX 2

| **Inter Site Distance (ISD)** | **500** | **500** | **500** | **500** | **500** | **500** |
|---|---|---|---|---|---|---|
| Distance between | B & C | B & D | B & E | B & F | B & G | B & H |
| Distance | 500 | 500 | 1000 | 1000 | 707.11 | 707.11 |
| Free Space Path Loss (dB) | 86 | 86 | 92 | 92 | 88 | 88 |
| Interference | -43 | -43 | -22 | -49 | -61 | -53 |
| Total Interference | -21.9191 | | | | | |
| Carrier Power (dbm) | -16 | | | | | |
| C/I | 5.9191019 | | | | | |
| | | | | | | |
| **Inter Site Distance (ISD)** | 600 | 600 | 600 | 600 | 600 | 600 |
| Distance between | B & C | B & D | B & E | B & F | B & G | B & H |
| Distance | 600 | 600 | 1200 | 1200 | 848.53 | 848.53 |
| Free Space Path Loss (dB) | 87 | 87 | 93 | 93 | 90 | 90 |
| Interference | -44 | -44 | -23 | -50 | -63 | -55 |
| Total Interference | -22.91991 | | | | | |
| Carrier Power | -17 | | | | | |
| C/I | 5.9199088 | | | | | |
| | | | | | | |
| **Inter Site Distance (ISD)** | 700 | 700 | 700 | 700 | 700 | 700 |
| Distance between | B & C | B & D | B & E | B & F | B & G | B & H |
| Distance | 700 | 700 | 1400 | 1400 | 989.95 | 989.95 |
| Free Space Path Loss (dB) | 88 | 88 | 94 | 94 | 91.4 | 91.4 |
| Interference | -45 | -45 | -24 | -51 | -64.4 | -56.4 |
| Total Interference | -23.92018 | | | | | |
| | | | | | | |
| **Inter Site Distance (ISD)** | 800 | 800 | 800 | 800 | 800 | 800 |
| Distance between | B & C | B & D | B & E | B & F | B & G | B & H |
| Distance | 800 | 800 | 1600 | 1600 | 1131.4 | 1131.4 |
| Free Space Path Loss (dB) | 89.5 | 89.5 | 95 | 95 | 92 | 92 |
| Interference | -46.5 | -46.5 | -25 | -52 | -65 | -57 |
| Total Interference | -24.92728 | | | | | |
| | | | | | | |
| **Inter Site Distance (ISD)** | 900 | 900 | 900 | 900 | 900 | 900 |
| Distance between | B & C | B & D | B & E | B & F | B & G | B & H |
| Distance | 900 | 900 | 1800 | 1800 | 1272.8 | 1272.8 |
| Free Space Path Loss (dB) | 90 | 90 | 96.5 | 96.5 | 93.6 | 93.6 |
| Interference | -47 | -47 | -26.5 | -53.5 | -66.6 | -58.6 |
| Total Interference | -26.41172 | | | | | |
| | | | | | | |
| **Inter Site Distance (ISD)** | 1000 | 1000 | 1000 | 1000 | 1000 | 1000 |

| | | | | | | |
|---|---|---|---|---|---|---|
| Distance between | B & C | B & D | B & E | B & F | B & G | B & H |
| Distance | 1000 | 1000 | 2000 | 2000 | 1414.2 | 1414.2 |
| Free Space Path Loss (dB) | 92 | 92 | 98 | 98 | 94.5 | 94.5 |
| Interference | -49 | -49 | -29 | -56 | -67.5 | -59.5 |
| Total Interference | -28.90113 | | | | | |
| | | | | | | |
| **Inter Site Distance (ISD)** | 2000 | 2000 | 2000 | 2000 | 2000 | 2000 |
| Distance between | B & C | B & D | B & E | B & F | B & G | B & H |
| Distance | 2000 | 2000 | 4000 | 4000 | 2828.4 | 2828.4 |
| Free Space Path Loss (dB) | 98 | 98 | 103 | 103 | 100.5 | 100.5 |
| Interference | -54 | -54 | -33 | -60 | -73.5 | -65.5 |
| Total Interference | -32.92025 | | | | | |
| **Inter Site Distance (ISD)** | 3000 | 3000 | 3000 | 3000 | 3000 | 3000 |
| Distance between | B & C | B & D | B & E | B & F | B & G | B & H |
| Distance | 3000 | 3000 | 6000 | 6000 | 4242.65 | 4242.65 |
| Free Space Path Loss (dB) | 101 | 101 | 107 | 107 | 104 | 104 |
| Interference | -58 | -58 | -37 | -64 | -77 | -69 |
| Total Interference | -36.91991 | | | | | |
| | | | | | | |
| **Inter Site Distance (ISD)** | 4000 | 4000 | 4000 | 4000 | 4000 | 4000 |
| Distance between | B & C | B & D | B & E | B & F | B & G | B & H |
| Distance | 4000 | 4000 | 8000 | 8000 | 5656.9 | 5656.9 |
| Free Space Path Loss (dB) | 103 | 103 | 110 | 110 | 106.6 | 106.6 |
| Interference | -60 | -60 | -40 | -67 | -79.6 | -71.6 |
| Total Interference | -39.90211 | | | | | |
| | | | | | | |
| **Inter Site Distance (ISD)** | 5000 | 5000 | 5000 | 5000 | 5000 | 5000 |
| Distance between | B & C | B & D | B & E | B & F | B & G | B & H |
| Distance | 5000 | 5000 | 10000 | 10000 | 7071.1 | 7071.1 |
| Free Space Path Loss (dB) | 105 | 105 | 112 | 112 | 108.5 | 108.5 |
| Interference | -62 | -62 | -42 | -69 | -81.5 | -73.5 |
| Total Interference | -41.90203 | | | | | |
| | | | | | | |
| **Inter Site Distance (ISD)** | 6000 | 6000 | 6000 | 6000 | 6000 | 6000 |
| Distance between | B & C | B & D | B & E | B & F | B & G | B & H |
| Distance | 6000 | 6000 | 12000 | 12000 | 8485.3 | 8485.3 |
| Free Space Path Loss (dB) | 107 | 107 | 113 | 112 | 110.1 | 110.1 |
| Interference | -64 | -64 | -43 | -69 | -83.1 | -75.1 |
| Total Interference | -42.91778 | | | | | |
| Carrier Power | -37 | | | | | |
| C/I | 5.9177776 | | | | | |
| | | | | | | |
| **Inter Site Distance (ISD)** | 7000 | 7000 | 7000 | 7000 | 7000 | 7000 |
| Distance between | B & C | B & D | B & E | B & F | B & G | B & H |
| Distance | 7000 | 7000 | 14000 | 14000 | 9899.5 | 9899.5 |

| | | | | | | |
|---|---|---|---|---|---|---|
| Free Space Path Loss (dB) | 109 | 109 | 114.5 | 114.5 | 111.4 | 111.4 |
| Interference | -66 | -66 | -44.5 | -71.5 | -84.4 | -76.4 |
| Total Interference | -44.42721 | | | | | |
| | | | | | | |
| **Inter Site Distance (ISD)** | 8000 | 8000 | 8000 | 8000 | 8000 | 8000 |
| Distance between | B & C | B & D | B & E | B & F | B & G | B & H |
| Distance | 8000 | 8000 | 16000 | 16000 | 11314 | 11314 |
| Free Space Path Loss (dB) | 110 | 110 | 115.6 | 115.6 | 112.6 | 112.6 |
| Interference | -67 | -67 | -45.6 | -72.6 | -85.6 | -77.6 |
| Total Interference | -45.52587 | | | | | |
| | | | | | | |
| **Inter Site Distance (ISD)** | 9000 | 9000 | 9000 | 9000 | 9000 | 9000 |
| Distance between | B & C | B & D | B & E | B & F | B & G | B & H |
| Distance | 9000 | 9000 | 18000 | 18000 | 12728 | 12728 |
| Free Space Path Loss (dB) | 111 | 111 | 116.6 | 116.6 | 113.6 | 113.6 |
| Interference | -68 | -68 | -46.6 | -73.6 | -86.6 | -78.6 |
| Total Interference | -46.52587 | | | | | |
| | | | | | | |
| **Inter Site Distance (ISD)** | 10000 | 10000 | 10000 | 10000 | 10000 | 10000 |
| Distance between | B & C | B & D | B & E | B & F | B & G | B & H |
| Distance | 10000 | 10000 | 20000 | 20000 | 14142 | 14142 |
| Free Space Path Loss (dB) | 112 | 112 | 117.5 | 117.5 | 114.5 | 114.5 |
| Interference | -69 | -69 | -47.5 | -74.5 | -87.5 | -79.5 |
| Total Interference | -47.42728 | | | | | |
| Carrier Power | -42 | | | | | |
| C/I | 5.427281 | | | | | |