A Novel Sea Communication Topology and IP Routing Algorithm by Using LTE and WMN in NS3

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This is to certify that we have read this thesis and that in our opinion it is fully adequate, in scope and quality, as a thesis for the degree of Master of Science in Electronics and Computer Engineering.

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Rashad KASIM

Abstract

This thesis presents a new heterogeneous network topology and an IP routing algorithm for marine communication system involving ships and other marine vessels from a terrestrial point on the shore. The proposed topology involves a collection of LTE systems and Wi-Fi mesh networks. Every cluster/ship in the network is provided with a LTE system and there could be similar multiple clusters in the network. Connections between individual clusters happen through LTE and within each cluster mesh networking is employed. Every end-user in the ship accesses the server application by means of mesh networking from respective access points in the ship. The proposed routing algorithm is designed based on the best SINR path and minimum time delay combination. This automatically results in the selection of best modulation scheme and hence the best data rate. The algorithm employs a new parameter that is derived directly from SINR. The topology along with the algorithm provides a connection with a maximum coverage distance of 180 km and minimum data rate around 0.6 Mbps with 2 interconnection clusters. Presence of more interconnection clusters makes the coverage distance, data rate, and reliability greatly improved. Open source network tool NS-3 is used for the topology design, algorithm implementation, and simulations. Proposed topology and algorithm when implemented can be used to provide a long distance sea communication with improved reliability and higher data rate.

Keywords: Maritime Communication, LTE, Mesh Network, WMN, NS-3, Algorithm, Ship Communication, Sea Coverage

Yeni Bir Deniz İletişimi Topolojisi ve IP Yönlendirme Algoritması NS3'te LTE ve WMN'yi kullanma

Rashad Kasim

Öz

Bu tez, kıyıdaki karasal bir noktadan gelen gemi ve diğer deniz gemilerini içeren deniz haberleşme sistemi için yeni bir heterojen ağ topolojisi ve bir IP yönlendirme algoritması sunmaktadır. Önerilen topoloji LTE sistemlerinin ve Wi-Fi ağlarının bir araya toplanmasını içerir. Ağdaki her küme / gemi bir LTE sistemi ile sağlanır ve şebekede benzer çoklu küme olabilir. Münferit kümeler arasındaki bağlantılar LTE vasıtasıyla gerçekleşir ve her küme içinde örgü ağı kullanılır. Gemideki her son kullanıcı, gemideki ilgili erişim noktalarından gelen ağı vasıtasıyla sunucu uygulamasına erişir. Önerilen yönlendirme algoritması, en iyi SINR yolu ve minimum zaman gecikmesi kombinasyonuna dayalı olarak tasarlanmıştır. Bu, otomatik olarak en iyi modülasyon şemasının seçilmesine ve dolayısıyla en iyi veri hızına neden olur. Algoritma doğrudan SINR'den türetilen yeni bir parametre kullanmaktadır. Algoritma ile birlikte topoloji, 2 ara bağlantı kümesiyle maksimum kapsama mesafesi 180 km ve minimum veri hızı 0.6 Mbps civarında bir bağlantı sağlar. Daha fazla arabağlantı kümesinin bulunması kapsama mesafesini, veri hızını ve güvenilirliğini büyük ölçüde geliştirir. Açık kaynaklı ağ aracı NS-3, topoloji tasarımı, algoritma uygulaması ve simülasyonlar için kullanılır. Uygulandığında önerilen topoloji ve algoritma, gelişmiş güvenilirlik ve daha yüksek veri hızı ile uzun mesafe deniz iletişimi sağlamak için kullanılabilir.

Anahtar Sözcükler: Deniz iletişimi, LTE, Mesh Network, WMN, NS-3, Algoritma, Gemi iletişimi, Denizde kapsama alanı

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Abbreviations

1G	**F**irst **G**eneration
2G	**S**econd **G**eneration
GSM	**G**lobal **S**ystem for **M**obile communication **S**ystem
GPRS	**G**eneral **R**adio **S**ervice **N**etwork
EDGE	**E**nhanced **D**ata rates for **GSM** **E**volution
UMTS	**U**niversal **M**obile **T**elecommunication **S**ystem
CDMA	**C**ode **D**ivision **M**ultiple **A**ccess
WiMAX	**W**orldwide **I**nteroperability for **M**icrowave **A**ccess
LTE	**L**ong **T**erm **E**volution
3G	**T**hird **G**eneration
HSPA	**H**igh **S**peed **P**acket **A**ccess
ETSI	**E**uropean **T**elecommunications **S**tandards **I**nstitute
3GPP	**T**hird **G**eneration **P**artnership **P**roject
MSC	**M**obile **S**witching **C**enter
SGSN	**S**erving **G**PRS **S**upport **N**ode
PCU	**P**acket **C**ontrol **U**nits
ATM	**A**synchronous **T**ransfer **M**ode
UE	**U**ser **E**quipment
E-UTRAN	**E**volved **T**errestrial **R**adio **A**ccess **N**etwork
EPC	**E**volved **P**acket **C**ore
UICC	**U**niversal **I**ntegrated **C**ircuit **C**ard
eNB	**E**volved **N**ode **B**
PGW	**P**acket data network **G**ate**W**ay
SGW	**S**erving **G**ate**W**ay
MME	**M**obility **M**anagement **E**ntity
HSS	**H**ome **S**ubscriber **S**erver

WMN	**W**ireless **M**esh **N**etwork
InMarSat	**In**ternational **Mar**itime **Sat**ellite
VSAT	**V**ery **S**mall **A**perture **T**erminal
P2MP	**P**oint-**T**o-**M**ulti-**P**oint
LR	**L**ong **R**ange
TDMA	**T**ime **D**ivision **M**ultiple **A**ccess
RTT	**R**ound **T**rip **T**ime
ACK	**A**cknowledgement
CSMA	**C**arrier **S**ense **M**ultiple **A**ccess
TD-LTE	**T**ime **D**ivision-**L**ong **T**erm **E**volution
BS	**B**ase **S**tation
SS	**S**ubscriber **S**tation
PC	**P**ersonal **C**omputer
HeWiMuCS	**He**terogeneous **Wi**reless-**Mu**lti-**C**arrier **C**ommunication **S**ystem
SINR	**S**ignal-to-**I**nterference-plus-**N**oise **R**atio
RSRP	**R**eference **S**ignal **R**eceived **P**ower
RSRQ	**R**eference **S**ignal **R**eceived **Q**uality
OLSR	**O**ptimized **L**ink **S**tate **R**outing
ETX	**E**xpected **T**ransmission count
PLR	**P**acket **L**oss **R**ates
NAT	**N**etwork **A**ddress **T**ranslation
FSL	**F**ree **S**pace **L**oss
UAP	**U**ser **A**ccess **P**oint
P2P	**P**oint-**to**-**P**oint
MCS	**M**odulation and **C**oding **S**chema
CQI	**C**hannel **Q**uality **I**ndicator
NS-3	**N**etwork **S**imulator-**3**
HWMP	**H**ybrid **W**ireless **M**esh **P**rotocol
RB	**R**esource **B**lock
TDD	**T**ime **D**ivision **D**uplex
FDD	**F**requency **D**ivision **D**uplex
TBS	**T**rasnsport **B**lock **S**ize

Chapter 1

Introduction

Communication technologies in modern day do unbelievable things. Not only a person can contact any other person in any corner of the world, but also can enter into a new world of all fancy things with a flip on the phone. Modern day communication technologies make the other side of globe not miles away anymore but at the user's fingertips. Social networks brings news all across the world to computer screen and mobile without any intermediaries with technological advancements. All the developments happening all across the world can be accessed from the small device with no delay. New ways of communication are being invented and improved on daily basis and reach of these advancements are being reflected in our everyday life like never before.

Advancements in technology have been happening at a very rapid pace. Every new communication technologies are characterized by certain factors which determines if a new technology is good enough or not from the users' perspective. For any end user, a good modern communication system is characterized by parameters like its ability to provide high data rate, good coverage distance, seamless connection, low latency, low power usage and cost. Though additional requirements like support for fast mobile units, unaffected by extreme environment are specific to certain requirement, having those as a part of general requirements are even better.

Terrestrial mobile telephone systems started with analog radio signal transmission in 1981 and is named as 1G. This is followed by the introduction of digital radio signal and are placed under the 2G standard. Global System for Mobile communications (GSM) is a typical example of 2G technology and technologies like General Packet Radio

Service (GPRS) and Enhanced Data rates for GSM Evolution (EDGE) are treated as 2.5G and 2.75G respectively. With advancements in 3G technologies like Universal Mobile Telecommunication System (UMTS) and CDMA2000, there has been tremendous progress both in technologies and number of end users. Lately the focus has turned on technologies like Worldwide Interoperability for Microwave Access (WiMAX) and Long Term Evolution (LTE), which are normally classified under the later part of 3G. LTE advanced and WiMAX 802.16m, which are advanced version of LTE and WiMAX respectively, came into prominence later and has been dominating the terrestrial communication system until now.

Marine communication system is the system where communication take place between ships or with the shore either directly with the shore stations or indirectly by means of intermediate ships using certain connecting technologies or by satellites. The marine end user can access normal terrestrial service if the they are near to the coast. But for a long range marine communication, there is a need for extending the new technologies or combinations of new technologies to marine communication like its terrestrial counterpart.

1.1 Motivation

Communication systems for terrestrial applications have always been receiving the lion share of attention and all the technological advancements till date. All the recent developments in terms of wireless standards and technologies have been to provide even better services to the already well advanced terrestrial communications services. On the contrary, not much solutions are offered for providing high speed Internet services for maritime communication. A good communication system is required not only for terrestrial part but also for the marine part as we live in a world where high-speed Internet everywhere has become a necessity. It is unfair to treat millions of people around the world who are travelling in sea via ships and ferries, by not providing them with a good and cost effective Internet connection. We also can not forget the fact that 80% of the world trade occurs through sea. Besides, activities like weather ships, fish farming, oil exploration, maritime transportation, and other similar activities across the sea also need access to modern day Internet service.

A long distance, high data rate, reliable and a cost effective communication for maritime users are also required along with its terrestrial counterparts. Distance is one of the core feature that has to be taken into account. One of the evident sign of a maritime user is that the user will be far away from the shore for days or months or may be even for some years. It would be unimaginable for us to think of getting disconnected from Internet and other services for a few minutes or hours, let alone think of the days or months for a maritime user.

Cost of the service is another important parameter to be considered. Services, which could potentially provide long distance communication, are way too expensive for normal maritime customers to afford. Data rate and reliability are the other decisive parameters for the Internet service. We live in the time of an exponentially increasing data rate and a low data rate service is something that is of no use in the present time. A slight delay in video streaming cause heavy discomfort for the costumers and we no more live in an environment where customers would wait for buffering while video streaming. Thus, providing a high data rate and reliable service is an indispensable part of maritime communication as well.

Although there are only a few studies attempting to give the mentioned connection services, there are none to point out with most of the features being satisfied. Most of the previously proposed solutions for the maritime communication fail in one or more of the requirement of modern day services. They have high trade-off between the core parameters such that providing a good service for end users does not look like a good option. For a reliable long distance communication with moderate data rate, the cost of service subscription will be high. The case would not be different if tried to improve other parameter combinations.

An efficient IP routing algorithm is as important as a new topology with various technology combinations. The new topology gives the outline of the connection where as the IP routing algorithm is the one to select the best possible route for the signal path. For every communication system, there will be multiple option for the signal path and the one which suit best should be selected for the signal flow. This is an essential and indispensable component to be taken into account as the core parameters of our concern will be affected by routing path to be selected.

Hence, the motivation behind the topic selection is to come up with a maritime communication system with an efficient IP routing algorithm providing a reliable, long distance, high data rate, and a cost effective Internet service to marine end users.

1.2 Long Distance Communication

Advancement in technologies provide the modern world with multiple options for long distance communication. Until the first phase of 2G, telecommunication system mainly focused on the voice communication with no data component involved. But data part came into the network architecture in later part of 2G technologies like GPRS and EDGE. GPRS and EDGE has an additional packet switching component in the network architecture for data part, along with the circuit switching component for voice. Though these early technologies provides "always on" Internet access, the quality of service, data rate, and coverage distance are poor compared to the modern day requirements.

Later came 3G technologies like W-CDMA, CDMA2000, UMTS etc., and were derived from 2G technologies. A typical UMTS technology provide data rates around 150 Kbps for rural area, 385 Kbps for urban outdoor, and urban indoor with 2048 Kbps. These technologies are not quite enough and later got replaced with High Speed Packet Access (HSPA) technology having improved features like adaptive modulation and coding, enhanced air interface, and fast scheduling. Although it was providing good data rate and are compatible with previous technologies, other newly arrived technologies like WiMAX and LTE were outperforming them in all aspects. This was followed by WiMAX, which is an OFDMA based, data-centric and an all-IP technology best suited for delivering 4G mobile services. WiMAX is based on the IEEE 802.16 standard family and provide high data rate, advanced QoS, high throughput and low latency. Despite all these good sides of WiMAX, it is still a high cost and big power consumption technology and are not to be widely used in future.

1.2.1 Introduction to LTE

There are many technologies in the market that are capable of providing long distance communication service. LTE is one of the prominent one, which has been in use since the later part of 3G era. LTE is actually a trademark registered under European Telecommunications Standards Institute (ETSI) for wireless communication technology. Third Generation Partnership Project (3GPP) [1] was the telecommunication body which started this as a project in 2004. There are different versions of LTE and its advanced version (LTE-A) is being used in 4G standards. LTE in unlicensed spectrum (LTE-U) is another version of LTE that could be used. We all know that UMTS [2] is evolved from GSM [3]. LTE is in turn evolved from UMTS.

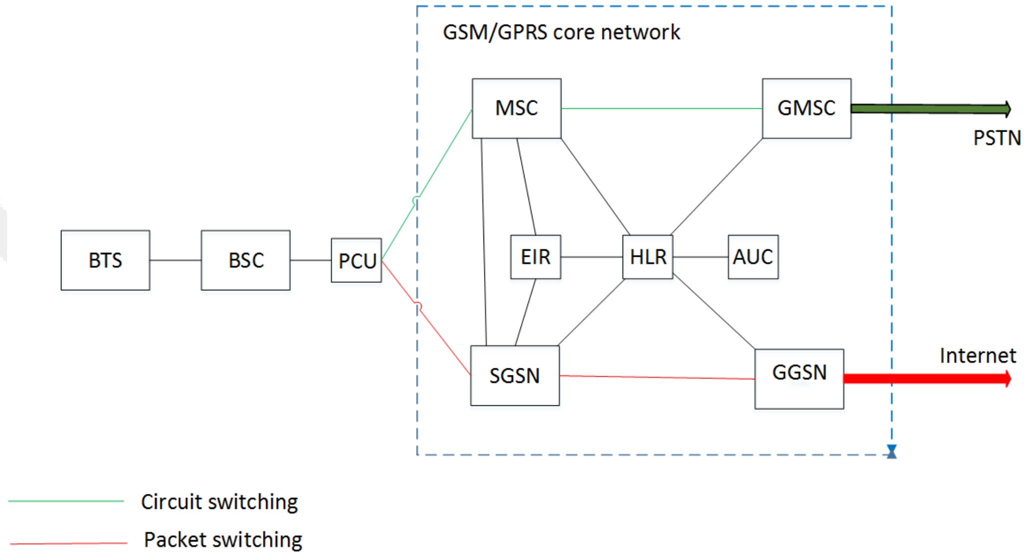

FIGURE 1.1: GSM GPRS network architecture

The architecture of a GPRS system, which is an enhanced version of GSM, is shown in Figure 1.1. In this model, voice and data is sent through different path where as the basic GSM model has only voice part without the data service. Voice part is sent to the Mobile Switching Center (MSC) like the standard GSM, and the data is sent to a node, Serving GPRS Support Node (SGSN) by means of the Packet Control Units (PCU). Hence, it use both circuit switching and packet switching techniques where circuit switching is used for the voice and packet switching for the data part.

The network architecture of LTE is designed to be completely IP-based such that data packets between any network nodes can be controlled through the IP address of the respective interfaces. The backhaul connection to the radio base stations also being IP based makes complete end-to-end packet control based on some specific IP routing algorithm. This is a great simplification compared to other earlier technologies. Most of the previous technologies were based on E1/T1, frame relay links, and Asynchronous Transfer Mode (ATM).

1.2.2 Network Architecture

The LTE high-level network architecture [4] involves 3 components and are shown in Figure 1.2.

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

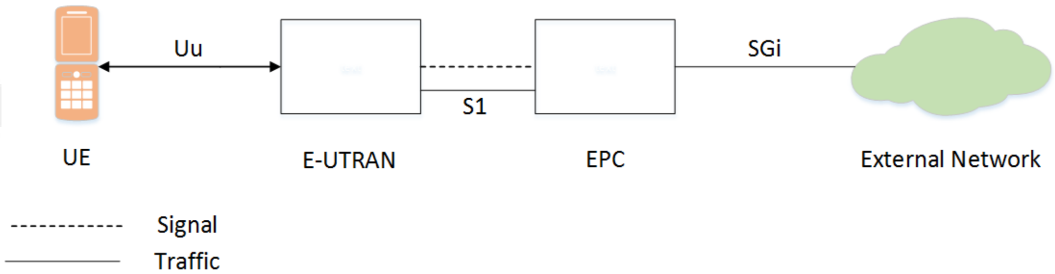

FIGURE 1.2: High level LTE network architecture

UE is the end-user equipment like mobile phones, laptops, tablets etc., which are in need of a network service to access data and voice line. Like previous technologies, it also has an subscriber identity module but known as Universal Integrated Circuit Card (UICC). The E-UTRAN [5] is the radio access network (RAN) part of the LTE system and its architecture is shown in Figure 1.3. E-UTRAN is that component of LTE that handles all the radio communication between EPC and UE. E-UTRAN is an evolved component from previous technologies. However, unlike its predecessors, E-UTRAN has only one component and is known as Evolved Node B (eNB). Generally the eNB use analogue and digital signal processing (DSP) functions of the LTE air interface to send and receive signals to all the UEs. It also performs low-level operation like sending signalling messages to UEs. Handover commands are a typical signalling messages sent by eNBs. Each eNB use S1 interface to make connection with EPC, X2 interface to connect with other eNBs, and Uu interface for connecting with UEs.

EPC is the core network of LTE where its various components are shown in Figure 1.4. Packet data network GateWay (PGW) is that component of EPC [6] [7] that communicate with outside world. In fact it act as the gateway for connections to any network outside the LTE via SGi interface. Serving GateWay (SGW) is that component of EPC,

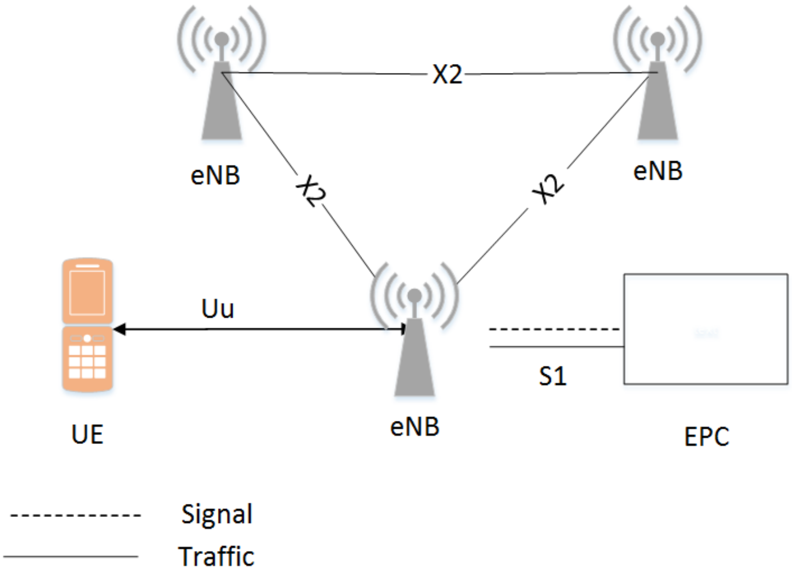

FIGURE 1.3: Architecture of E-UTRAN

which act as a router between the eNB and the PGW. Its main functionality is to forward data between the eNB and the PGW. There are other components of EPC like Home Subscriber Server (HSS) and mobility management entity (MME), and they are used for performing operations on signalling messages. The various other interfaces used in EPC for connecting various units of EPC are also shown in Figure 1.4.

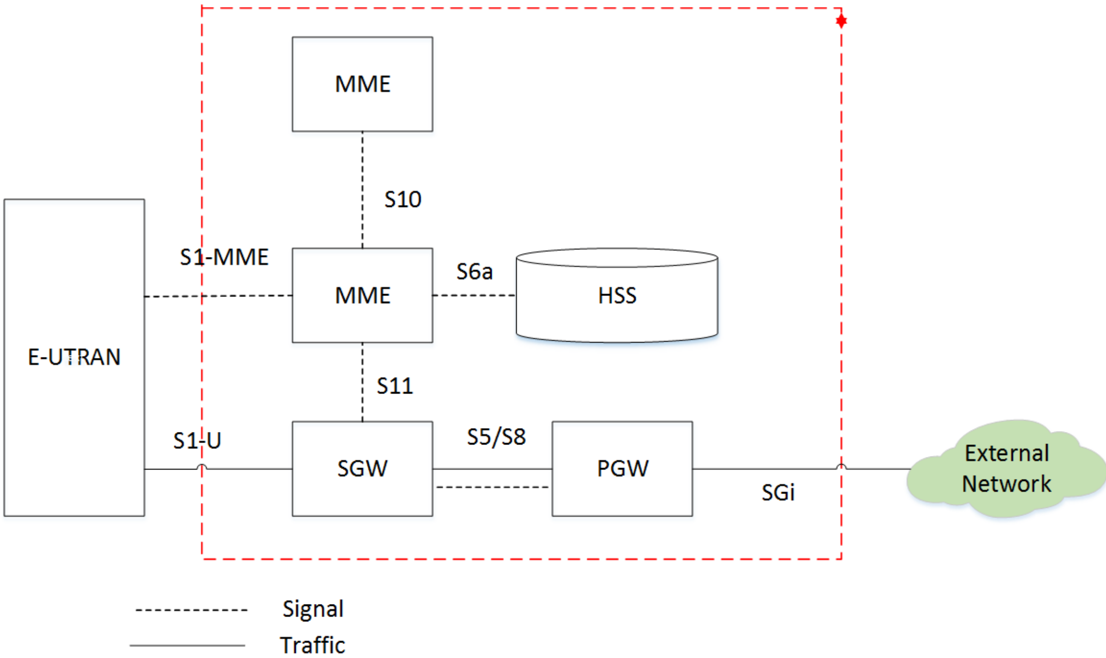

FIGURE 1.4: Architecture of EPC

Since LTE is completely IP based, any UE can be connected to service by routing directly using the IP address of the external service through PGW. The case would be simple if the LTE system has just one eNB but a typical terrestrial LTE system will have multiple eNB. In the case of multiple eNB, IP routing has to be done in such a way that serving eNB has the best signal strength at the geographical location. Physically a process called hand over happens when the signal strength from a near by eNB exceeds the signal strength from the serving eNB by a certain threshold value. In the network side, UE will be connected to service via new eNB. Hence, network routing happens based on the signal strength and similar approach can be used for marine communication for the fixed eNBs in the coastal part. For the moving eNBs in the outer sea, we have to come up with a different approach.

1.2.3 Why LTE?

High downlink and uplink data rates, and low latency in radio access network make it a good choice for our proposed sea communication topology [8]. LTE can have a peak data rate of 300 Mbps for downlink and a peak data rate of 75 Mbps for uplink. Generally LTE can be made to operate on bandwidths like 1.4 MHz, 3 MHz, 5 MHz, 10 MHz, 15 MHz and 20 MHz. The data rate can be further improved on selecting the highest bandwidth of 20 MHz. It need only a few hundred milliseconds for connection and also quick entering and exiting power states makes the latency [9] even better. Lower operating cost of LTE and support for fast moving mobile units make it an ideal choice for all topologies targeting mobile units, where initial and maintenance cost are also a concern. Good coverage distance between eNB and UE makes it an even better technology for our model.

LTE system provides a good coverage between eNB and the UE terminal. The coverage can be further increased to greater extent if a network is created with multiple clusters, with an LTE system placed around each cluster. This would result in a topology where each cluster could be connected to its adjacent clusters, by connecting their respective LTE systems. Also, utilizing a standard system like LTE reduces the overall cost compared to other proprietary technologies. LTE's support for legacy systems like 2G and 3G technologies, makes integration of user equipment of other technologies easy and cost effective. Utilizing the advantages of LTE systems and applying an effective routing mechanism can potentially provide modern day services like high data rates, low latency, good coverage with economical touch to marine consumers as well.

LTE is an all IP technology such that data packets between any network nodes can be controlled through the IP address of the respective interfaces. The backhaul connection from the Internet source to the base stations also being IP based makes complete end-to-end packet control based on some specific IP routing algorithm. This technology, along with an efficient IP routing algorithm based on key parameters, could potentially solve most of the problems in long distance sea communication, which remains largely untouched till now.

1.2.4 Wireless Mesh Networking

LTE can provide the long distance communication among the ships, but we also need another mechanism to provide service within each ship. This can be achieved using wireless mesh networking (WMN) [10]. Hence a long distance communication can be achieved in a sea communication scenario combining both LTE and Wi-Fi mesh networking. Here within in each LTE based cluster, mesh networking could be used to provide connection to individual costumers.

WMN is also a form of wireless ad-hoc network without any central infrastructure. It consists of participating nodes which are end-users and one of the other participating node will be the mesh interface of LTE part. The end-user can be a laptop, cell phone, and other wireless devices. In a mesh network, a participating node forms connection with all the surrounding nodes with which it can form connection. In the similar fashion, every node in the mesh network do the same process and final path is selected by the routing algorithm.

A typical mesh network is shown in Figure 1.5. Here Nodes 1-5 can directly connect with Internet source. But nodes 6 and 7 can not form a direct connection with the Internet source as they are far away from the Internet. Therefore, nodes 6 and 7 can access Internet services via nodes which have access to the Internet services by hoping the signal across the working nodes. In this fashion, mesh networking provides a reliable connection. WMN also has the feature of self forming and self healing [10]. Self forming is the feature in which the newly added node in the mesh network not only access the

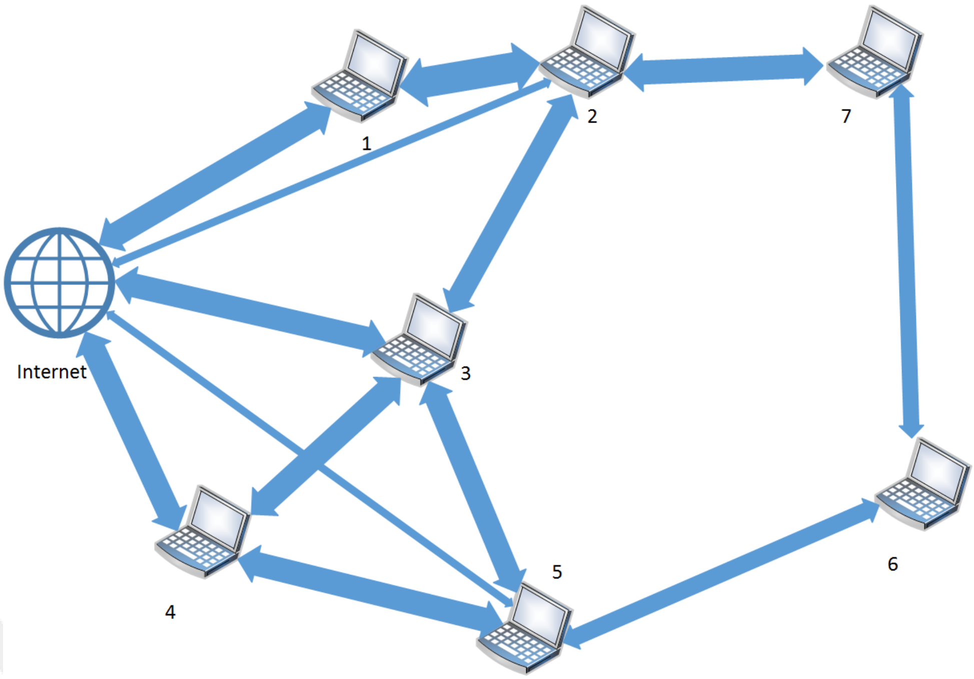

FIGURE 1.5: Mesh Networking

network for itself but also by acting as the access node for others. The term self healing means that if any already serving node is taken out of mesh network, some other node will take up its role of playing as intermediate node.

1.2.5 Conclusion

A heterogeneous topology using LTE and WMN can provide all the benefits of LTE like high data rate, good coverage distance, and a cost effective sea communication system. The mesh networking within every LTE system can be used to provide the Internet service to all the customers within the ship. Since the LTE is completely IP based, an effective IP routing algorithm on the heterogeneous topology can further enhance the coverage distance, maintain the data rate with minimum drop, and improve the reliability. The newly proposed topology should support the concept of interconnection between LTEs, which can improve the reliability. The algorithm should be based on parameters that can maximize data throughput, coverage distance, and reliability. The proposed study which includes a new topology and an IP routing algorithm can provide reliable, cost effective, and high speed long distance communication. All these good sides can be beneficial to all the section of the society who used to give a second thought before taking marine routes for these reasons.

1.3 Thesis Outline

The rest of the thesis is structured as follows: Chapter 2 presents literature review with historical background and the state of the art. In Chapter 3, the system design is presented with the design of the topology and the components used in the architecture along with the algorithm implementation. Chapter 4 details out the path loss model, simulation parameters, NS-3 simulation tool, and performance evaluation processes. Finally, Chapter 5 gives the conclusion and points out the future work.

Chapter 2

Literature Review

2.1 Introduction

This chapter introduces related previous studies and other current working models relevant to sea communication systems. It includes the working models that are being used for providing network services as of now and also the theoretical study models that are just proposed and may not be implemented yet. Though it is impossible to list out all the studies on this area, studies that are relevant and those, which inspired us for picking this topic of study and pursue with passion, have been briefly discussed. A brief discussion on routing algorithms and propagation models are also made in the last part of the chapter.

2.2 Current State of the Art

2.2.1 Satellite Systems

As mentioned in the previous chapter, there are no practical systems on the market providing a reliable, cost effective, and seamless high data rate Internet application for maritime users. Satellite communication systems have been the major player in providing the Internet services to ships and other marine platforms. A typical satellite providing Internet service is shown in Figure 2.1. There are quite a lot of satellite systems providing network connections to marine consumers. International Maritime Satellite

(InMarSat) [11] is one typical system providing long range wireless maritime communication from shore. InMarSat is a British satellite telecommunication company providing global mobile services via satellites. Very Small Aperture Terminal (VSAT) [12] and Iridium satellites [13] are other satellite systems providing similar services. VSAT satellite is a kind of satellites used for marine communication services with VSAT antennas. SeaTel is one of the first company to produce a stable VSAT satellite and put in service. Iridium satellite system is a system of 66 satellites used all the world for voice and data communication. It is owned by an an American company, Iridium Satellite LLC.

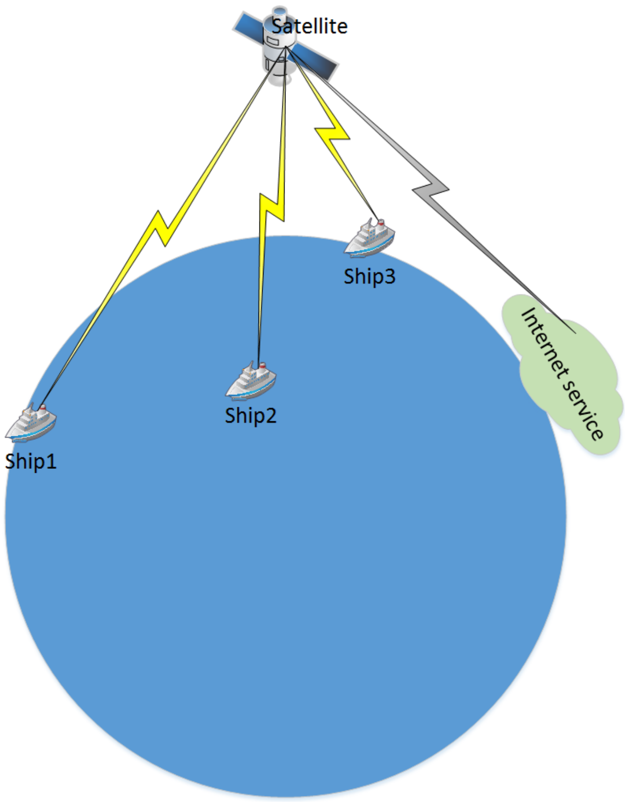

Figure 2.1: Basic satellite communication system

Though satellite communication provides global coverage, it is difficult for average maritime users to afford this service. This happens due to high communication fees, maintenance, and replacement costs [14]. Most of the satellites are controlled by one particular country and this can make it further expensive and also the access can be affected in case of diplomatic spat or any other bilateral issues. Also the data rates provided by the satellite communication systems are not very high and are often affected by the connection break. Furthermore, the latency induced by satellite communication further keep away the common users from subscribing it [15].

2.2.2 Long Range Wi-Fi Networks

This simple method of Over-the-Sea Communication is a hierarchical point-to-multi-point (P2MP) back-haul using long range (LR) Wi-Fi network [16]. The basic topology consists of a multi-hop network consisting of a base station and various clusters of ships and boats as shown in Figure 2.2. Each cluster can have a collection of ships/boats and the network will be made of similar multiple clusters. All these clusters are connected to the base station which is located at the shore, over an LR Wi-Fi back-haul link. One of the ship/boat in the cluster, which is nearest to the base station at the shore, access the signal from the base station. The acquired signal is then shared with other mobile elements in the cluster via mesh networking. The ship that initiate connection in a cluster is the one with best signal strength from the base station. If any cluster not having any connection and is in the proximity of another cluster with a stable connection, then signal sharing via mesh networking happens. The sharing is done between an element of cluster having signal and an element of another cluster without signal. This process continues and all the clusters in the network will get network connection if the mobile units are positioned in such a way that they are within the distance of making connection via mesh networking.

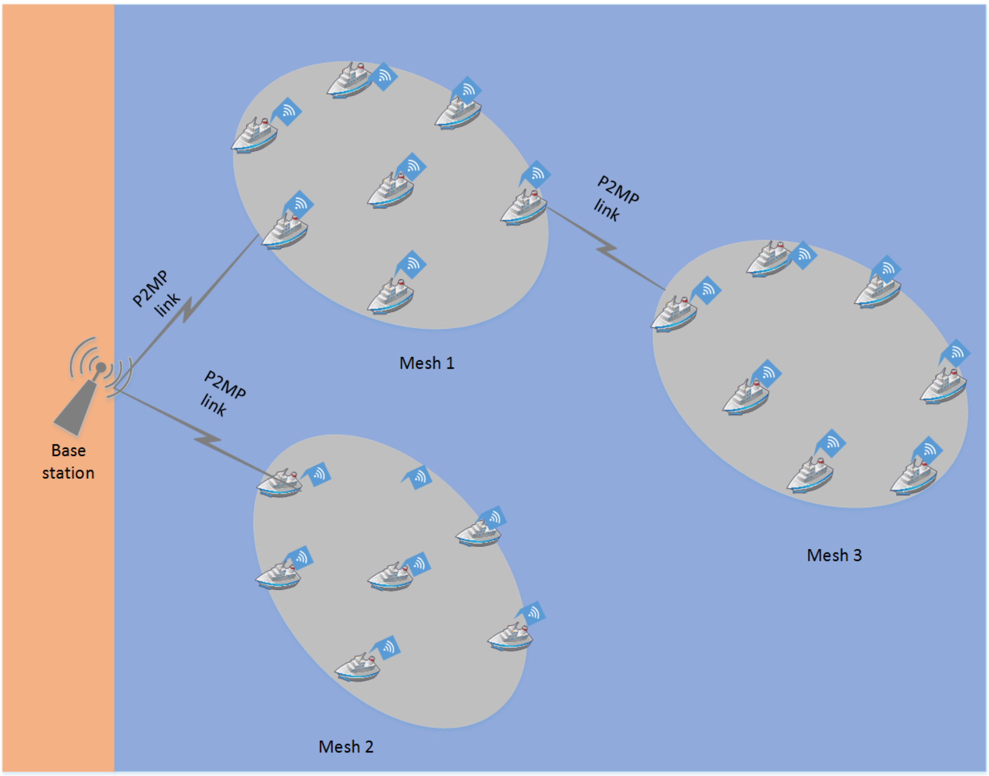

FIGURE 2.2: LR Wi-Fi Network

LR Wi-Fi is based on IEEE 802.11n [17] standard. In 802.11n, the time-division multiple access (TDMA) protocol with modified round trip time (RTT) and acknowledgement (ACK) times are used unlike other IEEE 802.11 series. In other standards the traditional carrier sense multiple access (CSMA) and small MAC-level AckTimeOUt values are used. IEEE 802.11n provides a bandwidth of 300 Mbps per access point whereas its previous standards were providing just 54 Mbps. The coverage distance is also much better for this wireless standard compared to its previous versions.

Though the discussed method of LR Wi-Fi network is cost effective, the best performance is limited to around 18 km. The data rate achieved is also not as high as the new terrestrial technologies like LTE-Advanced, Mobile WiMAX (IEEE 802.16e), and time division-long term evolution (TD-LTE). Besides, Wi-Fi performance with motion also limits the usage to mainly stationary and very slowly moving utilities.

2.2.3 WiMAX in Mesh Mode

Another method for sea communication is employing WiMAX 802.16d/e [18] technology in mesh mode [15], [19]. Network topology involves a base station (BS) in the shore and subscriber stations (SS)[1] in the open sea. SSs in the case of a sea communication system will be individual ships and boats in the open sea making their travel. If the individual SS are within the coverage distance of the terrestrial BS, then BS will directly communicate with individual SSs. If an SS is not in the range of the BS to make direct connection, then signal access happens through mesh via another SS with signal connection. The SS, which act as the signal provider of mesh networking for other SSs that can not make direct connection with BS, has either access to the BS directly or indirectly via mesh networking of other SSs.

Even though WiMAX systems provide long range coverage distance between BS and SSs, distance between individual SSs can not be higher. This is attributed to the reason that the mesh networking use Wi-Fi and Wi-Fi is widely known to have coverage distance limitation. Unlike its LTE counterpart, WiMAX also does not have a better technology for power management for its uplink and is not expected to be a widely used technology going forward [20], [21]. Since WiMAX is not as widespread as LTE, the typical costs are also expected to be higher.

[1]SS in WiMAX is the end user like UE of LTE system

2.2.4 2G/3G Services

Rather than going for advanced methods, there are simple methods for enabling sea communication services as well. One of the typical methods employed for coastal communication is to use 2G/3G services. This is a simple technique where the only requirement is a 2G/3G dongle from a service provider and a personal computer (PC). The user just need to plug the dongle into the PC and get the network service. The cost of these technologies can be much lower compared to other previous methods, as its requirements are very basic and no additional infrastructure is needed to setup for the service. Since almost all the service provider has plug-in service, there are quite a wide range of choices on the services to be selected as well.

Though the requirement is simple, the data rate that can be achieved will be very low and can not go beyond a certain limit. Restriction in setting up base stations in the sea, limits the hope of extending the coverage to outer sea. This makes the maximum distance between the terrestrial point and the user in the ships not to be more than 15 km. No GSM service provider setup base station around coastal area thinking the case of sea communication. It is that just base stations in coastal area will be used by marine users who are operating near to the cost. Applying a mesh networking also does not serve the purpose, as the connection is already weak and will not look good with this additional burden. The 2G/3G services are either completely circuit switched or just partly packet switched network. Hence, a full IP routing is not possible and also need to go back to inefficient routing techniques of technologies with partly or completely circuit switching.

2.2.5 Heterogeneous Wireless Multi-Carrier Communication System

A Heterogeneous Wireless Multi-Carrier Communication System (HeWiMuCS) was also proposed as in Figure 2.3, which involves satellite, WiMAX, Wi-Fi, GSM/3G cellular, and CDMA450 systems. The heterogeneous system try to combine the advantages of all the individual technologies used and thus improve the overall performance. HeWiMuCS provides global coverage by means of satellite system and the use of other technologies available in the package if they come in their respective coverage. Other technologies also back up satellite communication, if the connectivity via satellite communication connection is getting feeble.

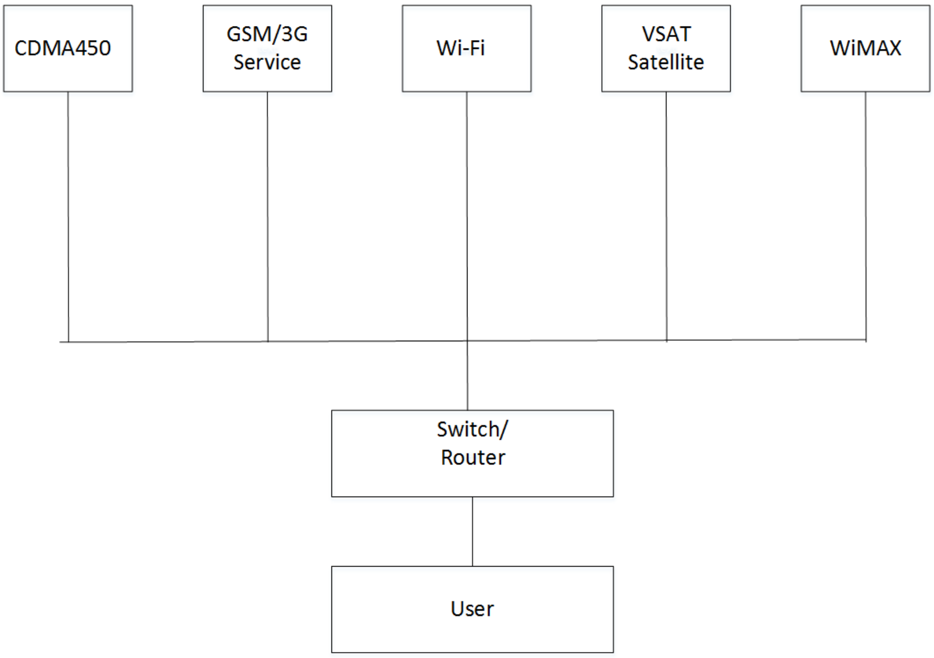

FIGURE 2.3: Block diagram representation of HeWiMuCS system.

However, the initial cost and maintenance cost of the satellite communication again becomes the obstruction. This along with the need for one set of antenna for satellite communication and another terrestrial antenna for the rest, make this a high-cost topology. The option of having another satellite system like Inmarsat as a backup along with main SatCom system will increase the cost further. Including additional technologies along with an already expensive satellite communication, will further raise the expense of the service.

2.3 Routing Algorithms

In a heterogeneous network containing LTE and WMN networks, a new routing protocol is required to support communication among the heterogeneous nodes of LTE and WMN [22]. A routing algorithm is needed to make the heterogeneous network to act like a single network. The data packets are to be routed through various wireless technologies, based on various metrics of corresponding networks or based on some common metric.

LTE network from the user plane is shown in Figure 2.4. From the IP perspective, it can be seen that UE of an LTE can be directly connected to PGW and hence to any other external network including Internet service provider with direct IP routing. Hence all UEs which are connected to PGW via a single eNB, can be routed to the destination using simple routing as all UE acts as different nodes of the single network. But in practical case, there will be multiple eNBs spread across the network for providing

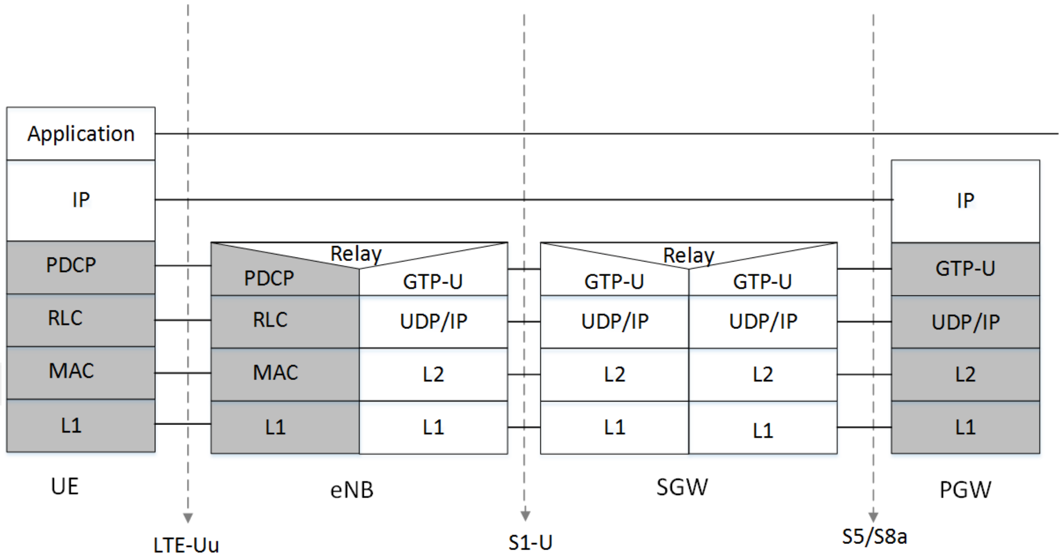

Figure 2.4: LTE user plane.

maximum coverage. A UE under a particular eNB, will stay under the signal of that particular eNB as long as the signal connection remains good. When the UE moves towards the coverage boarder of the serving eNB, signal strength checks are normally performed. This is to make sure that signal strength from the serving eNB has not gone below certain threshold value. When the signal strength from the serving eNB goes below the threshold, then signal strength comparison from serving eNB and neighbouring eNBs will be performed. If the signal strength of the serving eNB is less compared to a neighbouring eNB by certain amount, then hand over of the connection from serving eNB to the neighbouring eNB is done. On the network side, this occurs by changing the routing from previously serving eNB to newly serving eNB. Hence signal strength in terms of the metric signal-to-interference-plus-noise ratio (SINR) is used for determining the routing. Other LTE metrics like Reference Signal Received Power (RSRP) and Reference Signal Received Quality (RSRQ) can also be used for the same.

For WMN, there are 2 kinds of routing protocols. The first type is the reactive routing protocols where flooding of network is done with route requests on demand. The selected route is made active only for nodes with traffic activity. A typical example of reactive routing protocol for WMN is ad hoc on-demand distance vector protocol [23] and dynamic source routing [24]. Some delay is caused by the reactive routing as the route is setup only when there is a need for data to be sent. The second routing protocol for WMN is table-driven routing protocols or proactive protocols. This set of protocol periodically update the routing table of every nodes in the network. Optimized link state routing (OLSR) is a typical example for this kind of WMN routing protocol. Although periodic update minimize the delay factor in the transmission, sharing information on routing table with all other nodes in the network creates more overhead.

Hybrid routing protocols are another kind of routing protocol for WMN and are obtained by combining both reactive and proactive routing. This kind of routing protocol normally employ proactive routing for the nearby nodes and reactive routing for distant nodes and achieve a balanced overhead and delay. Other metrics used for routing protocols in mesh networks are normally hop count, delay time, expected transmission count (ETX), packet loss rates (PLR) etc.

The end user will be in the WMN part of the network and core part of our communication network will be in the LTE. Hence, some kind of bridging need to be done at the interface of LTE-WMN and this is achieved by a network technique called Network Address Translation (NAT)[25]. NAT need to be applied to LTE-WMN interface, so that a heterogeneous network containing LTE and WMN can work as a single network.

2.4 Propagation Loss Models

For any wireless communication channel, signal power fall off with distance. A propagation model is needed to predict the path loss a signal will encounter in a sea communication channel. Even though there are not many propagation models available for sea communication systems, general propagation model like free space loss (FSL) model is the simplest option. It is a line of sight propagation model in which there is an apparent line of sight path between the transmitter and the receiver. The receiver power, P_r is given by Equation (2.1)

$$P_r = P_t G_t G_r (\lambda / 4\pi d)^2 \tag{2.1}$$

where P_t represents the transmitted power, G_r and G_t represents the reception and the transmission gain respectively, and d is the distance. FSL model has a short coverage capacity and is valid only up to a maximum transmission coverage of 18.5 km.

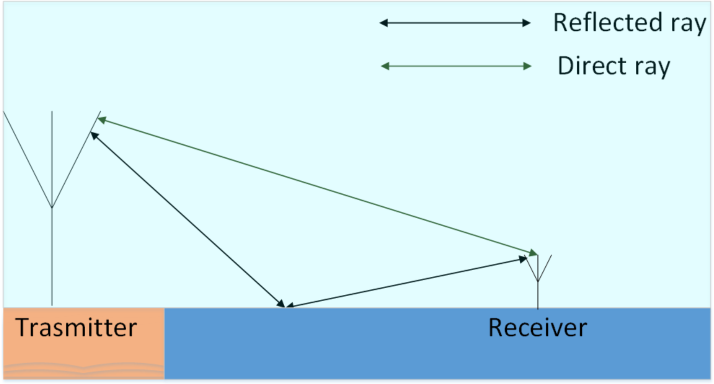

FIGURE 2.5: 2-Ray Propagation Model.

The other possible option we have is a 2-ray propagation model. 2-ray model consider a reflected ray along with the direct ray component in the path loss model and is shown in Figure 2.6. The 2-ray path loss model is mathematically represented as in Equation (2.2).

$$L_{2-ray}(dB) = -10\log_{10}\{(\lambda/4\pi d)^2[2sin(2\pi h_t h_r/\lambda d)]^2\} \tag{2.2}$$

Due to the distance-dependent refractivity conditions and rough sea surfaces, the estimated path loss is very site-dependent and may not be applicable for other sites. It also does not take into consideration the effects of evaporation duct over the sea surface. A modified version of 2-ray model was proposed in [26] with a better performance than its predecessor. It give better results for channel parameters such as path loss, RMS delay spread, received power, and power delay profile. But this technique can be used only for short ranges less than 2 km over the sea surface and also have limitation for higher frequency transmission.

For higher frequencies, evaporation duct over the sea is an important factor and can influence substantially in increasing the receiver signal strength. This happens as a result of refraction of the transmitted signal over the evaporation duct and this makes signal coverage possible even beyond the horizon [27]. Hence conventional propagation models can not be implemented and we need to implement a model that also takes the effects of evaporation duct into the account. These factors are considered in 3-ray propagation model proposed in the paper [28].

The model include the direct ray, the ray reflected from the water surface, and also the refracted ray. The ray is refracted by means of the evaporation duct due to the gradual

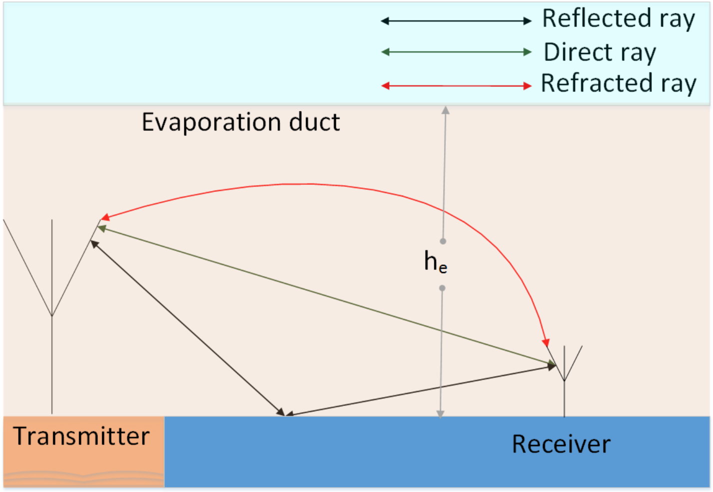

FIGURE 2.6: 3-Ray Propagation Model.

variation of the refractive index of the air. A simplified 3-ray model is shown in Figure 2.6 and path loss for the model is given in Equation (2.3) as:

$$L_{3-ray}(dB) = -10\log_{10}\{(\lambda/4\pi d)^2[2(1+\delta)]^2\} \tag{2.3}$$

with $\delta = 2\sin(2\pi h_t h_r/\lambda d) sin(2\pi(h_e - h_t)(h_e - h_r)/\lambda d)$. Here h_e is the effective duct height for refraction.

2.5 Conclusion

In this chapter, introduction to the previous works and the services presently available for marine consumers, were briefly presented. Most of the previous works we have reviewed were short of providing either one or more of the services like high data rate, good coverage distance, reliability, and cost effective services. This resulted in giving thoughts on this area and we realized a need for new topology using technologies like LTE and a different routing algorithm. Various routing protocols and path loss models for sea communication are also discussed and compared to select the best possible model for our design. The chapters to come will discuss the newly introduced heterogeneous topology and routing algorithm. It also involves various observations from simulations and comparing how performances are improved in various parameters.

Chapter 3

System Design And Algorithm Implementation

3.1 Introduction

In this chapter, system design and the algorithm implementation will be explained in detail. System design part will be explained in sub-sections, which detail out the topology of the proposed heterogeneous network, basic network designs involved, and the overall topology implementations. Algorithm section details with algorithm implementation and the parameters involved in the process.

3.2 System Design

3.2.1 Proposed Model

The proposed topology model is presented in Figure 3.1. It involves a base station server, a PGW, a terrestrial eNB, and ships/clusters. The former 3 components are located on the shore and the latter is in the open sea. Each cluster/ship in the open sea part comprises of a User Access Point (UAP), a marine PGW, a marine eNB, and multiple end-users. The server in the shore provides the application service and connects to the PGW part of the EPC. This connection happens by means of a point-to-point (P2P) connection. PGW is the gateway of EPC part of LTE system to any outside components.

The external component to which PGW forms a gateway can be an Internet service, a standalone network or even multiple collection of any other networks. In our case, the PGW is connected to the server, which is the source of application service. PGW is connected to the terrestrial eNB in the other direction. The terrestrial eNB is the one that broadcasts the signal to the clusters in the open sea.

UAP of the cluster, which comfortably accesses the signal from the terrestrial eNB can use the signal by sharing the network with end-users. The end-users in the cluster could be smart phones, tablets, laptops, etc., and are interconnected and they share the connection from cluster access node via mesh networking. The same signal is also passed to a marine PGW, present in the same cluster/ship via P2P communication. The marine eNB is connected to the marine PGW and it shares the network with other clusters/ships if they come in its coverage area. In short, every cluster/ship shares the network with their respective end-users via mesh networking, and with other clusters via LTE system. With these, we are able to establish a long-distance sea communication architecture.

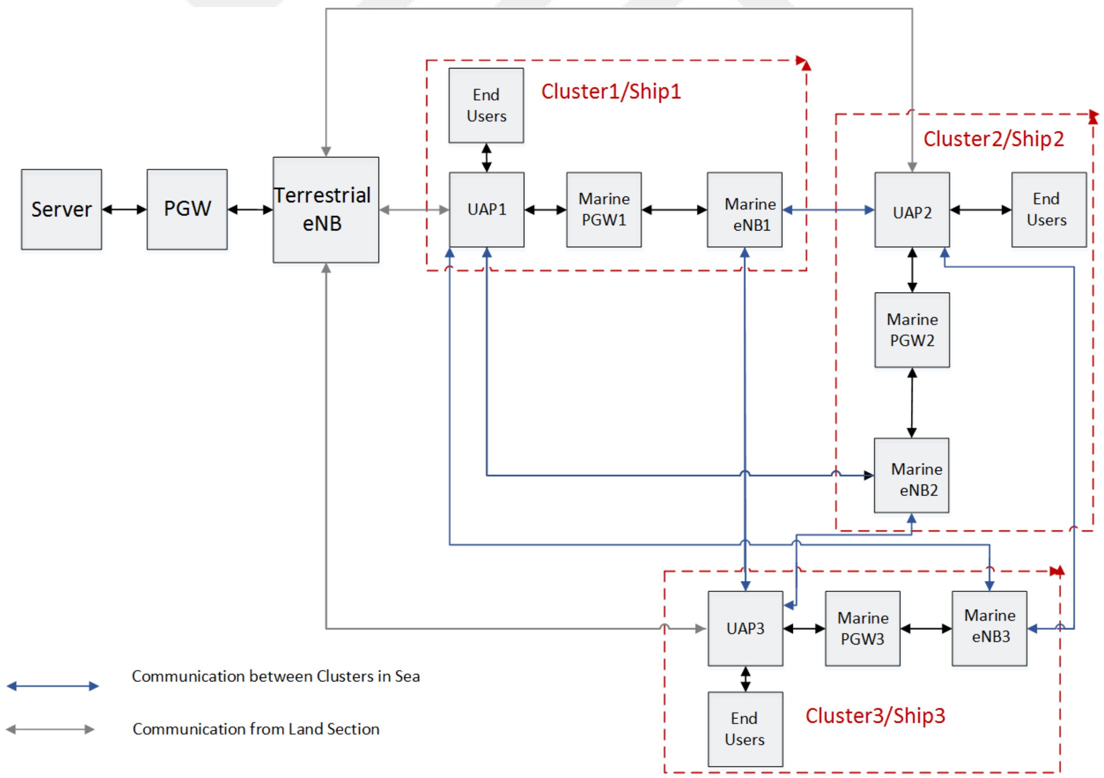

FIGURE 3.1: Topology of the proposed network

The terrestrial eNB is connected to all the UAPs of the involved clusters (as its end-users) to form a full LTE-like system centered around terrestrial eNB. Each cluster/ship has its own marine PGW, marine eNB, and UAPs of other clusters as their end-users. It is also important to note that UAP of a cluster/ship is not a part of its own end-users. Hence, every cluster acts as a sub-LTE system with UAPs of all other clusters except its own, as its end-users. In this topology, any cluster can communicate with terrestrial eNB, either directly or indirectly through other interconnection clusters.

3.2.2 Basic LTE-Mesh Interface Design Model

A basic design model of LTE-Mesh interface system is shown in Figure 3.2. As shown in the figure, it involves a server, an LTE system with UAP (as its end-user), and a user device[1]. The server is the source of application which will be accessed by the end devices. The UAP[2] of the system is provided with an LTE-Uu interface and a Wi-Fi interface. This enable the UAP to interact with both LTE and Wi-Fi systems.

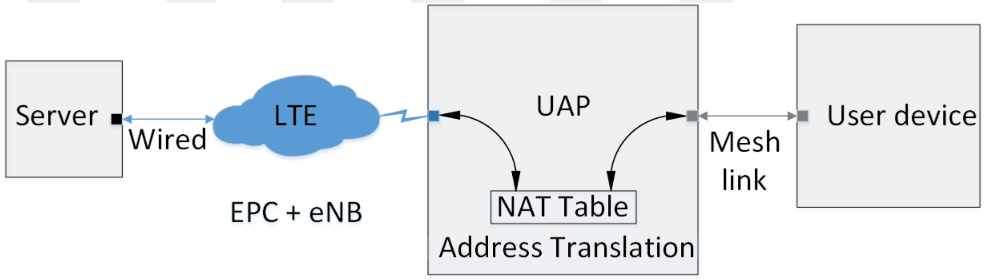

FIGURE 3.2: Basic LTE-Mesh network system

A NAT is applied at the UAP node of the system. NAT is the method in which one IP address space is re-mapped to another at one of the routing device. The routing device in this case is UAP. NAT is applied in our proposed system to make sure that all the packets coming from user device are routed to the server via LTE core. This is attributed to the reason that the IP address space of the user device and the UAP are different. Therefore, the IP address of the user device in the mesh network is translated to the IP address level of LTE UAP. Like any NAT operation, here also a NAT table which maps the original address and the translated address is created. The same NAT table will be referred to retrieve the original IP address when a packet arrives back from the LTE network to the Wi-Fi mesh system.

[1]user devices are the end users that are connected to the UAP via mesh. They are different from UE as they are not directly connected to eNB

[2]UAP is equivalent to UE component of LTE but made to work as access point for the end users.

NAT has the port number limitations and also the devices outside NAT can not initiate connections. The proposed topology contains end users that always initiate the connection and lies inside the NAT. Hence connection initiation problem is not encountered. Port number limitation's effect was reduced by using dynamic NAT where each port could be reused.

3.2.3 Multi-LTE Interface Design

A LTE-LTE interface design model is shown in Figure 3.3. In this situation, there are 2 LTE systems connected to each other and each of the LTE system has their user devices connected via their own mesh network.

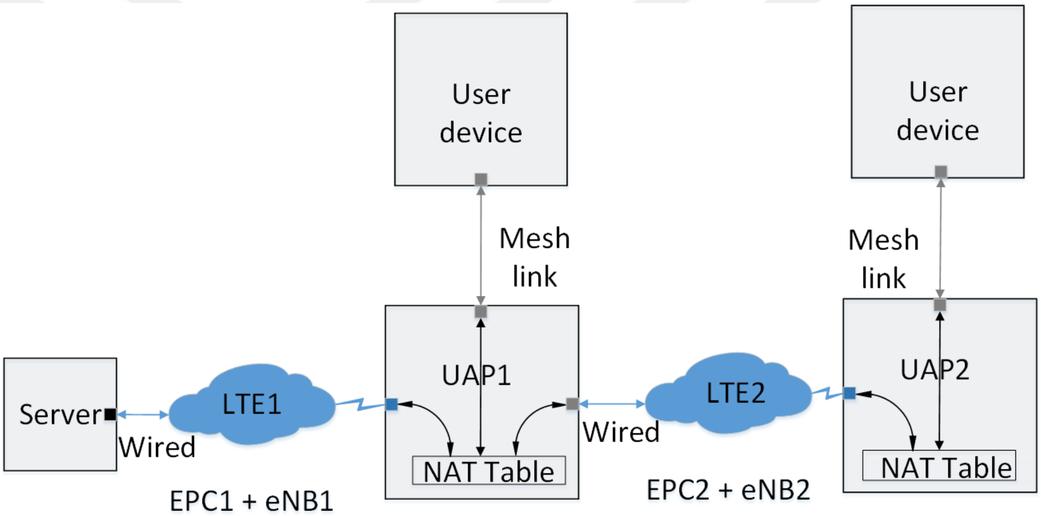

FIGURE 3.3: Basic LTE-LTE System with Mesh network

As explained in the previous subsection, NAT operation has to be performed on the interfaces to make the connections complete. For the first LTE system, 2 NAT operation has to be performed at UAP1. The first NAT operation on UAP1 is for IP packets coming from the LTE2. The second NAT on UAP1 is for IP packets coming from the user device connected to UAP1 via mesh. The second LTE system, LTE2 also need a NAT at the UAP2 for making sure that the IP packets from the user device connected to UAP2 via mesh, reach the destination server.

For a system with multiple LTE sub-systems, there will be multiple NAT operations happening at each UAP of the corresponding LTE system. Hence, for a system with a base station LTE and N clusters, N NAT operations occur at its corresponding UAP. Among the N NAT operations, N-1 are for other clusters and one is for its own mesh network. As a result a connection between two clusters can be achieved without any loss of packets in the interfaces.

3.2.4 Overall Architecture

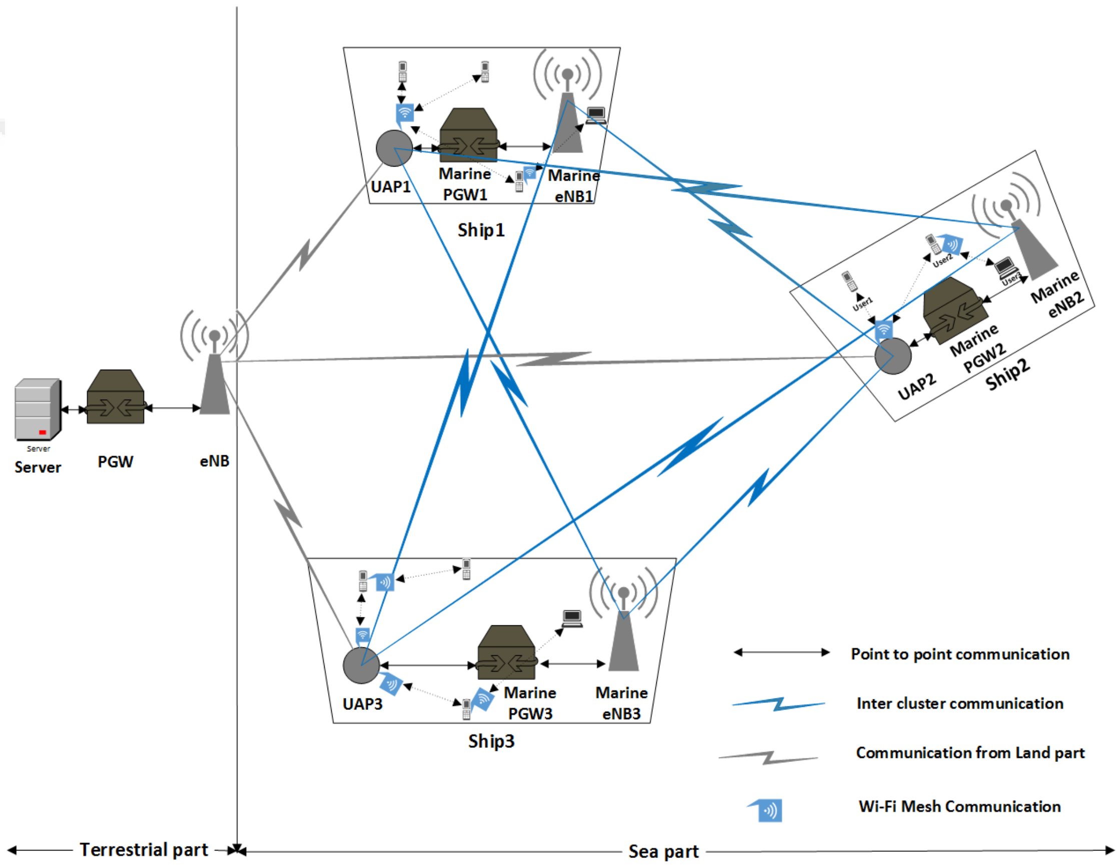

FIGURE 3.4: Architecture of the proposed network

The proposed overall heterogeneous architecture is presented in Figure 3.4 and is a different representation of Figure 3.1 in open sea. The represented overall architecture consists of a base station LTE and 3 clusters/ships in the open sea. UAP of each cluster will have 3 NAT operations. 2 of those connections are for IP packets from other 2 clusters and one is for its own end-users connecting through mesh network.

3.3 Algorithm

Having a topology alone will not serve the purpose of having a good connection as there is also a need for an algorithm that finds the best possible path. Any cluster in the sea can have multiple paths to reach the server in the shore and the best path must be selected by the algorithm. This section of the chapter introduce a new IP routing algorithm for the new heterogeneous topology proposed in the Section 3.2.

3.3.1 Design Parameters

The proposed algorithm is based on 2 parameters namely SINR [29] and delay. The routing mechanism is primarily focused on the best SINR followed by minimum delay while selecting the best possible path. Like mentioned above, SINR is the primary parameter of our concern and it will be used in our algorithm in the form a newly introduced parameter, RValue.

RValue is the parameter, which will be used in the design and implementation of the algorithm. The parameter is derived directly from SINR of any UAP from its corresponding eNB. The RValue parameter will be used in place of SINR for comparison process as it simplifies the operation and hence the process of finding the best path. Every path will have a RValue with respect to its source eNB and destination UAP. A separate pre-simulation is run to obtain the RValue parameter and the one time simulation is performed prior to the main algorithm part. Further parameter details and the way they are obtained or calculated are explained in Section 4.1.

3.3.2 MCS - RValue Mapping

The modulation with which the signal from eNB will be sent to UAP is decided by the modulation and coding scheme (MCS) index. The selection of MCS is based on the channel quality indicator (CQI) [30], which is obtained based on the SINR of the signal at UAP from the eNB. Hence, a relationship between MCS index and threshold SINR [dB] is obtained and is shown in Figure 3.5. The figure indicates the threshold SINR for obtaining various levels of MCS index and gives all the information regarding the threshold SINR required for various MCS indices.

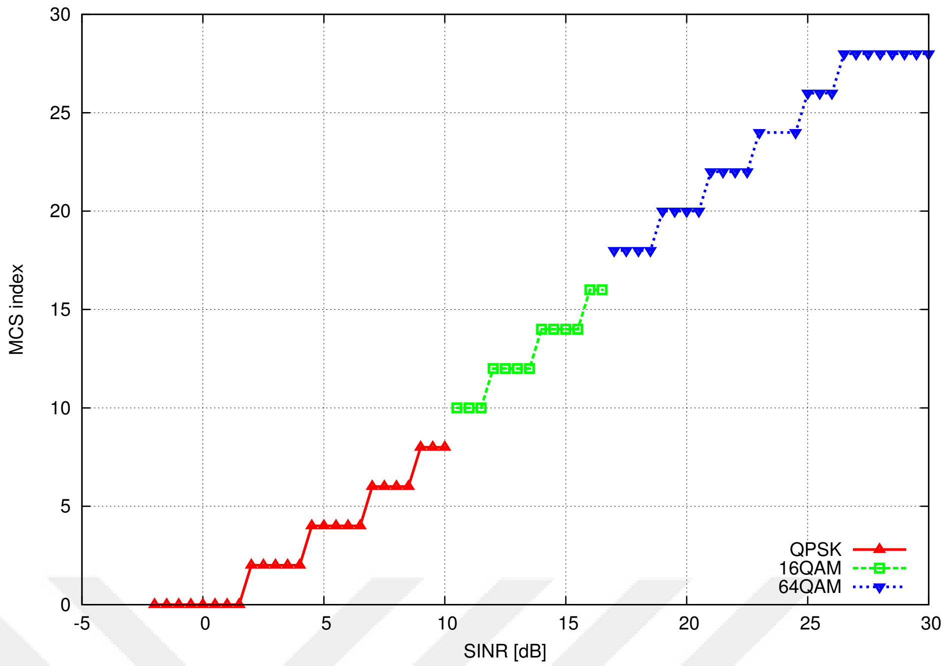

FIGURE 3.5: MCS Index vs SINR[dB]

Since RValue is directly related to SINR, a direct relationship can be brought about between MCS index and RValue threshold. The entire relationship between MCS index, modulation scheme, code rate, SINR threshold, and RValue threshold are shown in Table 3.1 [31], [32]. From the table, RValue threshold required for various MCS indices can

TABLE 3.1: MCS, SINR Threshold and RValue Mapping

MCS	**Modulation**	**Code Rate**	**SINR Threshold(dB)**	**RValue Threshold**
MCS1	QPSK	1/12	-0.04	PV1=0.00041
MCS2	QPSK	1/9	1.93	PV2=0.20416
MCS3	QPSK	1/6	4.44	PV3=0.40333
MCS4	QPSK	1/3	6.81	PV4=0.54625
MCS5	QPSK	1/2	8.94	PV5=0.64458
MCS6	QPSK	3/5	10.69	PV6=0.70958
MCS7	16-QAM	1/3	12.20	PV7=0.75583
MCS8	16-QAM	1/2	14.08	PV8=0.80333
MCS9	16-QAM	3/5	16.07	PV9=0.84375
MCS10	64-QAM	1/3	17.18	PV10=0.8625
MCS11	64-QAM	1/2	19.19	PV11=0.89083
MCS12	64-QAM	3/5	21.07	PV12=0.91208
MCS13	64-QAM	3/4	23.10	PV13=0.93041
MCS14	64-QAM	5/6	24.95	PV14=0.94375
MCS15	64-QAM	11/12	26.34	PV15=0.95208

be obtained and can be used wherever is required in the algorithm. $PV1$ represents the minimum RValue required to have a connection between eNB and UAP and any link with RValue above $PV1$ will be able to make connection. Any link with RValue above PVn and less than $PVn + 1$ will have a modulation and coding scheme corresponding to the PVn. For example, if a link has RValue of 0.85, which is more than $PV9$ and less than $PV10$, then the modulation and coding scheme corresponding to $PV9$ will be selected. Hence, the signal will be transmitted with 16-QAM modulation [33] and code rate of 3/5. Any link with RValue more than $PV15$ will have the best modulation scheme and the code rate and hence the maximum throughput.

3.3.3 Algorithm Design

Let us analyze a network with multipath from point A to point B as shown in Figure 3.6. Best overall signal path between point A to B need to be selected from multiple possible paths where each of the path have multiple links. Every link involved in the path play a key role in determining the overall throughput that the selected path can provide. If all the links involved in a path are good and just one of the link is in bad quality, then the overall connection of the path becomes poor. Strictly speaking, the overall throughput of a path is determined by the weakest link in the path. No matter how strong other links are, the weakest link mainly determines the final throughput. Therefore, the selected path should be the one where the weakest link of the selected path is having the best connection compared to the weakest link of other possible path. Since all our link quality are expressed in RValue, the selected path should be the one with RValue of the weakest link larger than the RValue of weakest link of other competing paths. When the RValue of the weakest link in two or more paths are the same, then the path with minimum interconnection links will be selected. The addition of an extra interconnection cluster in the path adds extra P2P delay within cluster, which will also be added up to the overall delay.

From Figure 3.6, there are 3 paths possible for a connection between point A and point B. The minimum RValues corresponding to upper path is 0.5, to middle path is 0.3, and to lower path is 0.6. Hence, the lower path represents the best path as it has the path with maximum of the minimum RValue link.

Thus, there are 3 operations to be performed in a multi-path scenario and they are:

1. Identify the link having minimum RValue in every possible path.

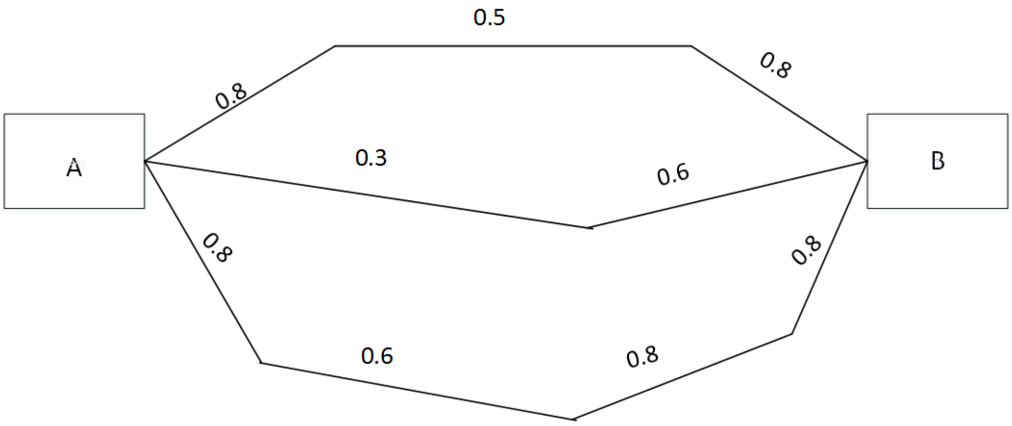

Figure 3.6: MultiPath Diagram

2. Find the link with maximum RValue among the links found in above step.

3. Select the path whose minimum RValue link is the one selected in the above step

Mathematically the path selection part of the algorithm in a multi-path scenario can be represented as in Equation (3.1).

$$\max_i \min \left(PV_{i,1} \cup PV_{i,2} \cup ... \cup PV_{i,j}\right) \quad \forall\, i, j \ \in \mathbb{Z}_{+}^{*} \tag{3.1}$$

The objective function in Equation (3.1) can be further simplified as given in Equation (3.2) and Equation (3.3).

$$\Phi_i = \min(PV_{i,1} \cup PV_{i,2} \cup ... \cup PV_{i,j}) \quad \forall\, i, j \ \in \mathbb{Z}_{+}^{*} \tag{3.2}$$

$$\text{maximize}(\Phi_i) \quad \forall\, i \ \in \mathbb{Z}_{+}^{*} \tag{3.3}$$

where $PV_{i,j}$ represents RValue of the j^{th} link in the i^{th} path.

Equation (3.2) represents the operation performed for finding the links with minimum RValue parameter for all the involved paths.

Equation (3.3) finds the path with maximum RValue for its weakest link compared to the weakest link of other paths.

3.3.4 Algorithm

Algorithmic steps for a basic system with a base station eNB and 2 clusters/ships are given in Algorithm. The algorithm represents the functionality of the second cluster/ship in the network for establishing connection with base station eNB.

Algorithm 1 Finding the best path based on PValues.

Require: $PV^{20}, PV^{10}, PV^{21} \geq PV1$

  for $x = 15; x \geq 1; x--$ **do**

    if $PV^{20} \geq PVx$ **then**

      return Direct connection with the base station eNB.

    else if $((PV^{21} \geq PVx) \wedge (PV^{10} \geq PVx))$ **then**

      return Interconnection via eNB1.

    end if

  end for

FIGURE 3.7: Algorithm

Variable x used in the algorithm steps is the index for RValue for representing different levels as shown in Table 3.1. PV^{ij} represents the RValue of i^{th} cluster's UAP from the eNB of j^{th} cluster. Hence PV^{20}, PV^{21}, and PV^{10} represent RValue of UAP2 of cluster 2 from the base station eNB, the RValue of UAP2 of cluster 2 from eNB1 of cluster 1, and the RValue of UAP1 of cluster 1 from base station eNB, respectively.

There are 2 ways of establishing connection for the second cluster and they are direct and indirect connections. Direct connection is the connection second cluster makes directly with the base station eNB. Indirect connection is the connection cluster 2 makes with base station eNB indirectly by making an intersection connection through cluster 1. Direct connection is the preferred connection mode if the second cluster has the top position RValue (i.e. $RValue >= PV15$) parameter from base station eNB. This make sure that the selected connection gets best modulation scheme and hence the maximum throughput. Indirect connection via intermediate cluster 1 will be preferred if the RValue of cluster 2 to cluster 1 and the RValue of cluster 1 to base station eNB are individually the top position value (i.e. $RValue >= PV15$) but the RValue of the cluster 2 to the base station eNB directly is less than $PV15$. In this case, indirect connection will provide a better modulation scheme than direct connection and hence better throughput will result in. It is also important to note that priority is given to direct connection and this reduces the extra time delay due to intermediate clusters. This minimizes the overall time delay.

In the next round of the loop, check be will done to see if RValue of the involved link is matching with that of $PV14$ level. In the similar fashion all the RValue levels given in Table 3.1 will be checked. This will go until the RValue goes below $PV1$, beyond which a reliable connection is not possible. Therefore, if the RValues of considering clusters are greater than $PV1$, then connection will be established with modulation scheme corresponding to its RValue in one of the loop iteration.

The steps explained in Algorithm consider all of the possible combinations of scenarios that could arise for a 2 cluster network. However, for a multi-cluster network, the situation will be the same for all direct connection scenarios but not for the interconnection scenarios. For indirect connection scenarios, there would be multiple paths satisfying the condition. In those cases Eqs. (3.1)- (3.3) will be applied to get the best path. The path whose weakest link's RValue is greater than the RValue of weakest link of other possible paths will be selected. If there are more than one path with the same maximum RValue for its weakest link, then the path with minimum number of interconnection cluster will be selected. This is attributed to the fact that the presence of more interconnection clusters introduces more delay as every cluster has an extra P2P delay component as part of its architecture. The resulting path will be the best path with the best throughput and minimum latency.

3.4 Additional Performance Parameters

Apart from our core parameters like coverage distance, throughput, and reliability, network parameters like jitter, packet loss, and end-to-end delay are also needed to be evaluated for network performance. Jitter parameter is defined by the Equation (3.4) [34] and the mean value of this parameter for all the received packets will be taken in our evaluation table given in Table 4.2.

$$\text{Jitter} = (\text{T}_4 - \text{T}_3) - (\text{T}_2 - \text{T}_1) \tag{3.4}$$

where T_1, T_2 are the time at which 2 consecutive packets leave the source node, and T_3, T_4 are the time at which those packets arrive the target node.

The end-to-end delay is another network performance parameter and it can be defined as the time a packet takes to reach the destination from the source node [34] [35]. In our evaluation we use mean delay by taking the mean of the delays of all the packets received. The packet loss parameter is given in Equation (3.5) [34] and is defined as the packets which are lost while transmitting from source node to destination node in percentage.

$$\text{Packet Loss} = (P_{\text{sent}} - P_{\text{rec}}) * 100/P_{\text{sent}} \tag{3.5}$$

where P_{sent} and P_{rec} are the packets sent and received during the simulation.

The parameter Jain index, given in Equation (3.6) [36], is employed to see if any negative impact in the resource sharing in multi-user scenarios happens as part of the algorithm implementation.

$$F = \left(\sum_{i=1}^{N} T_i\right)^2 \Big/ \left(N \sum_{i=1}^{N} T_i^2\right) \tag{3.6}$$

where T_i is the throughput of i^{th} user.

3.5 Conclusion

A heterogeneous topology using LTE and Wi-Fi mesh network is developed and an IP routing algorithm is designed for the proposed topology. The LTE system provide connection among the clusters to provide long distance communication and within each cluster, mesh networking is employed to provide service to the end users. The algorithm which is designed for the proposed topology is to select the best path possible and is based on a new parameter. The algorithm select the best signal path from all the possible paths and also minimize the delay factor by making decision of direct or intermediate connection. The following chapter will detail out the simulations and the performance evaluation process. Performance evaluation section will also indicate how and to what extend the core parameters are improved with the proposed topology and algorithm.

Chapter 4

Simulations and Performance Evaluation

4.1 Introduction

This chapter deals with the simulations and performance evaluation process of various parameters concerning sea communication system and also other general network system for the proposed architecture given in the previous section. Simulations part starts with a description on the simulation tool that we use. This is followed by a quick review of the simulation parameters and the propagation model used in the simulation. The simulation part also contains a brief process of how our newly introduced parameter, RValue, is calculated. Performance evaluation part explains a couple of scenarios that will be considered and also shows how various parameters are improved with our topology and algorithm together.

4.2 Simulations

Previous chapter gave us the description on the proposed heterogeneous topology and algorithm design. Now we need to perform simulations and see the results. Before performing the simulations, a brief description is required on NS-3 simulator, simulation parameters, and the propagation model used.

4.2.1 NS-3

Network Simulator-3 (NS-3) is a discrete-event network simulator used for the topology design and algorithm implementation in our study [37]. NS-3 simulator is a free software, available to public under the GNU GPLv2 license for research, development, and other use. Prior to NS-3, there were previous versions like NS-1 and NS-2. However, the present day NS-3 has completely abandoned backward-compatibility with its previous versions and other versions are no more being used. NS-3.24 package is the version used for our simulations. NS-3 supports scripting capability in both C++ [38] and python. Mostly the code is written in C++, with binding available for python as well. NS-3 simulator is called a discrete-event network simulator as the simulator time advances in discrete jumps from event to event. These discrete events can be scheduled to occur at specific simulation time using C++ scheduling functions.

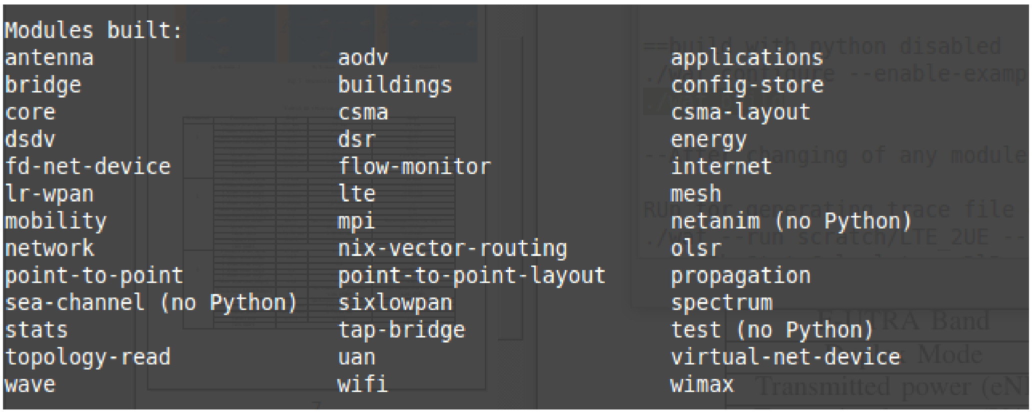

Figure 4.1: NS-3 Modules

There are a lot of built-in modules of communication system available in NS-3. All the available modules as a part of our simulation are shown in Figure 4.1. Besides other networking modules, we mainly used the modules of LTE, Wi-Fi, and Mesh for our NS-3 implementation [39] [40]. The default LTE module in NS-3 cannot be used directly for our proposed topology and therefore it needed to be modified with some additional member functions to support multi-LTE systems. Changes are mainly done for overriding the duplicate IP allocation when LTE is used more than once. Modification is also done to prevent cell ID allocation issue for multi-LTE systems. NAT module, which does not come along with NS-3 packages, was also separately coupled with rest of the packages. The mesh module used in the simulation uses Hybrid Wireless Mesh Protocol (HWMP) and Peer management protocol [41]. HWMP is the routing protocol defined as default for IEEE802.11s standard and the 802.11s standard draft also contain a peer management protocol in it. The latter is needed for HWMP in order to manage the peer links and this is similar to association mechanism as in IEEE802.11.

4.2.2 Simulation Parameters

The details of NS-3 simulation parameters are given in Table 4.1. The bandwidth given

Table 4.1: NS-3 Simulation Parameters Table

Parameters	**Values**
Bandwidth	5MHz
E-UTRA Band	Band 1 (2100MHz)
Duplex Mode	FDD
Transmitted power (eNB)	30 dBm
Transmitted power (UAP)	10 dBm
eNB height	5 m
UAP height	1 m
Noise figure (eNB)	9 dB
Noise figure (UAP)	5 dB
Noise PSD	-174 dBm/Hz
Height of Evaporation Duct	25 m

in the simulation parameter table is the LTE bandwidth, which is 5 MHz. This is performed by setting the UlBandwidth and the DlBandwidth parameter of LTE to 25. Here 25 indicates that the bandwidth is 25 resource block (RB) [42], which is equivalent to 5 MHz. Of the various available frequency bands, 2100 MHz carrier frequency band is used for the LTE. Though LTE can be made to run on frequency division duplex (FDD) and time division duplex (TDD), the simulation is set to run on FDD mode [43]. FDD mode use different uplink and downlink frequencies whereas TDD uses same frequency in both uplink and downlink but in different time slots [43]. The evaporation duct [44] parameter will be explained in Section 4.2.3.

The RValue parameter, which is the decision making parameter in the algorithm design is found in a pre-simulation run before the main simulations, using an LTE system with one eNB and one UE. Initially, the UE is positioned exactly on the eNB and it is gradually moved away from eNB in a regular pattern until the UE loses connection with the eNB. The SINR measurements are taken at every required positions and the SINR obtained from the simulation is normalized to $[0-1]$ range. The SINR value corresponding to the position, which is exactly on eNB, is given 1 and the point at which no more connection can be established between eNB and UE is given as 0. SINR at any point in between starting point and no connection point will be able to make connection with eNB and also will have a RValue between 0 and 1. The SINR measured and its corresponding RValue obtained will be stored in a separate file and will be used in our main simulation. Whenever a SINR value of an UAP is taken, a function with SINR as a parameter will be called and it will return the corresponding RValue.

4.2.3 Propagation Model

Various possible propagation models for sea communication system are discussed in Section 2.4. From the discussion it was concluded that a 3-ray propagation model proposed in the paper [28] is to used in the simulation part. Selection is primarily due to the inclusion of the evaporation duct factor in the path loss of the signal and it is very important to be considered for high frequency and long distance communication over sea. Presence of evaporation duct increases the signal coverage even beyond the horizon and this happens by the refraction effect of transmitted signal over the evaporation duct [27].

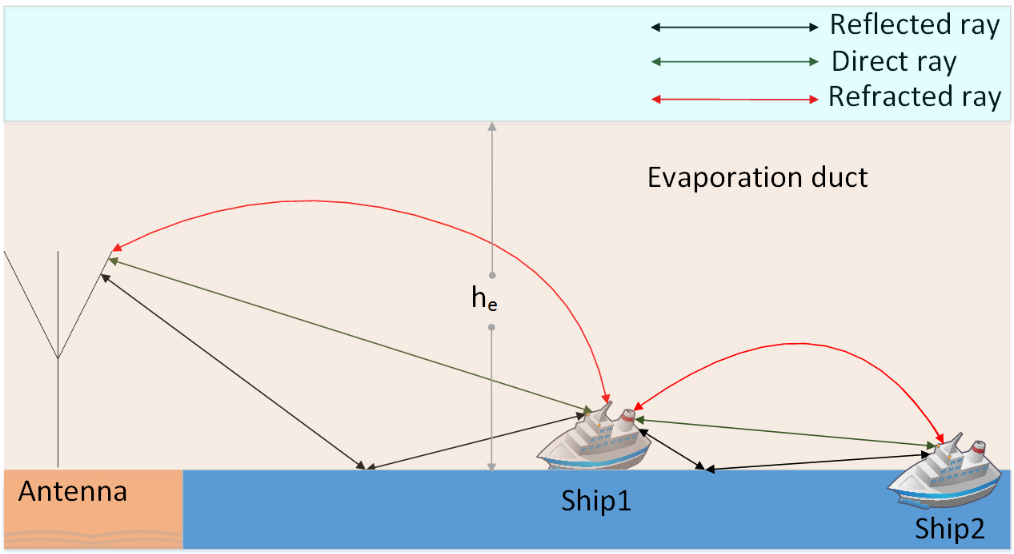

FIGURE 4.2: 3-Ray Sea Channel Model

Thus, in this study, a 3-ray model propagation model proposed in the paper [28] is used in the simulation part. The model include the direct ray, the ray reflected from the water surface, and also the ray refracted by means of the evaporation duct. A simplified 3-ray model is shown in Figure 4.2 and path loss for the simulated model is given in Equation (2.3). The value of h_e normally comes in the range of 20 to 40 m. For our simulations 25 m is used as the effective duct height.

4.3 Performance Evaluation

Here we primarily deal with the evaluation of the results of the simulation. We analyze various scenarios with the proposed topology and algorithm applied and also evaluate the core parameters of the sea communication system like throughput and coverage distance. We also evaluate network related parameters like delay, jitter, and packet loss besides the LTE resource sharing fairness factor, Jain index. All those mentioned parameters for a couple of scenarios were evaluated and were compared with other scenarios and also with their theoretical evaluations. This section of performance evaluation also includes 3 scenario evaluations on how reliability improves with the increase in the number of the interconnection clusters in the network.

End-to-end data throughput is the rate at which data is sent between the destination cluster and the application server. End-to-end data throughput, T, is calculated in the simulation as

$$\mathrm{T[Mbps]} = \mathrm{Rx} * 8/(\mathrm{T}_{last\_Rx} - \mathrm{T}_{first\_Tx}) * 1024 * 1024, \quad (4.1)$$

where Rx is the number of bytes received during the simulation, $\mathrm{T}_{(last\_Rx)}$ is the time (in seconds) at which the last packet is received, and $\mathrm{T}_{(first\_Tx)}$ is the time (in seconds) at which first packet is transmitted. These measurements are taken by setting probes in both source and destination node using FlowMonitor [45] utility of NS-3.

3 different scenarios are provided in Figs. 4.3, 4.4, and 4.5. All those scenarios include 3 clusters in various possible positions and it include all possible scenarios that would be countered in the normal sea communication. Both clusters with direct connection and indirect connection via intermediate clusters are also included in those scenarios.

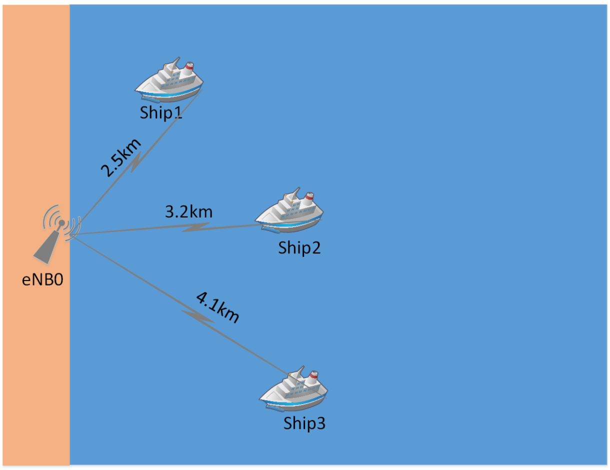

FIGURE 4.3: Scenario 1

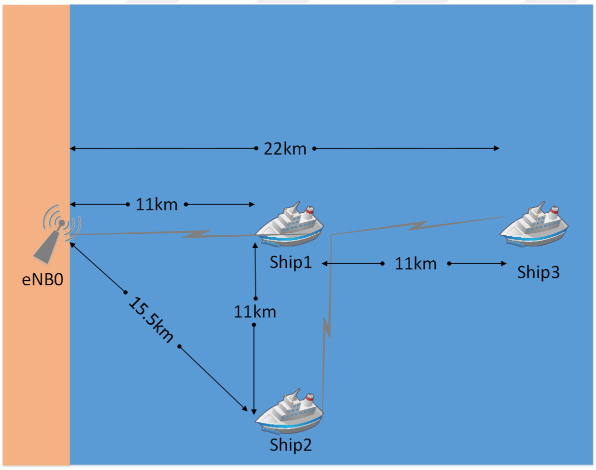

FIGURE 4.4: Scenario 2

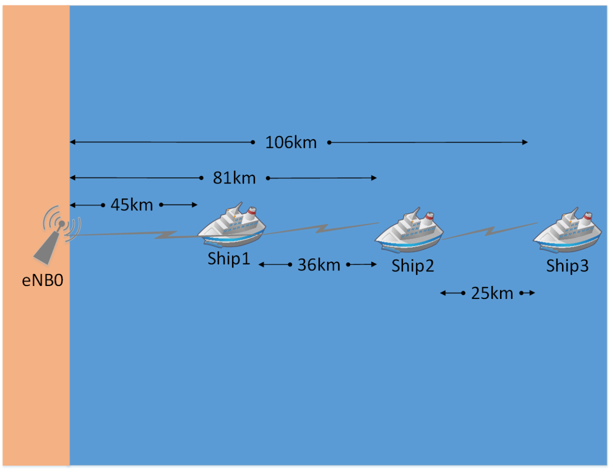

FIGURE 4.5: Scenario 3

In Scenario 1, all the 3 ships are in the range to have good direct connections. It is to be noted that none of the ships formed interconnections via other ships. This is because of the reason that overall throughput will be reduced as result of extra delay within the cluster if going for interconnections via clusters. The Ship1 is the one which is nearest to eNB0. Obviously it should be having the best RValue, which is above $PV15$, and it will go to a direct connection definitely. The Ship2 has RValue above $PV14$ from eNB0 and same range of RValue from Ship1 as well. Since interconnection via Ship1 will have extra delay factor added up, direct connection will be preferred here as well. The Ship3 has a RValue of above $PV13$ from eNB0. Hence, Ship3 also makes a direct connection with eNB0 rather than going for intermediate connection.

In the second scenario, Ship1 makes a direct connection with RValue above $PV8$ threshold of Table 3.1 and it will not attempt for any indirect connection. Ship2 can also make direct connection with base station eNB0 with RValue above $PV6$ and an indirect connection to base station eNB0 via Ship1 with RValue above $PV8$. Hence, Ship2 will go for intermediate connection via Ship1 and attain better throughput than by the direct connection. Ship3 also follows the operation as it can also either make a direct connection with base station eNB0 with RValue above PV4, or an indirect connection via Ship1 with RValue above PV8. As a result, Ship3 will make interconnection via Ship1 and attain a throughput for PV8 and it does not opt for the direct connection.

The third scenario considers the extreme end-situation where Ship2 and Ship3 can not make a direct connection with base station eNB0. Like shown in Figure 4.5, Ship1 makes direct connection with RValue of $PV3$. Since Ship2 has a RValue less than $PV1$ from eNB0, it can not make direct connection with eNB0. As a result, Ship2 is forced to make an indirect connection via Ship1. The RValue of connection between Ship2 to Ship1 is $PV3$ and the indirect connection from Ship2 to eNB0 via Ship1 will have a throughput of $PV2$ as the least of RValue decides the throughput. The case of Ship3 is the extreme one as it is far away from eNB0 and Ship1 that it can make connections only with Ship2 with RValue of $PV4$. Hence, the Ship3 will form an indirect connection with 2 interconnections with Ship2 and Ship1. The RValue of Ship1 to the base station eNB0 is above PV2, the RValue of Ship2 to Ship1 is above PV3, and the RValue of Ship3 to Ship2 is above PV4. However, the overall throughput for Ship3 of third scenario will be determined by the PV2 threshold as the overall throughput is decided by the lowest of RValue group.

Table 4.2: Observation Table

Scenario#	**Parameters**	**Ship1**	**Ship2**	**Ship3**
1	Distance from shore	2.5 km	3.2 km	4.1 km
	RValue from eNB0	0.95833	0.94666	0.93166
	Max. data rate[Mbps]	16.37	14.4	12.77
	Theoretical MDR[Mbps]	16.4	15.2	13.5
	Connection mode	Direct	Direct	Direct
	Mean delay	5.48882 ms	9.67598 ms	10.4387 ms
	Mean jitter	0.50805 ms	0.47383 ms	0.41143 ms
	Packet loss	0.32%	0.33%	0.35%
	Jain index	0.98		
2	Distance from shore	11 km	15.5 km	22 km
	RValue from eNB0	0.81666	0.74166	0.63333
	RValue from Ship1	-	0.81666	0.81666
	RValue from Ship2	0.81666	-	0.74166
	RValue from Ship3	0.81666	0.74166	-
	Max. data rate[Mbps]	6.08	6.03	6.03
	Theoretical MDR[Mbps]	6.4	4	2.57
	Connection mode	Direct	Interconnection via Ship1	Interconnection via Ship1
	Mean delay	27.2537 ms	49.9765 ms	49.9765 ms
	Mean jitter	0.54550 ms	0.63940 ms	0.63940
	Packet loss	0.31%	0.38%	0.38%
	Jain index	0.99		
3	Distance from shore	45 km	81 km	106 km
	RValue from eNB0	0.25	0	0
	RValue from Ship1	-	0.4	0
	RValue from Ship2	0.4	-	0.58333
	RValue from Ship3	0	0.58333	-
	Max. data rate[Mbps]	1.02	1.01	1.004
	Theoretical MDR[Mbps]	1.09	No connection possible with eNB0	No connection possible with eNB0
	Connection mode	Direct	Interconnection via Ship1	Interconnection via Ship2 & Ship1
	Mean delay	89.4393 ms	118.735 ms	162.214 ms
	Mean jitter	0.47016 ms	0.73144 ms	1.78862
	Packet loss	0.39%	0.39%	0.4%
	Jain index	0.99		

The observation table is shown in Table 4.2 captures all the required parameters of our simulations. It demonstrates how coverage distance and data rate is improved and to what extend with the use of proposed heterogeneous topology and the IP routing algorithm. The theoretical value of the data rate for individual ships in Table 4.2 is the data rate obtained from transport block size (TBS), which in turn is obtained by the (I_{TBS},N_{PRB}) combination entry of Table 7.1.7.2.1-1 from TS 36.213 [46]. I_{TBS} is the value derived from the MCS index, which is used in the algorithm design.

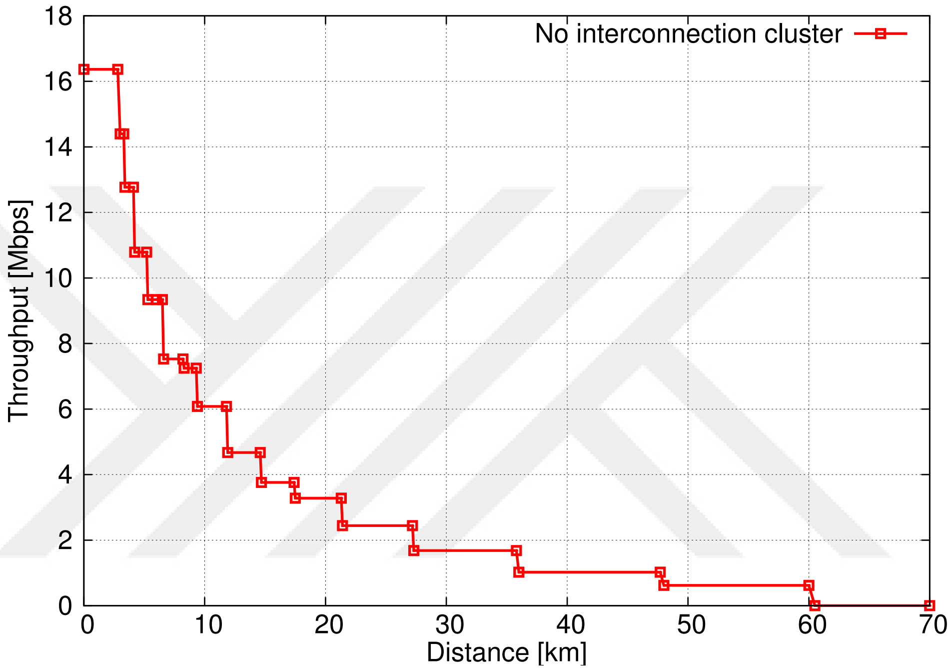

FIGURE 4.6: Throughput Vs Distance for direct connection

Reliability is another important factor which needs to be evaluated. It indicates how reliable our network is for providing a seamless connection to the end-users. Figure 4.6 illustrate the variation of the throughput with distance for a network with no interconnection cluster (i.e. direct connection). The graph indicates that the ship can be as far as 60 km without their connection being cut-off.

The second scenario shown in Figure 4.7 shows the variation of throughput against the distance for one cluster interconnection scenario. The graph also considers the position of the intermediate cluster, with intermediate cluster placed in different positions. The evaluation is performed with intermediate cluster positioned at 15 km, 30 km, and 60 km away from the base station eNB. The relationship diagram indicates that with one cluster at 60 km, a maximum distance of 120 km can be achieved as the coverage distance.

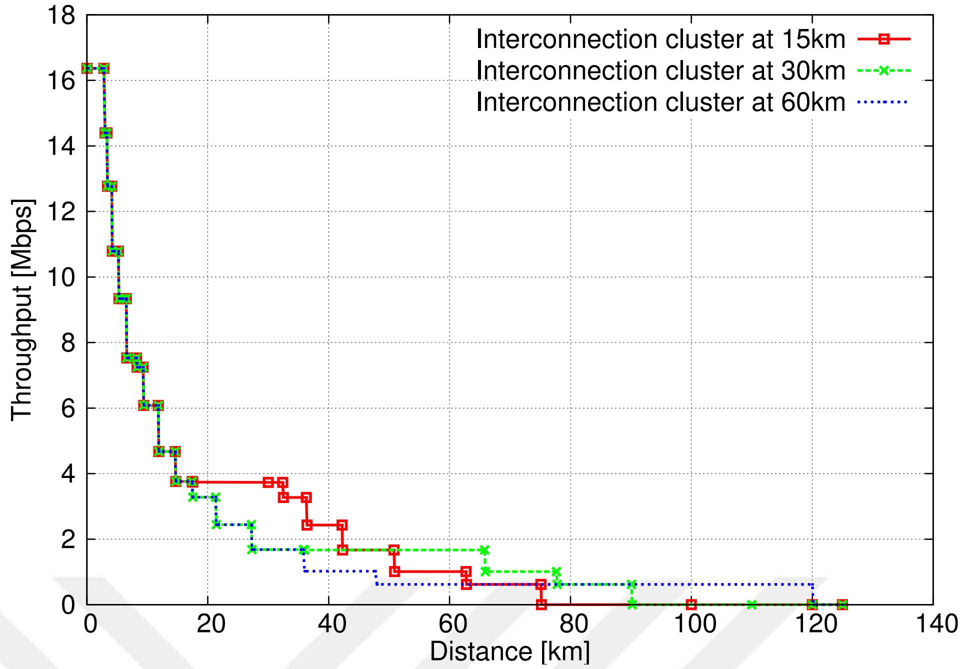

FIGURE 4.7: Throughput Vs Distance with one interconnection cluster

The third scenario shown in Figure 4.8 illustrates the throughput variation against the distance for a network with 2 intermediate clusters. 3 different sub-scenarios are considered with each sub-scenario with different cluster location combinations. We considered our 2 intermediate clusters to be positioned at 15 km and 30 km, 30 km and 60 km, and 60 km and 120 km in 3 sub-scenarios. Besides providing information on throughput variation, it also gives the information that a maximum coverage distance of 180 km can be achieved with 2 intermediate clusters positioned at 30 km and 60 km. Though a better coverage distance is provided, it is to be noted that there is trade-off with the data rate. The data rate is 0.6 Mbps after 48 km for the third sub-scenario, but previous 2 sub-scenarios have better data rate though their coverage distance is not in par with the third sub-scenario.

The variation of delay against distance for scenarios with no intermediate cluster, one intermediate cluster, and 2 intermediate clusters are shown in Figure 4.9, 4.10 and 4.11 respectively. From Figure 4.9, it is clear that the delay variation with distance is smooth until the connection is cut-off. However, in the delay variation with distance for scenarios with intermediate clusters, surge happens and this is attributed to the extra delay from intermediate cluster. Figure 4.10 has a single surge as it has only one intermediate cluster whereas Figure 4.11 has 2 sudden increase in the delay because of the presence of 2 intermediate clusters.

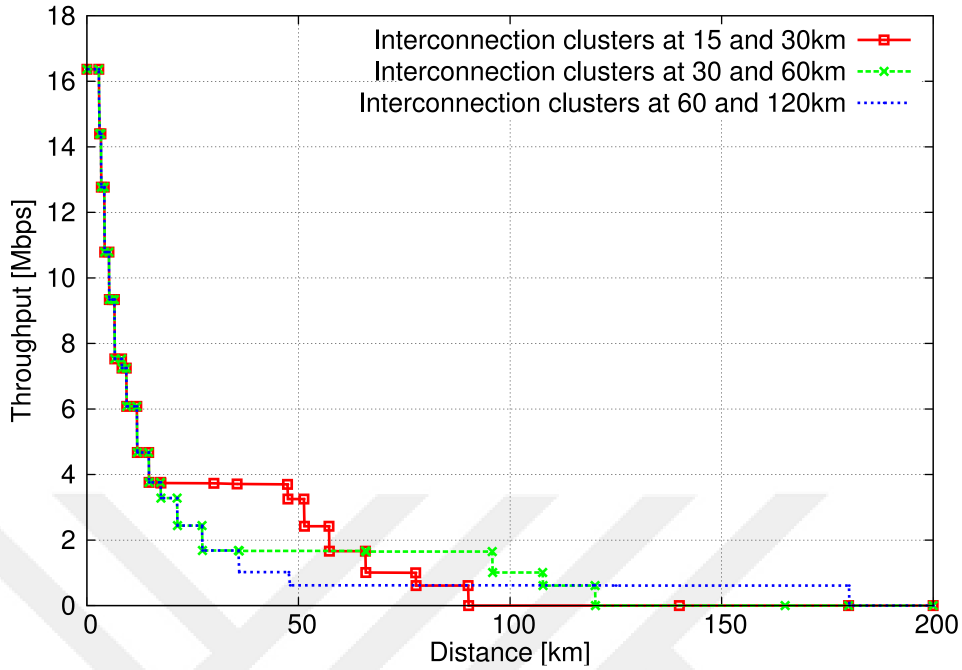

FIGURE 4.8: Throughput Vs Distance with 2 interconnection clusters

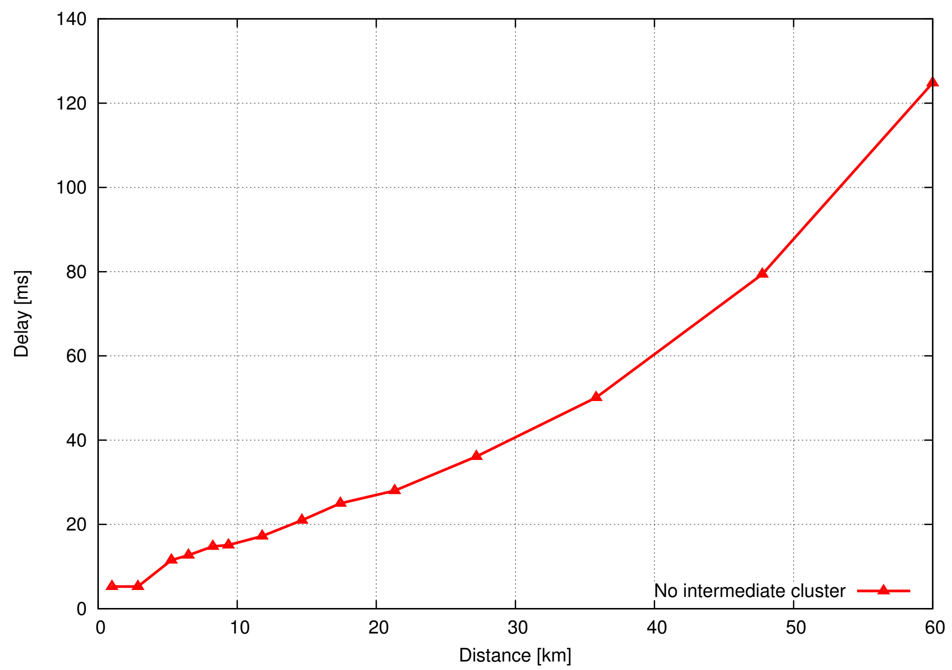

FIGURE 4.9: Delay vs Distance for direct connection

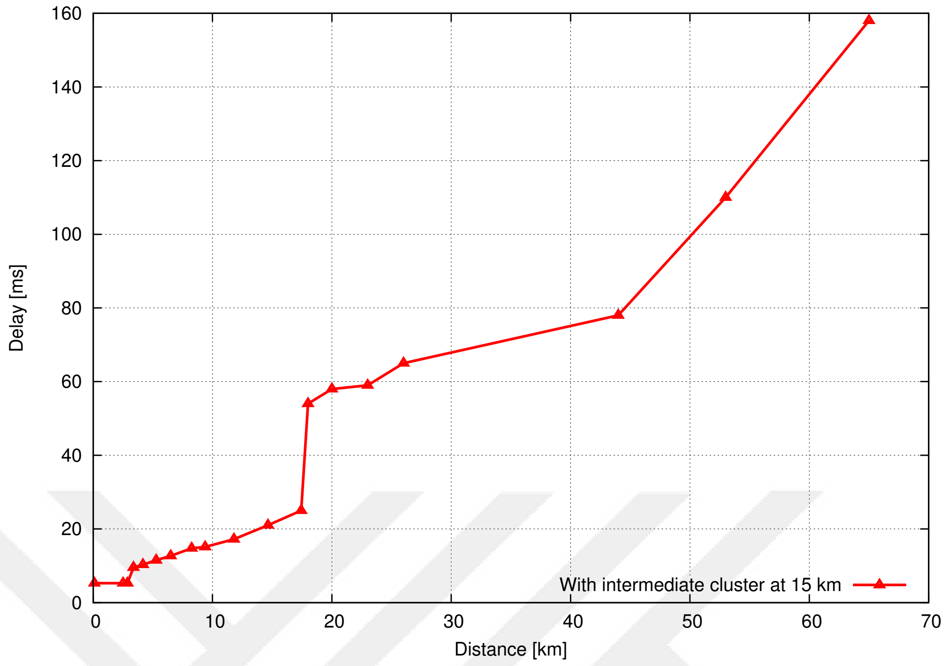

FIGURE 4.10: Delay vs Distance with one interconnection cluster

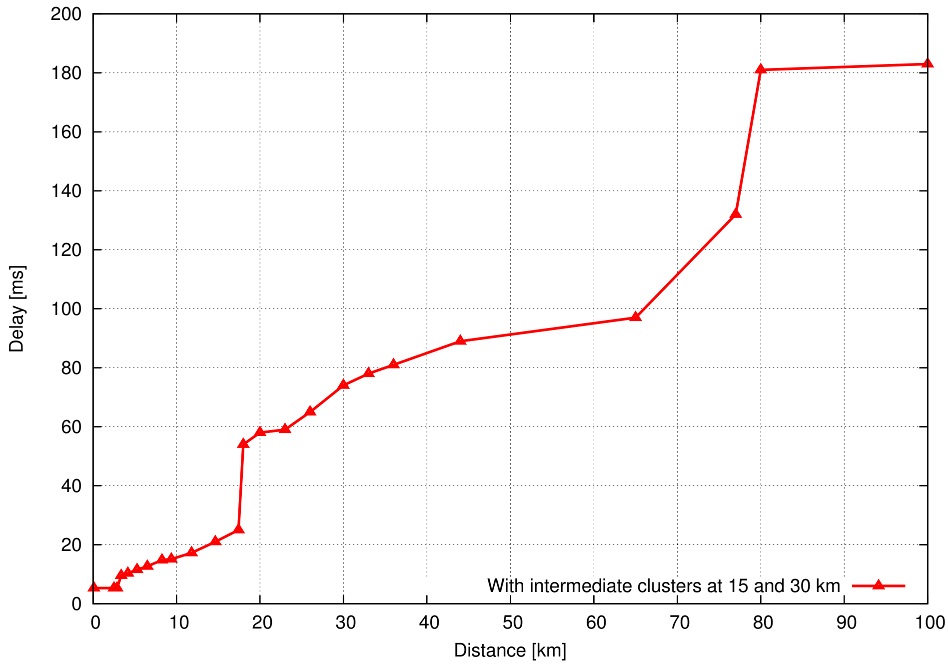

FIGURE 4.11: Delay vs Distance with 2 interconnection cluster

From the scenarios and illustrations in Figs. 4.6-4.8, it is evident that the reliability is improved tremendously with the increase in interconnection clusters. Table 4.2 also provides the information on how the data rate and coverage distance are improved using the proposed topology. Thus, the proposed heterogeneous topology along with the newly introduced IP routing algorithm satisfies all the major requirements of a long distance sea communication system like long coverage distance, improved throughput rates, and seamless connection with more interconnection clusters in the network.

4.4 Conclusion

The proposed heterogeneous topology with the newly designed algorithm is simulated and observed results are found to be promising. Simulation results from Table 4.2 and Figure 4.6-4.8 show that a maximum distance of 180 km can be achieved in 3 cluster network with a minimum data rate of 0.6 Mbps. The network can also be made more reliable by increasing the clusters. It was also observed from Table 4.2 that the network parameters like mean delay, mean jitter, and packet loss are not negatively affected by the topology and routing enhancement. Hence, a sea communication system using a heterogeneous topology and newly introduced IP routing algorithm satisfies all the major requirements of a long distance sea communication system like long coverage distance, improved throughput rates, and seamless connection with more interconnection clusters in the network. With the completion of the simulation and performance evaluation, we move on to the chapter that concludes our study with some high level descriptions on the future works.

Chapter 5

Conclusion and Future Work

Long distance sea communication systems are not given enough attention in spite of all the technological advancements. The call for attention on this and thus rectifying the lag in technology in the area was neither less. We have already discussed in Section 1.1 that there are millions of passengers who are depending the sea route all around the world as a medium of transport and about the importance of sea for trade and commerce. To overcome the technological deficit over sea, a new heterogeneous topology and a routing algorithm were proposed.

In our study, with the proposed topology and IP routing algorithm, a communication system over sea with unprecedented improvement in the parameters like reliability, data rate, and coverage distance have been achieved. The simulation test result indicates that a maximum coverage distance of 180 km can be achieved using two interconnection clusters with a minimum data rate of 0.6 Mbps. Since the simulation is performed with 5 MHz LTE system, it is to be noted that the minimum data rate achieved can be further extended to 2.7 Mbps by using 20 MHz bandwidth of the LTE system. The reliability factor for sea communication was also improved to a great extent by the presence of more interconnection clusters in the network. It was also observed that as the number of clusters in the network increases, the coverage distance, the target data rate, and the reliability are improved to an unprecedented level. Besides the core parameters, Jain index and other network parameters like mean delay, mean jitter, and packet loss, are also observed not to have any negative impact on the performance.

In our test simulation, we did not consider the case of a permanent cluster in sea. All the clusters in our consideration were in relative motion all the time. Providing a permanent cluster in the sea can help in providing a permanent link and hence a better performance in all the parameters of our concern. The use of islands, oil fields, and floating points in the sea can be used to provide a permanent connection link between clusters. This addition can take the reliability to a next level and provide a seamless Internet connection.

All the clusters in the simulation were used as static nodes. Making all the components within the cluster moving with same velocity and along the same direction as a unit, can make the cluster as a single mobile unit. This could take the effects of signal strength variation for mobile units and also the effects of doppler shift.

In the proposed algorithm, signal path comparisons are performed to select the best among all the possible paths. This would have included some redundant comparisons as an all out comparison will be performed for finding the best path. A 2 cluster network would have 4 comparison to be performed and 3 cluster network would need to do 12 comparisons. Hence, an n cluster network will have $n*2^{n-1}$ comparisons to be performed and it can be huge for a network involving large number of clusters. Many of these comparisons are redundant and are not quite useful. Avoiding these redundant comparisons could improve the performance of the algorithm and hence the overall network.

A better algorithm can be designed by first finding the cluster with best connection from the base station. This cluster will be made as reference cluster instead of the base station as the path of reference cluster to the base station is already known now. If any new cluster is looking for connection and has good connection with the new reference cluster, then a connection is formed. This process continues until all clusters get connected and as the process continues, the number of active reference clusters also increase.

Hence, the algorithm can be extended by focusing more on optimizing the algorithm further by minimizing the comparison process. The proposed algorithm can also be modified and extended for the upcoming 5G networks as these networks are expected to be highly heterogeneous and IP based.

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