TRAFFIC SCHEDULING AND GROOMING OF OPTICAL AND WIRELESS NETWORKS

Ph.D. Thesis

by

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DISCIPLINE OF ELECTRICAL ENGINEERING
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CANDIDATE'S DECLARATION

I hereby certify that the work which is being presented in the thesis entitled **"TRAFFIC SCHEDULING AND GROOMING OF OPTICAL AND WIRELESS NETWORKS"** in the partial fulfillment of the requirements for the award of the degree of DOCTOR OF PHILOSOPHY and submitted in the DISCIPLINE OF ELECTRICAL ENGINEERING, Indian Institute of Technology Indore, is an authentic record of my own work carried out during the time period from January 2014 to April 2019 under the supervision of Dr. Vimal Bhatia, Professor, Indian Institute of Technology Indore, India.

The matter presented in this thesis has not been submitted by me for the award of any other degree of this or any other institute.

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This is to certify that the above statement made by the candidate is correct to the best of my knowledge.

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Dedicated to my wife Sarita and son Sidhant

ABSTRACT

Telecommunications networks have graduated from primarily being pure wire line networks to present day Heterogeneous Telecommunication Network (HTN). These HTNs predominantly incorporate wireless access networks integrated to high speed backbone optical networks. The wireless access networks include Wireless Mesh Networks (WMN) based on Long Term Evolution (LTE) protocols and can be incorporated in the fifth generation cellular technologies. The high data rate backbone wireline networks primarily imbibe optical fiber media and incorporate technologies like Dense Wavelength Division Multiplexing (DWDM) and Multi Protocol Label Switching (MPLS). Each of the above technologies has their own capabilities specific to the media of operation.

Present day HTNs are an amalgamation of both the wireless and wireline technologies, and include an ensemble of present and future technologies for operation. Hence, it becomes imperative that these HTNs should be optimized to ensure that their limited network data carrying capacity be fully utilized as the user base is increasing exponentially. Further, there is an inescapable requirement to ensure classification of service in these HTNs thus; enforcing prioritization of traffic and ensuring end-to-end Quality of Service (QoS) in the entire telecommunication network.

This research aims to optimize both optical and wireless networks by incorporating optimum Traffic Scheduling Algorithm (TSA) in each segment of the network. A unique TSA has been conceived in this research work, which ensures classification of each connection request in the HTN. The algorithm thereafter extracts certain traffic parameters from every connection request entering the network. These traffic parameters may be the number of hops the connection request needs to traverse inside the network, data rate requested by the connection, delay tolerated by the connection request to ensure faithful reproduction of the information at the destination and finally the prioritization assigned to each connection request based on, the location of origin and destination of the connection request inside the HTN.

The above extracted traffic parameters from each connection request are utilized by the TSA to assign a value of weight to each connection request. The algorithm utilizes this value of weight assigned to each connection request in the algorithm, to effectively schedule the connection requests at every node in the HTN. The incorporation of the TSA ensures prioritization of traffic and ensures QoS in the HTN.

Initially, the study of pure optical networks was undertaken and the proposed TSA has been implemented in the backbone optical networks, thus ensuring optimization of this segment of HTN. Further, results obtained by implementation of TSA have been compared with the existing algorithms to prove that the proposed TSA has better performance in terms of connection blocking probability.

The study of wireless networks has thereafter been undertaken in this research work to understand channel conditions in the wireless links of such networks. Channel sounding and channel measurements have been undertaken for multiple terrain types in the Indian Sub-continent. The measurement results have been proposed to be referred for designing of present and future wireless transreceivers for LTE and for future wireless networks.

Study of defence network based on WMN has thereafter been undertaken to implement TSA to ensure high QoS. Finally TSA has been implemented in LTE networks and efficacy of the TSA in such networks has been adequately analyzed.

By implementing TSA in each and every segment of HTN, it has been shown that the connection blocking probability and packet loss in HTN have been substantially reduced. The incorporation of TSA for both the backbone and access segments of HTN are strongly recommended to intelligently optimize the HTN, and substantially improve its performance for future deployments.

Contents

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List of Abbreviations

AN	Adhoc Networks
ATM	Asynchronous Transfer Mode
AUC	Authentication Center
BER	Bit Error Rate
BLSR	Bi-directional Line Switched Rings
BP	Blocking Probability
BS	Base Stations
BSC	Base Station Controller
CIR	Channel Impulse Response
CN	Core Network
CoS	Class of Service
CQI	Channel Quality Indicator
CSPF	Constraint based Shortest Path First
CWDM	Coarse Wavelength Division Multiplexing
DFSI	Dynamic Fiber State Information
DMN	Defence Mesh Networks
DR	Data Rate
DS	Delay Spread
DWDM	Dense Wavelength Division Multiplexing
eNB	enhanced NodeB
EPC	Evolved Packet Core
EPS	Evolved Packet System
FDD	Frequency Division Duplex
FF	First Fit
FSC	Fiber Sensing Controllers
FWNs	Future Wireless Networks
GBR	Guaranteed Bit Rate
GMPLS	Generalized Multi Protocol Label Switching

HSDPA	High Speed Downlink Packet Access
HSS	Home Subscriber Server
HTN	Hybrid Telecommunication Networks
IETF	Internet Engineering Task Force
IN	Infrastructure Networks
IP	Internet Protocol
ISDN	Integrated Services Digital Network
IS-IS	Intermediate System to Intermediate System intra-domain
ITU	International Telecom Union
LER	Label Edge Routers
LIB	Label Information Base
LoS	Line of Sight
LSR	Label Switch Routers
LSP	Label Switched Path
LTE	Long Term Evolution
MCS	Modulation and Coding Schemes
MIMO	Multiple Input Multiple Output
MME	Mobile Management Entity
MPLS	Multi Protocol Label Switching
MS	Mobile Station
NIC	Network Interface Cards
NGN	Next Generation Networks
O - E – O	Optical - Electrical - Optical
OFC	Optical Fiber Cables
OFDMA	Orthogonal Frequency Division Multiple Access
ONMS	Optical Network Management Systems
OSC	Optical Supervisory Channel
OSNR	Optical Signal to Noise Ratio
OSPF	Open Shortest Path First
PCC	Path Computational Client
PCE	Path Computation Element

PCECP	PCE Communication Protocol
PCRF	Policy Control and Charging Rules Function
PDH	Plesiochronous Digital Hierarchy
PDP	Power Delay Profile
PDN-GW	Packet Data Network Gateway
PRB	Physical Resource Blocks
PS	Packet Scheduling
PSA	Priority Scheduling Algorithm
QCI	QoS Class Identifier
QoS	Quality of Service
RAN	Radio-Access Network
RF	Random Fit
RNC	Radio Network Controller
RSS	Received signal Strength
RSVP- TE	Resource Reservation Protocol with Traffic Engineering
RWA	Routing and Wavelength Assignment
SAE	System Architecture Evolution
SC-FDMA	Single Carrier Frequency Division Multiple Access
SDH	Synchronous Digital Hierarchy
S-GW	Serving Gateway
SINR	Signal to Interference and Noise Ratio
SISO	Single Input Single Output
SLA	Service Level Agreement
SNR	Signal to Noise Ratio
STM	Synchronous Transport Module
TDD	Time Division Duplex
TDM	Time Division Multiplexing
TE	Traffic Engineering
TED	Traffic Engineering Database
TFT	Traffic Flow Templates
TGA	Traffic Grooming Algorithm

TI	Traffic Intensity
TSA	Traffic Scheduling Algorithm
TTI	Transmission Time Interval
UE	User Equipment
UMTS	Universal Mobile Telecommunications System
UTRAN	Universal Terrestrial Radio Access Network
VoIP	Voice over IP
VPNs	Virtual Private Networks
WA	Wavelength Assignment
WCC	Wavelength Continuity Constraint
WDM	Wavelength Division Multiplexing
Wi-Fi	Wireless Fidelity
WiMAX	Wireless Interoperability for Microwave Access
WLANs	Wireless Local Area Networks
WMANs	Wireless Metropolitan Area Networks
WMN	Wireless Mesh Networks
WSNs	Wireless Sensor Networks
3GPP	3rd Generation Partnership Project
4G	Fourth Generation
5G	Fifth Generation

List of Symbols

Basic arithmetic and calculus notations have standard definitions.

Notataion	Definition
P_R	Received Signal Power
P_N	Noise Power
dB	Decibels
$\bar{\tau}$	Mean Excess Delay
σ_τ	Delay Spread
B_c	Coherence Bandwidth
B_D	Doppler Spread
f_c	Carrier Frequency
f_d	Doppler Shift
T_C	Coherence Time
H_{max}	Maximum Hop count
M_d	Maximum Data Rate
C_{max}	Maximum Hop Count
$x_i(t)$	Average rate at which i_{th} user serviced
$r_i(t)$	Rate allocated to i_{th} user

Chapter 1

Introduction

1.1 Overview

Telecommunication networks over the years have evolved considerably, from capacity or bandwidth enhancements to improvements in speeds and reduction in costs. In 1990's Integrated Services Digital Network (ISDN) switches, which integrated voice, video and data services in a single switch, largely got prominence in the telecommunication networks. By the end of the century, ISDN switches gradually paved way for Asynchronous Transfer Mode (ATM) switches, which brought in the concepts of service guarantees and prioritizing traffic. These concepts were termed as Class of Service (CoS) and Quality of Service (QoS) respectively. ATM switches based integrated backbone networks started competing with the already popular, prominent, and existing Internet Protocol (IP) based networks. IP based networks had by this time developed extensive reach, due to their low installation costs, and high speeds. Major drawbacks with IP based networks, was that it could not imbibe CoS and QoS, as incorporated in ATM networks [5]. It was thus felt that there is a requirement of a technology to be developed which could incorporate the features of ATM (primarily CoS and QoS) and IP (simplicity and low installation costs). Multi Protocol Label Switching (MPLS) was conceptualized which incorporated features of both ATM and IP networks. It operated on universal labels being appended in front of already existing protocols and thus transparently integrated ATM and IP networks.

The three types of services viz. voice, video and data had been integrated, due to user requirements and advancements in technologies. With increasing number of services being provided to the end user, ranging from internet data to video conferencing services involving both voice and video, large portions of the network bandwidth were consumed. The existing copper cabled backbone networks could not handle large data rates of these bandwidth hungry services. Optical fibers are used as an alternative to copper cables, and possessed enormous bandwidth capabilities for backbone telecommunication networks. Optical fibers are also not susceptible to electromagnetic interferences [2]. Further the communication data rate depends on the terminal equipment capability, as the optical media provides ideally infinite bandwidth. This changed the way backbone services were viewed till then.

1.2 Pure Optical Telecommunication Networks

Initially optical fiber rings were based on Plesiochronous Digital Hierarchy (PDH) standards. PDH standard supported data rates of E1/T1, E2/T2, E3/T3 and E4/T4. For higher data rates, Synchronous Digital Hierarchy (SDH) [2] standard was incorporated in backbone networks. SDH standard supported data rates of Synchronous Transport Module (STM) 1, STM 4, STM 16 and STM 64. These SDH networks were run on multiple ring structures preferably Bi-directional Line Switched Rings (BLSR) thus ensuring redundancy. For larger span lengths (more than 60 km), repeaters were employed at designated distances, which helped to improve the deteriorating Optical Signal to Noise Ratio (OSNR). At these repeater stations, regeneration of the optical signal was implemented using Optical - Electrical - Optical (O - E - O) regeneration process which was dependent on electronic processing speeds. The greatest drawback of O - E - O conversion was that the data rate transmission in the network was limited to the slow processing speeds of these regenerators.

Hence, there was a need for pure optical regeneration which could match with very high data rates/speeds of optical links [3]. Further, laying of an optical fiber is very expensive [3]. Therefore existing laid fibers needed to be utilized to the maximum. This was not the situation in the beginning of the new millennium when SDH ring structures were used. SDH rings could carry a single wavelength (or a communication link) in each optical fiber pair, and each such wavelength could only support small data rates. This was a waste of fiber resource which by this time had become critical. Hence, a technology was required which could extract the maximum from an existing laid fiber. Wavelength Division Multiplexing (WDM) technique provided with a solution to this problem. WDM could multiplex high number of wavelengths (or communication channels) on to a single fiber.

Thereafter, variations to WDM in the form of Coarse Wavelength Division Multiplexing (CWDM) and Dense Wavelength Division Multiplexing (DWDM) techniques were conceived. They only differed in the inter-wavelength space between the multiplexed wavelengths. By using the DWDM technology, an existing fiber can transport up to eighty wavelengths, each carrying data rates ranging from 10, 40 to 80 Gigabits per second (Gbps) in a single strand of optical fiber. Hence, on a single optical fiber strand, these new technologies can transport up to 6400 Gbps. Erstwhile SDH networks could at maximum transport STM 256 i.e. 40 Gbps. This mammoth increase in transport capabilities (up to 160 times when compared to earlier SDH networks) forced most of the backbone networks to graduate to DWDM technology. Further DWDM networks employed optical amplifiers which has much enhanced ranges (upto 300 km). The regeneration mechanism is purely optical in nature. There is no O – E – O conversion employed, hence improved ranges are achieved. These networks employ mesh topologies due to the availability of multi-directional optical transponders and thus, fallacies of ring topologies are eliminated. Due to the above reasons, DWDM networks have become the backbone network of the future and employed throughout the world for backbone communication requirements.

Further, with large technological advancements in wireless technology, the data rates provided to cellular users have substantially jumped from few hundred kilobits per second to presently megabits per second. This results in a colossal jump in the bandwidth requirements of the backbone for these wireless networks. Hence, pure optical DWDM networks suit the backbone requirements of these high data rate wireless networks.

Optical dense wavelength division multiplexers can multiplex up to hundreds of uniquely identifiable optical wavelengths. Each such wavelength has a capability to support data rates up to tens of Gbps. Such high data rates, of the order of tens of thousands of Gbps, carried by a single strand of fiber seems sufficient for the present. But with telecommunication, cellular and internet user base increasing in an exorbitant manner around the world [3], soon this bandwidth will seem meager in comparison to backbone data rate requirements of the future.

1.3 Wireless Mesh Networks

Wireless Mesh Networks (WMN) can be characterized as networks which are totally wireless in nature or may have a wired backbone utilizing Optical Fiber Cables (OFC) or microwave radio links but the access links to the end user equipment is primarily wireless. In order to ensure redundancy of paths in case of link failures in the backbone of the wireless network, the wireless nodes are connected to more than one wireless node to create a mesh architecture thereby creating a WMN.

WMNs can be broadly classified into Infrastructure and Adhoc Networks (AN) [4]. Infrastructure Networks (IN) has intelligence of the network at certain decision making nodes. The deployment cost of the infrastructure equipments is high but the cost of end equipments is low. The IN is suited for static Base Stations (BS) and mobile end user equipment called as Mobile Station (MS). AN on the other hand has distributed intelligence in the network, and all nodes in the AN are capable of decision making/switching. The cost of an AN end user equipment is high and is suited for dynamic changes in the network. The nodes of the AN can be on a mobile platform and termed as Mobile AN (MAN).

1.4 Channel Sounding for Wireless Mesh Networks

Wireless communication differs from a typical microwave link which is classified as point-to-point communication link. A mobile communication environment is not characterized as Line of Sight (LoS) communication but largely depends on refracted, diffracted and scattered copies of the original signal transmitted by the eNodeB of an LTE network [5] or any legacy cellular standard to the User Equipment (UE). The UE does not see the eNodeB as direct LoS, however receives highly attenuated copies of original signal from various paths through reflection, diffraction, and scattering. These copies of original signal are time delayed as they traverse different paths in the mobile environment and suffer relative phase differences as they reach the UE. Due to the difference in the phases of the multiple copies received at the UE, constructive, and destructive interferences occur at the UE at any instant, leading to large variation in received signal strength at the UE. This effect is called as small scale fading in the mobile environment or the multipath effect [6], which is largely detrimental to the received signal quality in a mobile environment.

Channel sounding is a technique that evaluates the radio environment for wireless communication. To minimize or use the multipath effect, channel sounding is used to process the multidimensional spatial-temporal signal and estimate channel characteristics. Channel sounding for a multipath channel is the process of analyzing and understanding the behavior of a channel for a specific band of frequency for duration of measurements. An impulse is transmitted through the channel and consequently the response of the channel to the impulse is measured. This process is carried out for multiple times. The above measurements are thereafter analyzed to ascertain distortion in amplitude and phase of the transmitted signal by the channel in that duration. Further, the transceivers are designed for a specific band to minimize the effect of channel distortion. These transceivers incorporate equalizer circuits, which undo the effect of the channel distortion in the amplitude and phase, during channel sounding process.

1.5 Long Term Evolution Networks

Long Term Evolution (LTE) is also termed as 3rd Generation Partnership Project (3GPP) Universal Terrestrial Radio Access Network (UTRAN) evolution to meet the needs of future broadband cellular communications [7].

LTE standard for advanced cellular communications is an emerging standard embraced by commercial carriers. It holds the promise of an interoperable network based on non-proprietary, commercially available technology. LTE embodies a vision of wireless access that assumes a path-breaking transition towards a packet switched only system that is distinctly non-hierarchical, and which makes wide use of Internet Engineering Task Force (IETF) protocols and practices. LTE is further designed to be interoperable with legacy UMTS systems and offers support for seamless mobility through non-3GPP wireless accesses including Worldwide Interoperability for Microwave Access (WiMAX) and Wireless Fidelity (Wi-Fi).

The LTE access network incorporates state-of-the-art air interface technologies including OFDMA (Orthogonal Frequency Division Multiple Access) and advanced antenna techniques to efficiently use the RF spectrum. It also accommodates several options for frequency bands, carrier bandwidths and duplexing techniques in order to effectively utilize the different portions of unused spectrum available in different countries and geographies. Additionally, and significantly, the LTE network architecture evolved to an-all IP architecture. Thus, enabling the seamless delivery of applications and services over what were previously two separate and distinct networks. The QoS options, which allow for real time packet data services like Voice over IP (VoIP) and live video streaming, were also incorporated.

As a wireless network which improves spectral efficiency, simplifies deployment of all-IP real-time services, facilitates integration with non-wireless networks and supports interworking with legacy wireless technologies, LTE is strongly positioned to lead the evolution in the communications industry for several years [7]. It achieves all of the above issues through a flat, scalable architecture which is designed to manage and maintain QoS in a mobile environment. The fine granularity (180 KHz resource block times 1 millisecond transmission time interval) in LTE allows for packing efficiency and exploitation of time/frequency channel selectivity through opportunistic scheduling, thus enabling higher user throughputs. Thus packet scheduling is an important aspect of LTE.

1.6 Heterogeneous Telecommunication Networks

Present day telecommunication networks cannot be classified as pure optical networks or pure WMN but are actually a combination of both. The backbone telecommunications networks are primarily pure optical networks as they provide very high data rates for transport of aggregated traffic from end users. Further, pure optical networks provide robustness and flexibility in the backbone of telecommunication networks by the incorporation of efficient wavelength routing and assignment techniques.

The WMN primarily forms part of the access telecommunication networks. WMNs provide easily deployable, flexible, and adaptive access telecommunication infrastructure. LTE and the proposed fifth generation cellular standards will enable WMNs to support very high data rates to end users.

The amalgamation of backbone pure optical networks and access high data rate WMNs can be termed as heterogeneous telecommunication networks. Heterogeneous telecommunication networks are the networks of the future and will incorporate state of the art optical and wireless standards in times to come.

1.7 Need and Motivation for Scheduling Telecommunication Networks

The heterogeneous telecommunication networks will provide high bandwidth with high data rates in access WMNs and robustness in the backbone pure optical networks. Due to exponential increase of telecommunication, cellular and internet user base around the world, this bandwidth will soon seem meager in comparison to backbone and access data rate requirements of heterogeneous telecommunication networks in the future. Traffic grooming is a process of combining various flows of data into a single channel, thus optimizing existing bandwidth.

Further, traffic grooming can prioritize the flow of data as per various classes of service. Hence, an efficient traffic grooming algorithm needs to be formulated to enhance the bandwidth utilization and to further optimize future heterogeneous telecommunication networks.

The future heterogeneous telecommunication networks are based on IP packets which is also the case for LTE and proposed fifth generation cellular standards. The heterogeneous telecommunication users demand high quality and high definition display devices, and therefore utilize high data rate services from the service providers. The requirement of high data rate connections at access networks and further more at aggregated traffic carrying pure backbone networks is an inescapable requirement. Presently for countries with growing economies like India, the heterogeneous telecommunication networks are unable to provide the desired QoS as per the growing needs of the users.

The heterogeneous telecommunication networks will be prone to congestion and require a mechanism to prevent large packet losses. Further, it is important to understand and appreciate that any heterogeneous telecommunication network will be designed and implemented with only 40 to 50 % of peak traffic load statistically. This makes the network practical and economical to implement. However, in the event of increase in aggregated traffic due to any factor will lead to total blocking of the heterogeneous telecommunication network or partial failure of certain subnets of the heterogeneous telecommunication network. Hence, in such situations, it is necessary to classify traffic and prioritize traffic according to the type of service (voice, video and data), area of origin in the heterogeneous telecommunication network, amount of network resource utilization the service desires and delay tolerable by the service. The above prioritization will result that important traffic reaches the destination without loss or substantial delay.

Hence, there is need to optimize the heterogeneous telecommunication networks by designing and implementing a traffic grooming algorithm on these networks which can improve the QoS and throughput. The proposed traffic grooming network should address both the requirements of backbone pure optical network and access WMN of the heterogeneous telecommunication networks separately, while considering the distinct constraints and topology of both networks.

1.8 Thesis Objective

The thesis aims to study the characteristic and nature of the following:

(a) Pure optical networks

(b) WMN

(c) Channel Sounding for WMN

(d) Defence WMNs

(e) LTE networks

The thesis further proposes incorporation of traffic grooming algorithm in pure optical networks, WMN, defence based WMN and LTE networks for improvement in QoS and throughput of the above telecommunication networks. The proposed traffic grooming algorithms incorporated in each of the above networks is required to be simulated and the results analyzed for inferring on the improvements observed in packet loss and resultant throughput in each of the above networks as part of overall telecommunication networks.

Thus, the traffic grooming algorithm is proposed to be incorporated in the heterogeneous telecommunication networks to improve throughput and QoS of the network.

1.9 Organization of the thesis

The thesis is organized into the following chapters:

Chapter 1.Introduction:
The first chapter of the thesis deals with the basic understanding of pure optical networks, WMN, channel sounding for WMN, LTE networks and heterogeneous telecommunication networks. Further, the chapter brings out the need and motivation for optimizing telecommunication networks and elaborates the objective of the thesis.

Chapter 2. Traffic Grooming and Optimization of Pure Optical Networks: The second chapter of the thesis deals with the wavelength routing and assignment in optical networks and Generalized Multi Protocol Label Switching (GMPLS) based optical networks. Traffic grooming algorithm for pure optical networks is discussed next along with the simulation results and analysis.

Chapter 3. Channel Sounding and Measurements for Wireless Networks:

The third chapter deals with the basics of channel sounding concepts. The channel measurement setup is thereafter discussed. Further, channel measurements for various terrains in multiple bands are elaborated. At the end, channel measurement analysis is done.

Chapter 4. Traffic Scheduling in Defense Wireless Mesh Networks:

In the fourth chapter the characteristics of wireless mesh networks along with the typical requirements of DMN are discussed. The need to optimize DMN is thereafter elaborated. At the end, incorporation of traffic scheduling algorithm in DMN and the simulation results have been analyzed.

Chapter 5. Traffic Scheduling in Long Term Evolution based Wireless Mesh Networks:

The fifth chapter discusses the 3GPPstandards for LTE and the packet scheduling features in LTE standard. Thereafter, the incorporation of packet scheduling algorithm in LTE based WMN is discussed followed by the simulation results and their analysis.

Chapter 6. Conclusion and Future Work:

The final chapter of the thesis gives summary of the thesis and finally discusses the future implementation of traffic scheduling algorithms in LTE/ LTE–Advanced and pure optical networks based heterogeneous telecommunication networks.

Chapter 2

Traffic Grooming of Pure Optical Networks

Optical dense wavelength division multiplexers can multiplex up to hundreds of uniquely identifiable optical wavelengths. Each such wavelength has a capability to support data rates up to tens of Gbps. Such high data rate, of the order of tens of thousands of Gbps, carried by a single strand of fiber seems sufficient for the present. However, cellular and internet user base has increased exorbitantly [7]. Soon this high bandwidth will seem meager in comparison to the backbone data rate requirements of the future. In view of the above, it is pertinent to study the various wavelength routing and assignment techniques along with the efficient optical architectures to develop and propose efficient traffic grooming algorithms to improve data rates of future pure optical networks.

2.1. Wavelength Routing in Optical Networks

Optical networks comprise of optical switches, multiple add drop multiplexers and cross-connects that are interconnected by a mesh of optical fiber cables. Each optical fiber cable comprises of multiple strands of optical fiber which in turn may have a capability to carry tens of wavelengths. These wavelengths can transport massive data rates. Thus the most critical resources in an optical network are these operational wavelengths supported by the existing fiber architecture.

2.1.1 Wavelength Routed Networks

All optical networks define a Lightpath [8] as a channel used for communication, established between an optical node having information and an optical node desirous of that information, which may be interlinked by multiple optical nodes. These nodes may be organized in a meshed architecture and the lightpath uses a single wavelength in every link it traverses as shown in Figure 2.1.

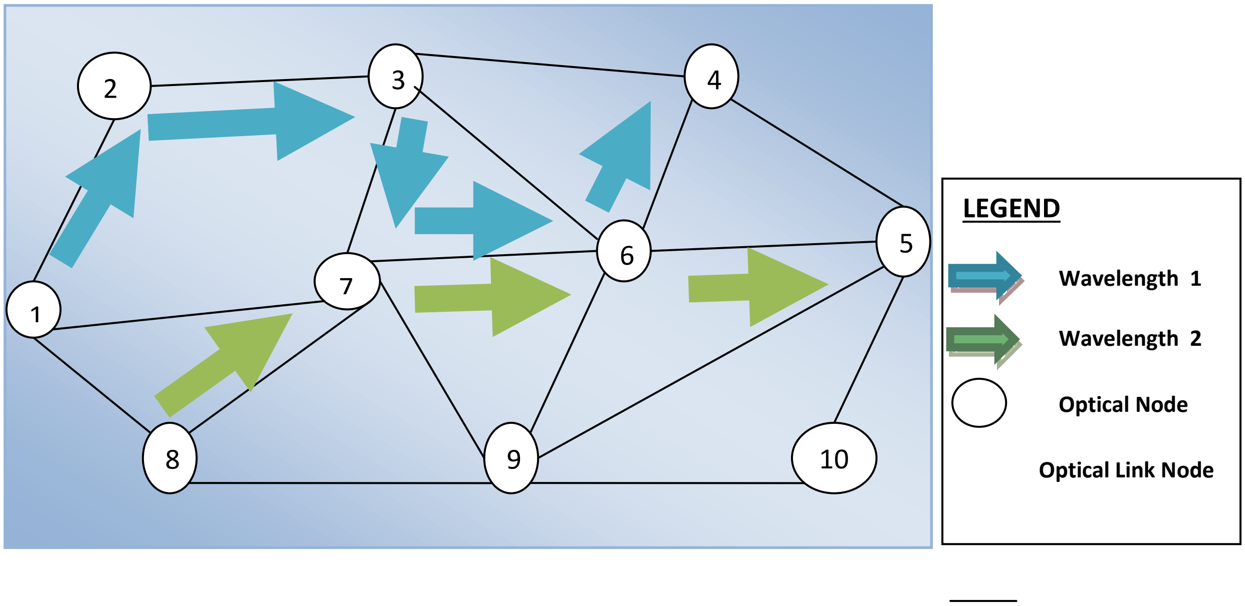

Figure 2.1: Lightpaths in a wavelength routed optical network.

These optical nodes route wavelength of the lightpaths, using optical switches, by the best and shortest route possible as calculated by the algorithm in the network. The wavelength in every link of the lightpath may be same or different. If wavelength converters are used at intermediate nodes, then these wavelengths may be different, else same wavelength is used throughout all the links of the lightpath. Wavelength convertors may have full range conversion capability, for the entire range of wavelengths, or may have partial range conversion capabilities. An optical network, employing convertors at all nodes which can convert the entire range of operational wavelengths, is similar to a telephone network which is circuit switched in nature. However, the drawback in employing these wavelength convertors is the fact that these convertors are mostly non-linear devices which degrade the OSNR on the link, after wavelength conversion, and further prove costly when used at every node. Another option is to have wavelength convertors at specific locations and these networks are called as 'optical networks with sparse conversion capabilities'.

In view of the above issues, it is assumed that the wavelength convertors are not used in the network. However, this brings us to another complex problem which is to ensure that every lightpath in the optical network should have the same wavelength in all intermediate links from originating node to destination node. This requirement is termed as Wavelength Continuity

Constraint (WCC), i.e., the wavelength will be continuous (it will not be converted by any of the intermediate nodes) from initial to the last link of every lightpath. This constraint further has a requirement to ensure that on every optical link, having multiple lightpaths, should have distinct wavelengths assigned to them to ensure WCC.

Hence it is evident that there is an inherent requirement to find the best route for the lightpath, and after finding the route, assign wavelength to each link of the lightpath, so as to ensure WCC. The above is referred to as Routing and Wavelength Assignment (RWA) in optical networks. The RWA problem can be further subdivided into two sub parts- first the routing problem and second the wavelength assignment problem.

2.1.2 Wavelength Routing

Routing refers to the establishment of lightpaths through the best route according to some predefined metric [9]. There are various routing algorithms already available in computer networks like – Djikstra or Belman-Ford algorithms. Whenever a request for a lightpath establishment is received at the ingress optical node a predefined routing algorithm is run, to find the best suited path for that instance, and lightpath establishment process starts in the selected route. The wavelength chosen is also important to ensure lower blocking probability of the network. There are various routing methodologies [10] which can be incorporated and are explained below.

2.1.2.1 Fixed Routing

This is the most simple and straight forward routing scheme in which a predefined fixed route is always chosen for a source destination pair. All the possible routes, for all mix and match of the nodes desirous of transmitting and receiving information, are pre-calculated offline and fed to the nodes. The algorithms used may be Djikstra or Belman-Ford to calculate the shortest path. Though the scheme is simple, however it can lead to high connection blocking probability in case of multiple traffic scenarios for a source destination pair. Further, this scheme performs poorly with link faults and component failures which occur randomly in the optical networks.

2.1.2.2 Fixed Alternate Routing

In this scheme of routing, multiple alternate paths for the same source-destination pairs are found over and above the primary shortest path found. The condition for the alternate path is to ensure that this path does not share in common, any of the links (i.e., it is link disjoint) of the primary shortest path and even other alternate paths. For simplicity one or two alternate paths can be calculated for a primary path to ensure redundancy. When the primary path has failure, the originating node routes the lightpath to the pre-calculated alternate path. This reduces probability of the network being blocked substantially.

2.1.2.3Adaptive Routing

In this scheme route for the source and destination pair is chosen dynamically which will vary on the present state of the network. Adaptive routing is dependent on the control and management plane, wherein GMPLS is generally used, which continuously updates the routing tables at each decision making optical node. The advantage of this routing scheme is that the connection blocking probability is significantly reduced. One adaptive routing scheme, for a sending and receiving node pair, may select a number of alternate routes, as in alternate routing scheme, however the path which is least congested among these routes will be selected.

2.2. Wavelength Assignment in Optical Networks

After successfully choosing a route or a path for a lightpath by the corresponding wavelength routing protocol, the next job is to decide on a wavelength for every link, from the first link to the last link, ensuring wavelength continuity constraint. The aim is to ensure that the overall connection blocking probability of the network is minimum. Wavelength assignment schemes can either be static or dynamic in nature. Both the schemes are discussed below:

2.2.1 Static Wavelength Assignment

In wavelength assignment the goal is to ensure that for any link in the optical network, optical connections spanning over that link should not have the same wavelength assigned, else the effect will be detrimental to the connection carrying capability of the optical network. Further another important criterion is to ensure that when wavelength assignment is done for all the optical connections, the summation of the required wavelengths in the network is minimal. Both the above criteria are however contradictory to each other.

In static wavelength assignment, the wavelength assignment is done offline for all the lightpaths, which could be required for the operation of the network. Objective of the static wavelength assignment is to accommodate all demands of lightpaths, while reducing sum of all the wavelengths used in all the links of the optical network. The static wavelength assignment can be done using an algorithm called the ‘Graph Coloring’ algorithm. Various steps of this algorithm are enumerated below:-

(a) Auxiliary graph G (V,E) is created, in which V comprises of a series of nodes and E comprises of a series of edges and each lightpath is shown as a node in G. Undirected edge is created between the nodes of the graph Gif the optical connections span over an overlapping fiber connection.

(b) The nodes are colored such that two nearby nodes do not have the matching color.

The above problem turns out to be NP-complete, and it is difficult to determine the number of colors to be used.

The second approach is to simultaneously consider routing and wavelength assignment. This approach uses relaxed linear programming methods. Relaxed linear programming methods are used to solve the difficult integer linear programs. The approach leads to optimal multi-commodity flow formulation.

The linear programming based optimization is possible for optical networks with fewer amounts of nodes. For commercial optical networks with tens of nodes, it has been shown [10] that, to find an optimization solution for the RWA problem with linear programming approach, thousand of equations have to solved which is practically not feasible. Hence, for commercial networks of large sizes, various heuristics based methods of dynamic wavelength assignments are used which are discussed next.

2.2.2 Dynamic Wavelength Assignment

For dynamic wavelength assignment, the required lightpaths are not known initially as in static wavelength assignment, however here lightpath requests arrive randomly and independent of each other. The objective here is to minimize the connection blocking probability over the entire network. To proceed with wavelength assignment, heuristics have been designed to assign wavelengths in a dynamic scenario [10]. The designed methodologies are implemented during the computation process and further can be amalgamated with various available routing algorithms (like Djikstra and Bellman-Ford).

2.3. GMPLS based Optical Networks

To understand the GMPLS architecture for optical networks, we first introduce the concept of MPLS, which is the founding technology for GMPLS.

2.3.1 MPLS Concepts

MPLS is commercially used by networks which provide backbone communication for voice as well as data. MPLS had the potential to improve the services that were provided by networks that predominantly operated on IP, incorporating traffic engineering, guarantying QoS and provisioning Virtual Private Networks (VPNs). MPLS successfully replaced connection oriented ATM networks and connectionless packet forwarding IP networks, by incorporating the strong features of both of these core technologies, and thus had been widely successful. MPLS worked on label switching and thus, was transparent to various Layer 2 and 3 technologies [11]. MPLS introduced the concept of Traffic Engineering (TE) and incorporated TE in various existing routing protocols like Resource Reservation Protocol with Traffic Engineering (RSVP- TE). The architecture of MPLS networks predominantly composed of Label Edge Routers (LER), which are an interface to outside services/technologies and Label Switch Routers (LSR), which are the core switching elements and perform label switching in the MPLS networks. The label switching is performed according to a Label Information Base (LIB) table, akin to routing tables in the IP networks. The path created from a transmitting node to a receiving node in a MPLS network is called a Label Switched Path (LSP), and may comprise of multiple hops in the MPLS network. MPLS was primarily designed for data networks, and hence, there was a need to modify MPLS technology so that it could adapt to operational transport network technologies like Time Division Multiplexing (TDM), WDM and its variants. This unified approach for a single control plane technology, for the above transport networks, brought in the technology coined GMPLS.

2.3.2 Need for GMPLS

GMPLS brought in a common control plane, which could be put to use on any of the prevailing backbone technologies. GMPLS brought in the concept of dynamic provisioning of network services, using the control plane and thus providing TE [12]. GMPLS aims to apply the concepts of MPLS to backbone networks, and uses connection oriented technologies. WDM as a technology had huge futuristic value, as it promised enormous bandwidth potential, and hence to utilize its network resources efficiently, an intelligent control plane was an imminent requirement. Further the basic concept of WDM lambda switching, i.e. to convert an input wavelength to an output wavelength was very similar to MPLS label mapping/switching. Thus, the concept of MPLS Lambda was used for photonic networks. Similarly, time slot switching used in TDM networks could also employ control plane of MPLS, modified for its requirement. Hence, the work for MPLS Lambda was broadened, to cover switching in fiber, switching in timeslots, switching at layer 2, and other existing packet/frame/cell switching technologies. For optical networks using WDM technologies, MPLS techniques were used for establishing LSPs and further providing TE. This resulted in placing traffic on already computed and selected routes in the cloud or network, to optimize the utilization of network resources. This ensured routing service traffic away from congested subnets of the network. GMPLS also employed Traffic Engineering Database (TED), which contained all the information of the network, related to TE. In MPLS, labels are arbitrary values and do not represent any physical source, but in GMPLS a label associates to a specific resource, i.e. wavelength for a lambda switching cloud or network and a time slot for a TDM network. Further, GMPLS provides for bidirectional LSP in contrast to unidirectional LSP in MPLS, which helps the control plane greatly. Another important facet of GMPLS is that the control and data planes are separated, which is an inherent requirement for transport networks, but makes the standard complex. Lastly, the hierarchal nesting of LSPs in GMPLS has a different meaning. In GMPLS nesting of wavelengths can be inside a fiber, nesting of time slots can be within a wavelength and nesting of packets inside a timeslot. This ensures aggregation of tunnels offering more scalable TE and more organized use of bandwidth in the backbone of these transport networks. This also ensures integration of various switching technologies to provide end-to-end connectivity.

2.3.3 GMPLS Architecture

The computation of path for big clouds or networks, which may have multiple regions or domains, is complex. Hence, specific computational objects will be required and further, synergy between these objects in various domains is an inherent requirement. Therefore, an architecture for GMPLS was proposed and comprised of Path Computation Element (PCE)-based model [13]. The IETF has effectively proposed the PCE architecture in multiple cloud architecture, having layers of identifiable domains, which may have specific requirements or constraints. The PCE can be described as an object or a component of a network node which can compute a route if it has been provided with a cloud or network graph. PCE can further apply very specific considerations or constraints during this mechanism of path estimation. It is designed to have a dedicated data plane and linked to other PCEs for information sharing. A TED is defined as a matrix, which has all the information regarding the nature of cloud connectivity and all data regarding the available resources in that cloud. TED contains the topology and resource information of the domain. Further, a Path Computational Client (PCC) is part of the architecture. PCC is described as a customer program application which actually requests PCE for the specific path computation. The PCE then accesses the TED and other resource constraints, to optimally estimate the required path. The PCE can be located at any point in the network domain, but should be connected to all LSRs via the data plane.

The protocol between PCE and PCC has also been defined in [14]. There may be various situations wherein PCC may be co-located with PCE in the cloud, or there may be a situation where the PCC may be actually physically separated from PCE, and may be present in a different cloud altogether. Hence, there was a requirement perceived to define a send/receive protocol for communication between PCC and PCE. IETF has defined the PCE Communication Protocol (PCECP) for this purpose. This specific send/receive communication protocol will contain the specific path request from PCC to PCE, and the estimated path calculated by PCE to PCC. The request for the estimation of path by PCC will include the IP addresses of sending and receiving nodes in the cloud, and any specific resource constraints, if required. The PCE after optimum estimation of the desired path will respond to PCC using the above communication channel, and in case of not being able to estimate the path, will intimate the same to the PCC with reasons for the path estimation failure. The performance of PCE-based routing with combined and separated routing schemes has been duly verified [15]. It has been seen that a central PCE for routing and wavelength assignment is an efficient architecture as shown in Figure 2.2.

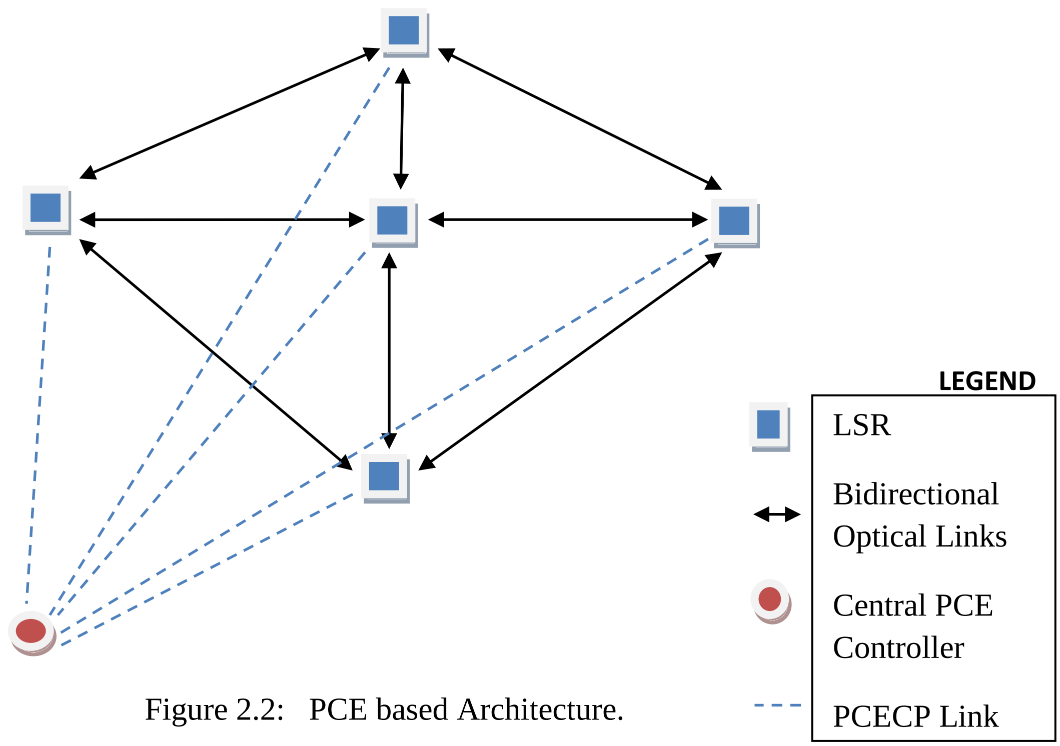

Figure 2.2: PCE based Architecture.

2.3.4 GMPLS Routing and Signaling

This section is divided into GMPLS routing concepts and GMPLS signaling implementation. GMPLS has been standardized for optical networks by IETF. The above standard has been used as a guideline in incorporating the routing and signaling model for this dissertation.

2.3.4.1 GMPLS Routing

In IP, routing is the phenomenon of discovering the next link for an IP datagram, on the least weighted path towards its receiving node. Each routing unit runs a specific procedure to compute the next link, as the data unit traverses through the cloud. The decision making is established on the intelligence available with the routing matrix, which is either an intelligence provided by the network administrator (static routing) or developed over many iterations by the routing agreement (dynamic routing). The primary routing agreements used within an area are Open Shortest Path First (OSPF) and Intermediate System to Intermediate System intra-domain (IS-

IS), which are both link state agreements. It is desirous from each routing unit in an IP cloud to circulate routing intelligence of its own. The circulated information primarily consists of:

(a) state of links (active or not) and

(b) cost of forwarding data on a link (metric or weight of that link).

The above intelligence is circulated by the routing agreement to all routing units in the cloud. Each routing unit uses a procedure to determine the ‘open shortest’ path towards a receiving node, whereas ‘open’ means the connections emanating are alive and can carry the data units, and ‘shortest’ means the path chosen is having the least cost [12]. Therefore, the aspiration is to minimize the aggregation of weights of all the connections towards the receiving node. Each routing unit in an IP cloud is only concerned with the next link on the open shortest path, as the next routing unit will do the same.

In GMPLS optical networks, routing is the circulation of intelligence, that will be incorporated as the ground of route determination, that brings out how optical virtual connections (LSPs) will be placed inside the optical cloud. GMPLS routing is different from IP routing which uses routing matrix (static or dynamic). The routing agreements used in GMPLS routing incorporate TE.TE involves optimum utilization of network resources by allocating data units on chosen, pre-measured paths within the optical cloud. The aspiration of TE is to direct data units away from clogged links and select links that accommodate aspired QoS and other constraints. IP routing agreements do not achieve the above; rather IP routing tends to focus the data units on to the generic core (more used links in the cloud).

Computation of path requires approach to link state intelligence, circulated by the routing agreement. However, this link state intelligence does not suffice for routing agreements incorporating TE [12]. Link state gives intelligence about the condition of the connections (active or dead) and their associated weights. Additional TE information required for computation of paths is as given below:

(a) existing links

(b) availability of unused bandwidth on links

(c) cost of using such links

(d) other constraints on the flow of data

From the above intelligence we can estimate a path that employs only links that have ample resources (bandwidth) and also the least weighed path to the receiving node. This paradigm for path estimation is called Constraint based Shortest Path First (CSPF). The paradigm can also be of a path that encompasses multiple connections with ample resource (bandwidth), and also assures least sending node to receiving node delay aberration. Further, constraint criterion of avoiding certain links and routers can also be used.

RSVP-TE is used as the routing model which satisfies the requirements of optical networks using TE [16]. RSVP-TE divides the routing model into routing process and then the signaling process. The routing process is discussed here and the signaling process will be discussed in section 2.3.4.2.

In the GMPLS routing process, TE links are defined, which represents available network resources for TE path computation. TE links can be mapped to a bundle of links, between a source – destination pair. All TE link capabilities are advertised by the end routers to all routers in the network. In this process, with the help of TE links and their associated information, a TED is built and distributed to all the LSRs in the network. Each LSR advertises its learned TE information to adjacent LSRs by 'flooding'. 'Hello' messages are advertised to discover new LSRs. These messages are exchanged in the control plane. TED is actually handled by the path computation procedure to estimate a TE path. A TE cloud visual representation (graph) is constructed using the intelligence contained in TED. The path computation algorithm operates on TE network graph. The TE intelligence which characterizes aptitudes of TE links can be route address, connection type, TE weight, sustainable connection bandwidth, largest engaged bandwidth and priority bandwidth.

GMPLS optical networks are complex TE networks [12]. Over and above the basic TE information we need to appreciate the switching capabilities of the connections at each optical routing unit (LSR). The information on protection links for the primary links, in event of failure may also be required and links with protection links available will be favored. Further, the greatest and the least possible bandwidths that can be designated to any optical routing unit (LSP) on the connection also need to be defined.

TE intelligence used to construct TED is circulated by OSPF routing agreement, which is a link state routing agreement. Each routing unit in the link state agreement is responsible for announcing intelligence about the status of all the connections it concludes. Each routing unit redistributes all intelligence that it acquires from other routing units. The result is that, all routing units receive intelligence about all links in the optical cloud from all other routing units, and thus constructs the same routing matrix of available connections and routing units.

Routing adjacency is a routing agreement exchange, among a pair of routing units and dictates the transaction of link state intelligence. These include 'discover' their peers and institute adjacency by transmitting 'hello' messages. These messages are sent periodically to all other routing units in the network. The process of 'flooding' means re-broadcasting of link state intelligence. Flooding ensures that this global intelligence reaches all routing units.

OSPF is extended with TE for GMPLS based optical networks. The aim is that the TE and GMPLS intelligence for TE links are passed on to every optical routing unit (LSR) in the cloud. GMPLS optical networks have a disjoint control and data planes. Hence, the routing agreement messages are only exchanged in the control plane. The routing agreement is used only to circulate the TE intelligence and not used to estimate the path.

The routing model for this dissertation will have a routing controller, which will be incumbent for broadcasting routing intelligence about the TE links terminated on the data plane of each LSR. Routing controller can physically be separated from the LSR, and may be responsible for group of LSRs to coordinate between them.

A separate wavelength (lambda) for the management agreement is dedicated to correspond between the LSRs in the data plane and routing controller in the control plane. Since, control and data planes are separated, hence their addresses are also in separate domains.

In GMPLS a LSP is defined as a route passing over the optical cloud, constituted of interlinked labels (resources here are wavelengths), on a succession of data plane connections [12]. The various types of routing procedures which can be used are:

(a) Implicit routing: Computed at each LSR, best route to the destination is chosen for the next hop. TED is used to compute the next hop.

(b) Explicit routing: Route of LSP completely detailed by the client application. The client application is aware of the present situation of the optical cloud and uses particular path using specific resources.

(c) Constraint – based path computation: The application provides a set of constraints and the selection of route is left to the control plane. Control plane chooses a path for an optical virtual connection (LSP) through the optical cloud, taking into consideration a group of constraints such as optical bandwidth, kind of service and particular connections and specific optical virtual connections (LSRs) to be contained in the route to be chosen.

Once the explicit path of an optical virtual connections (LSP) has been estimated (using TED) by the routing controller, this computed path is handed over to the signaling controller, which starts the process of establishing the LSP along the desired path. The specific path is provided to the signaling process as a succession of TE link terminating point IP addresses, or a succession of LSR IP addresses (all data plane addresses). Signaling messages travel in the control plane. Routing controller address is an IP address which is common to both the control and data plane domains, to ensure mapping between both these domains.

2.3.4.2 GMPLS Signaling

Signaling is the mechanism of interchanging messages inside control plane to establish, sustain, adapt and abolish data links in the data plane. Hence, there is a requirement of a signaling protocol. The signaling model has signaling controllers at each LSR in the network architecture. Each signaling controller is accountable for administering the data plane entities of more than one optical routing nodes (LSRs). Signaling controllers acquaint with their peers through control links in the control plane.

Optical channels do not incorporate in-band signaling as in MPLS and IP networks. In optical channels, each LSR is required to extract the signaling messages from the data flow and transmit it to the signaling controller. Hence, in-fiber-out of band control connection mechanism is used. This mechanism dedicates a specific wavelength for a group of wavelength traffics. This channel is also called the Optical Supervisory Channel (OSC) [12].The OSC ceases at each optical routing node (LSR), and the signaling information is forwarded to the signaling controller which is collocated.

Alternatively, the control channel can be out-of-fiber-out of band control connection. This mechanism employs a separate wavelength following an exhaustive divergent route from that of the existing data route. This is in the form of a signaling connection for a group of traffic wavelengths. The advantages of this scheme are that a solitary control connection may be utilized to administer greater than one data connection, and this also counters against individual link failures in the control plane.

There is a requirement of an addressing scheme, to identify link nodes during the process of establishing the LSP. Further, signaling controllers should be uniquely identifiable to deliver signaling messages to designated signaling controllers in the control plane. IP addressing scheme will be incorporated as identifiers interior to the control and data plane, to identify the following:

(a) Links
(b) Nodes
(c) Signaling controllers
(d) Routing controllers
(e) PCE controller

The addressing domains of control and data planes are separate entities. The mapping point will be the IP address of the Routing controller, which will have common addresses in both domains. Hence, the signaling messages contain two groups of addressing intelligence viz. one which interests dispatch of messages interior to the control plane, and the other which concerns path of an optical virtual connection (LSP) interior to the data plane.

GMPLS signaling has been constructed on messages elucidated for RSVP-TE [17]. The various terms of RSVP-TE signaling are:

(a) Session: defined as a categorization of data unit drifts to a particular receiving node. The session is established by an IP address of the receiving node and the port identifier of the receiving node. The attribute of the session is that all data unit drifts that form part of a session can stake resources within the optical cloud.
(b) GMPLS Tunnel:a virtual path created for a group of traffic flows originating from the same LSR and destined to the same LSR. Infusion of data unit flows into the tunnel assures its dispatch to the end of the tunnel. Each tunnel is acknowledged by the

receiving node identifier and a 16 bit tunnel identifier (instead of port identifier) for multiple tunnels. The LSPs behave as a tunnel in GMPLS.

A service may be sustained by more than one optical virtual connection (LSP), due to load sharing, bandwidth aggregation, and provision of protection capabilities. This architecture is called parallel LSP, which support same source – destination pair with a solitary service. Each optical virtual connection (LSP) is determined as constituent of a session using session object.

RSVP-TE uses the IP address of the sending node and unique 16 bit LSP identifier corresponding to the sender identifier, as identification for each LSP. Elements used to determine a LSP with reference to a session are composed in a session-template object. Control plane LSP manages data plane LSPs.

GMPLS signaling is created on messages characterized for RSVP-TE [18]. The basic messaging types are:

(a) LSP establishment is proposed by the ingress LSR (upstream end).
(b) LSP requisitioned using LSP setup message.
(c) LSP authenticated from downstream employing LSP confirm message.
(d) Errors propagated using LSP downstream/upstream error message.
(e) LSP teardown (release) message.
(f) LSP notify message gives the cue about the data plane condition of an LSP.

The LSP establishment begins with the initiation of LSP establishment by the ingress LSR, which sends an LSP setup message to the succeeding link in the course of the LSP [12]. Next hop is determined by looking at either explicit or implicit routing. Downstream LSR accepts the request by sending a LSP Accept message and supplies the specific label (wavelength) to be used to identify the traffic. The detailed LSP establishment procedure is given below:

(a) The LSP Setup message is dispatched downstream link by link in expectation of the egress LSR.
(b) At every LSR, data unit specifications are analyzed to be assured that the LSP can be sustained and the next link is resolved.
(c) When LSP Setup extends to the egress, the request is transformed to a LSP Accept message that is reverberated upstream link by link to the ingress.

(d) At each LSR, the label announced from downstream is constrained to the label for upstream interface; the process is called as label mapping. The associated resources (wavelengths), which are referred to as 'labels' here, are cross-connected in the data plane in the process of label mapping.

(e) On receipt of LSP Accept message by the ingress LSR, all resources (wavelengths) are cross-connected, and eventually the ingress is ready to start communicating data.

(f) A pre-reservation concept can be done in a way that a downstream LSR could choose an upstream label and provision it to avoid contention with future LSP Setup messages.

(g) There is an explicit break down maneuver that is utilized if an LSP aborts to free any resource (wavelength) in case of pre-reservation concept.

The various messaging during LSP establishment process is diagrammatically explained in Figure 2.3.

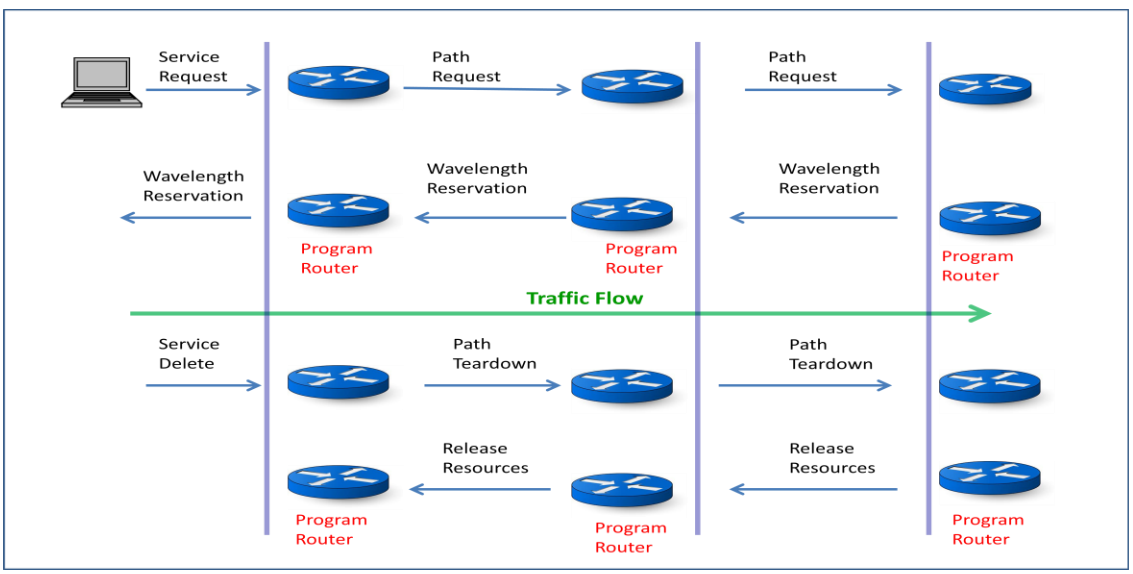

Figure 2.3: Messaging during LSP establishment process.

The above GMPLS RSVP-TE signaling messages are enclosed in IP data units that are directed to the subsequent signaling controller. Unlike IP networks, in GMPLS optical networks the data traffic follows the resource reservation [12]. This implies that the control plane messages pursue a well described route between the signaling controllers and thus institute more stable paths interior to the data plane.

GMPLS RSVP-TE runs directly over IP, and is thus incumbent for its own reliable delivery. This is done by giving a unique identifier for every message. On failure of an acknowledgement, the sender retransmits the message with an exponential delay, until an acknowledgement is received. GMPLS is generally utilized with an explicit path, where the route of an LSP will not deviate even if there are alterations in the network. This is done because dynamic and fluid changes in the LSP are not desired in circuit switched transport networks.

The usual process in LSP breakdown is that the ingress LSR (that initiated the LSP request) sends an LSP Downstream Release message. As LSP Downstream Release message advances through the optical cloud, the LSP is detached from the data plane and all control plane states are abandoned. This is the normal Downstream Release message. Another release (teardown) process is by LSP Upstream Release message, which makes an egress LSR to incite an LSP teardown. The entire architecture of GMPLS with routing and signaling components is illustrated in Figure 2.4.

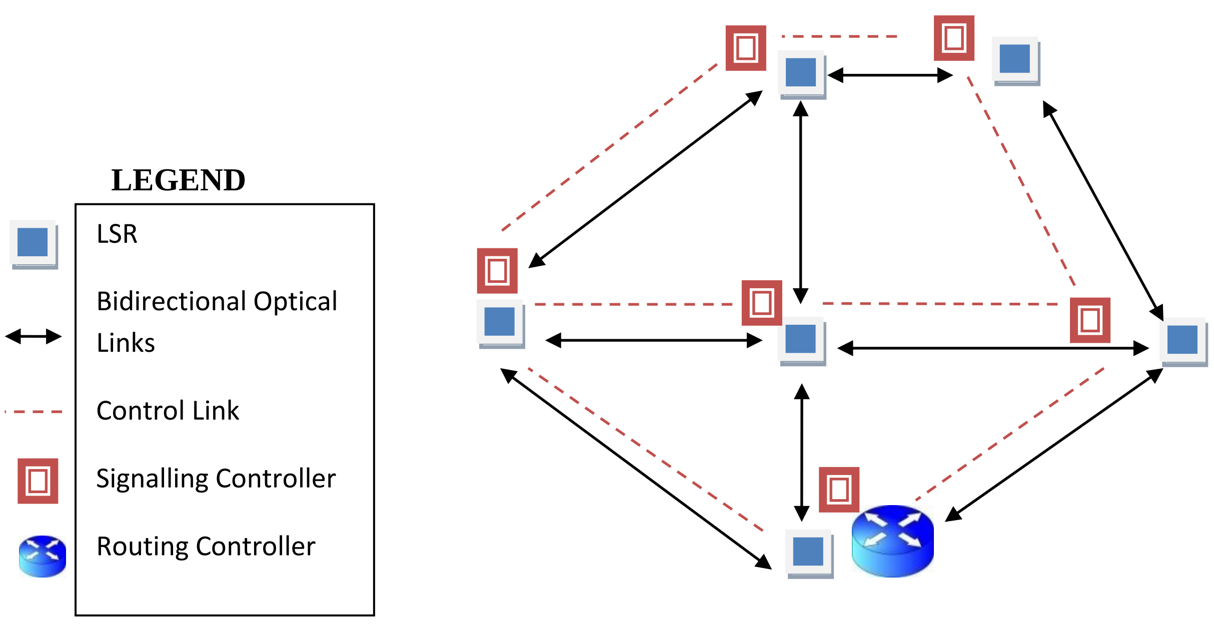

Figure 2.4: Architecture for GMPLS Routing and Signaling

2.4. Traffic Grooming Algorithm for Pure Optical Networks

It has been observed in optical networks that service requests data rates are a miniscule fraction of the data rate that optical lightpaths generally provide. In DWDM technology, each lightpath may have a capacity of transporting up to 80 Gbps of optical traffic [3]. The user data rate requirements generally average out in the range 500 Mbps. Hence, we see that allocating a single service request to a lightpath in optical networks is a sheer waste of optical network resource. Hence, the need arises to map more services on to a single lightpath, thus utilizing its capacity to the maximum. This in effect improves the capacity utilization of the optical network. The above phenomenon of optimum utilization of network resources in telecommunication networks had been termed as TE [12]. TE is essential for Next Generation Networks (NGN) and is an ever growing area of research.

2.4.1 Traffic Engineering in Optical Networks

TE was defined extensively for MPLS networks [19], as a tool which would ensure performance optimization of operational networks. The two basic aspects of TE in GMPLS are traffic oriented and resource oriented. Traffic oriented aspect will work and improve upon the QoS parameter of the traffic in the network. These QoS parameters may include data unit loss minimization, delay minimization, throughput maximization and Service Level Agreement (SLA) enforcements which ensure prioritization of data traffic.

Resource oriented aspect of TE refers to optimization of network resource utilization. Hence efficient management algorithms are required to optimize the utilization of network resources. This logically infers that to the fact that, all subnets of the network are equally utilized or else an over-utilized subnet may result in congestion inside the network.

Optical networks have graduated from telecommunication networks and hence are also in need of TE. The only difference here is that packets are replaced by lightpaths, which constitute of available wavelengths or lambdas in the network. Further, these wavelengths are such a powerful data rate carrying resource that importance of TE becomes more significant in optical networks. One of the dominant network resources in optical networks is bandwidth, as that decides the traffic carrying capacity of the network. Hence, the important factor of TE in optical networks is efficient management of bandwidth resources, which are lightpaths and more specifically available wavelengths. TE gives appreciable results for well used networks and its importance reduces for under used networks. Next generation optical networks have also to factor QoS requirements and ensure prioritization of traffic, to guarantee SLAs in situations when congestion is observed inside the network. Further, optical networks require efficient RWA algorithms for protection against failures of optical links. The RWA combined with TE can provide maximum utilization of network resources.

2.4.2 Optimization of Optical Networks

Optical networks employing pure optical regeneration provide high data rates/speeds in the backbone network [2]. WDM technique employed with optical amplifiers could multiplex a large number of wavelengths (or communication channels) on a single strand of fiber. C/D WDM technology is driving backbone pure optical networks of the future, and providing these networks with data rates in the range of thousands of Gbps in a single strand of fiber. Due to exponential increase in cellular and internet users around the world [3], this bandwidth will soon seem meager in comparison to backbone data rate requirements of the future. Traffic grooming is a process of combining various flows of data into a single channel thus optimizing existing bandwidth. Further, traffic grooming can prioritize the flow of data as per different classes of service. Hence, an efficient traffic grooming algorithm needs to be formulated to enhance the bandwidth utilization and further optimize future telecommunication networks.

The future telecommunication networks are IP packet based which is also the case for 4G and 5G mobile networks. The telecommunication users demand high quality and high definition content and therefore utilize high data rate services from the service providers. Presently for countries with growing economies like India, the networks are unable to provide the desired QoS as per the growing needs of the users.

A Traffic Grooming Algorithm (TGA) is proposed in this research work which assigns weights to each connection request for every node in the multi-fiber optical network. Every connection request is classified into three different classes, thus, ensuring differentiated service. The number of hops and data rate requested by each service request is adequately utilized with the class of service to calculate weight for each connection request. The weights thus assigned to each connection request on the basis of the above connection parameters are arranged in a fashion that the lighter requests are given higher priority and are assigned a better quality of optical fiber for transmission. The incorporation of above traffic grooming algorithm will ensure to lower the overall blocking probability of the network. The incorporation of the proposed algorithm will substantially improve the QoS requirements of the present day and future telecommunication networks.

2.4.3 Problem Statement and Related Work

2.4.3.1 Problem Statement

The current requirement of a telecommunication network is to efficiently use the existing resources provided by the backhaul network. A traffic scheduling algorithm has been proposed in this research which uses dynamic fiber state information, class of service quantization and prioritization of service requests. Architecture of PCE as standardized by GMPLS has been incorporated in the proposed TGA to facilitate routing and signaling requirements of complex optical networks. The proposed TGA can effectively groom and prioritize the service traffic to improve the overall connection blocking probability of the network in highly utilized optical networks, in which the effectiveness of the algorithm becomes significant.

The scope of this research work is to verify the performance of the proposed TGA with existing RWA techniques. Therefore, much emphasis has not been given to RWA techniques in the research work as this topic has been greatly researched. Hence, the standard dynamic RWA techniques like First Fit and Random Fit [20] have been incorporated with the algorithm in the simulations to demonstrate performance of the proposed TGA in comparison to other existing information scheduling algorithms. Further existing algorithms such as OSPF-TE [12], as used in MPLS and GMPLS networks, would be utilized to find the optimum path in the network for the service request.

2.4.3.2 Related Work

In this section, we present an overview of related work for traffic grooming in optical networks. The routing and wavelength assignment problem in GMPLS-PCE based architecture has been proposed in which combined and separate routing, and wavelength assignment schemes have been analyzed [15]. Research on various routing and wavelength assignment schemes and their comparison is also available [20]. TE in multilayer networks, for GMPLS network architecture, with heterogeneous routing and bandwidth engineering has been proposed and the performance analysis of the same is discussed [21]. Dynamic adaptive QoS routing algorithm which gives impetus to Bit Error Rate (BER) of links has been proposed in [22]. Traffic grooming approach to reduce number of wavelengths required to accommodate maximum number of connection requests has also been proposed in [23]. A new concept of priority based routing to assign wavelengths according to priority order of connection requests to reduce blocking probability in the network is discussed in [24]. Requirements of TE in MPLS networks is given in [25] and review of RWA approaches is done in [26]. Review of wavelength grouping for effective traffic scheduling to reduce blocking probability is also proposed in [27]. Traffic provisioning for various connection data rates incorporating optical launch power measurements has been researched in [28]. Heterogeneous traffic scheduling for future DWDM based optical networks utilizing network coding to improve connection blocking probability is available in the literature [29]. Further, QoS routing for various networks have also been researched in [30-31]. WDM systems and networks have also been researched well [32]. Performance analysis on RWA approaches is done in [33]. Load balancing in WDM networks through dynamic route changes [34], and optical power aware quality analysis for selection of optical connection over WDM networks have been adequately researched in [35]. Literature on heuristic algorithm for static Wavelength Assignment (WA) in optical networks [36] is also available. Priority based traffic scheduling and utility optimization for smart grids [37] has shown that priority based traffic scheduling is an imminent requirement for all networks, be it wireline or wireless, to optimally utilize the bandwidth resource of all types of networks. Traffic grooming in PCE based and similar architectures has been researched [38-42]. In recent research literature, prioritizing traffic in wireless networks akin to that done in optical networks have gained much importance since bandwidth in wireless networks is a critical resource which needs to be optimized. Prioritizing traffic in wireless networks has also been reviewed [43-45]. Traffic grooming with BER/OSNR considerations in optical networks has been researched in [46-49].

2.4.4 Traffic Grooming Algorithm (TGA)

Pure optical networks require efficient dynamic RWA algorithms for protection against failures of optical links. The dynamic RWA combined with TE can provide optimal utilization of network resources. Though various studies on priority based algorithms for traffic grooming in optical networks have recently been undertaken [20-24] and [27-29] as brought out, however the prioritization of user traffic to support QoS, enforcing SLAs, and use of fiber link state information has not been incorporated in these algorithms.

The TGA proposed addresses all the above issues and is discussed in the following sub sections.

2.4.4.1 Dynamic Fiber State Information

The optical networks undergo frequent fiber cuts in developing countries due to infrastructure developments. This results in cumulative losses and unusable fiber pairs in the optical links [3].

Therefore the knowledge of lossy fiber pairs in the entire optical network architecture is important for efficient TE and RWA.

In view of the above, Fiber Sensing Controllers (FSC) are used in the architecture of the proposed TGA at every optical node or LSR in the pure optical network. The FSC routinely calculates (every 5 ms) the OSNR of the fiber pairs. The time period for the above calculation of OSNR for all fibers in the optical network by the FSCs should be low to react to the dynamic nature of the network. A realistic value of 5 ms has been chosen based on the existing Optical Network Management Systems (ONMS) setup manufactured by JDS Uniphase Corporation (JDSU) [50]. The FSCs calculates the OSNR for every fiber pair emerging from each LSR, and this Dynamic Fiber State Information (DFSI) is passed on to the central ONMS collocated with the central PCE controller through a dedicated Ethernet link of 100 Mbps, from the FSC to the ONMS. DFSI is provided by the ONMS for the entire network to the central PCE controller via the 1 Gbps Ethernet Link. Further, at the central PCE, all the information regarding the fiber link state are analyzed and every fiber in the network is classified [38] as Fiber Class A (OSNR > 30 dbm, best quality fiber) or Fiber Class B (20 dbm < OSNR < 30 dbm, average quality fiber) or Fiber Class C (OSNR < 20 dbm, which is a poor quality fiber and all connections assigned to this fiber are not successful), as per the state of the fiber at present. This grading of all fibers in the network is used by PCE to assign the best strand of fiber in the optimum route for every request of the LSP. The above process is aptly explained in sub section 2.4.4.5.

2.4.4.2 Class of Service Quantization of Traffic

The service traffic is classified into multiple CoS [38-39] which ensures satisfying the SLA. As subnets of a network get congested due to high inflow of traffic, there is a requirement to prioritize the information/traffic flowing so as to ensure that higher priority information is passed first before passing the low priority information. In order to ensure the above, TGA grades the user information by classifying them into three levels of services:- Class A information (CS = 1) – for real time information (applications for video (live) and voice), Class B information (CS = 2) – for information which is non-real time (for compressed video and transactional data information) and Class C information (CS = 3) – for delay tolerant information (file transfer). The grading for CS ranges from 1 to 3, as explained above. The above grading is processed by an information grader called "CoS Prioritizer". CoS Prioritizer is available at every interface with the user in the optical network. The central PCE controller receives such information requests from PCC, collocated with the optical node, on the PCECP control link as per the GMPLS architecture and the above is adequately explained in sub section 2.4.4.5.

2.4.4.3 Prioritization of Label Switched Paths

All information requests in the GMPLS architecture are converted into a unique LSP. The virtual path of LSP is generated by flipping of labels for information transfer in the GMPLS based pure optical network [12]. The PCE receives a virtual path request from the PCC for LSP generation in the GMPLS architecture. The central PCE controller incorporates algorithms for routing (OSPF-TE) for generation of LSP. TGA incorporates a LSP prioritizer in the GMPLS architecture which interacts with the central PCE controller. Two significant parameters are extracted in the LSP prioritizer from every LSP request; the requirement of data rate for the LSP and quantum of hops requested by the LSP (utilizing existing dynamic routing information with the centralized PCE. The above process is discussed in detail in sub section 2.4.4.5.

2.4.4.4 Proposed Algorithm Architecture

The components which are inherent in the TGA architecture are: FSC, CoS Quantizer, LSP Prioritizer, central PCE Controller, Routing Controller, Signaling Controllers, LSRs with PCE components, ONMS, bidirectional optical links, control links and PCEP links. The flow diagram of the logic for the TGA imbibing multiple components is shown in Figure 2.5.

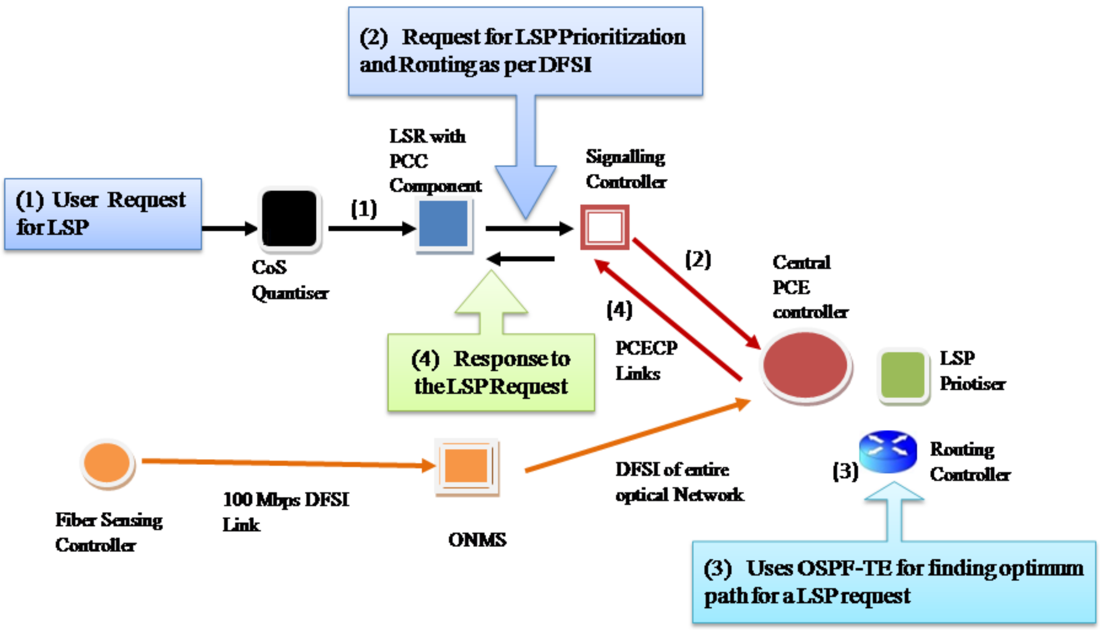

Figure 2.5: Logical flow of TGA processes

Various processes of the proposed TGA are enumerated below:

(a) Initial request for LSP is given to CoS Quantiser. The CoS Quantiser classifies the request as Class 1/2/3 as per the traffic classification given in sub-section 2.4.4.2 and forwards the request to the LSR with PCC component.

(b) The PCC component with LSR then forwards the requests for LSP to the central PCE controller through the Signaling Controller using the PCECP Links of PCE based architecture of GMPLS.

(c) The fiber state information is already updated at central PCE controller from the respective FSC and ONMS. The central PCE controller assigns the optimum LSP using the OSPF-TE routing protocol on the best fibers as per the DFSI given in sub-section 2.4.4.1.

(d) The assigned optimum route by the central PCE controller with best fiber allocation is sent as response to the user request back to the requesting LSR with PCC component through the Signaling Controller on the PCECP Link.

(e) This process continues for each LSP request by every LSR in the optical network. Further, the detailed architecture for the above components for implementation of the TGA is shown in 2. 6.

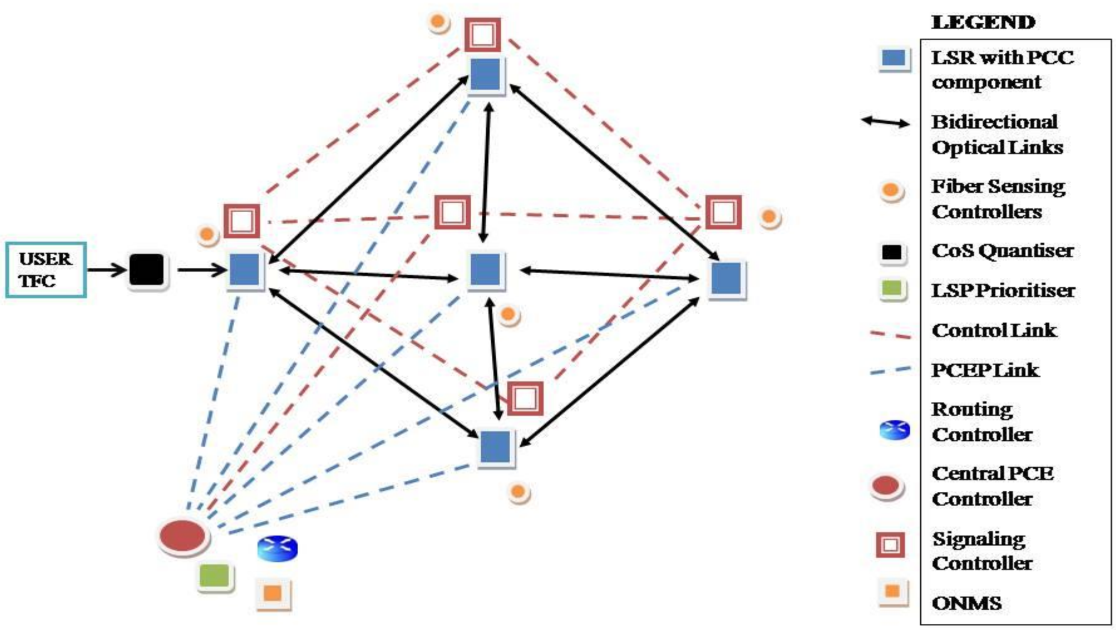

Figure 2.6: Architecture for Implementation of TGA.

2.4.4.5 Algorithm Functionality

We first detail the parameters used in this research work followed by the proposed algorithm. Parameters available with the central PCE controller are as follows:

(a) Type of fiber (A/B/C) – DFSI received from all the FSCs in the network and given to the ONMS available with the central PCE controller for fiber classification.

(b) Class of traffic (A/B/C) – received from the CoS quantizer, at each servicer/user access interface.

(c) Number of hops of LSP requested – received from LSP Prioritizer, collocated with the central PCE controller.

(d) Data rate of LSP requested –also received from LSP Prioritizer.

2.4.4.5.1 Variables Used

Variables to be used in the TGA [38] are enumerated below:

(a) MH: The highest value of spans from origin to any destination in the optical network, as computed by the routing algorithm OSPF-TE, incorporated in TGA. Maximum Hop (MH) is given a value of 4 for ease of assimilation of the functionality of the algorithm.

(b) MD: The highest data rate designed in the network architecture for every optical link. The network is so designed that each link has same amount of data rate capability. The value given to Maximum Data rate (MD)for assimilating the functionality of TGA is10 Gbps.

(c) DLSP: The requirement of data rate for each request of LSP.

(d) WLSP: The assignment of Weight (after computation) to every LSP (elaborated in Step 2).

(e) HLSP: Quantum of spans requested by every LSP.

(f) CLSP: Service classification of information of the user.

(g) PLSP: The assignment of Priority for the request of the LSP.

(h) WLSP(a-b): Assignment of wavelength for successful transport of information from node ‘a’ to node ‘b’.

(i) AWLSP(a-b): Wavelength available in the optical link from nodes ‘a’ to node ‘b’.

(j) The central PCE controller has all the above variables available for processing as per TGA steps elaborated below:

2.4.4.5.2 Steps of the Algorithm

Step 1: ‘LSP Requirement Matrix’ is created for all the requests of LSP for the entire optical network, as given in Table 2.1.a.

Table 2.1.a: LSP Requirement Matrix

Ser No	Source Id	Dest Id	No of Hops **H_{LSP}**	Data Rate in Gbps **D_{LSP}**	CoS **C_{LSP}**
1	01	03	4	0.5	2
2	02	05	3	1.0	1
3	01	04	2	0.5	3
4	02	06	4	1.5	2
5	03	06	3	2.5	3
6	05	02	3	1.5	1

<u>Step 2</u>: On generation and population of all the entries of 'LSP Requirement Matrix' from all the LSRs in the optical network, the computation of weight (WLSP) for every LSP request is done by PCE utilizing equation 2.1.

$$WLSP= \{ HLSP/ (MD) \} + \{ CLSP / (3) \} + \{ DLSP/ (MD) \} \qquad (2.1)$$

The concept of assignment of weight for a LSP request (WLSP) in equation (2.1) is that the computed weight is directly related to the ratio of network resources utilized by the individual serviced LSP requests. The factor of capacity utilization, which is termed the weight of the LSP request (WLSP), is computed with the aggregation of three terms in equation (2.1). The three terms are explained in the succeeding paragraphs:

(a) <u>First term of equation (2.1)</u> – provides the fraction of quantum of spans traversed (HLSP), in relation to the highest value of spans in the network (MH).

(b) <u>Second term of equation (2.1)</u>– provides the fraction of CoS (CLSP) graded, in relation to the greatest value of CoS (which is '3') as enumerated in section 2.4.4.2.

(c) <u>Third term of equation (2.1)</u>– The data rate utilization ratio (DLSP), in relation to the highest value of data rate designed in the network (MD) (assumed 10 Gbps in the algorithm).

The values of weights for each individual LSP requests are computed for all rows in the LSP requirement matrix in Table 2.1.a, and a fresh LSP weight matrix will be generated and called as Table 2.1.b.

Table 2.1.b: LSP Weight Matrix

Ser No	Source Id	Dest Id	No of Hops **H_{LSP}**	Data Rate in Gbps **D_{LSP}**	CoS reqd **C_{LSP}**	Weight **W_{LSP}**
1	01	03	4	0.5	2	1.716
2	02	05	3	1.0	1	1.183
3	01	04	2	0.5	3	1.550
4	02	06	4	1.5	2	1.816
5	03	06	3	2.5	3	2.000
6	05	02	3	1.5	1	1.234

Step 3: The rows populated in the LSP Requirement Matrix in Table 2.1.b are realigned in increasing order of values of weights (WLSP) of LSP requests in such a way that heavier weighted LSPs are at the bottom of the table and light weighted LSPs are above on the table. With the above realignment, a 'Prioritized Queuing Table' will be generated as given in Table 2.2.

Table 2.2: Prioritized Queuing Table

Ser No	Source Id	Dest Id	No of Hops **H_{LSP}**	Data Rate in Gbps **D_{LSP}**	CoS reqd **C_{LSP}**	Weight (ascending) **W_{LSP}**
2	02	05	3	1.0	1	1.183
6	05	02	3	1.5	1	1.234
3	01	04	2	0.5	3	1.550
1	01	03	4	0.5	2	1.716
4	02	06	4	1.5	2	1.816
5	03	06	3	2.5	3	2.000

The requests of the LSPs are aligned in a stack like virtual container for every LSR as demonstrated in the TGA architecture in Figure 2.2. The lighter weighted LSP requests are in the virtual container and the heavier weighted LSP requests are lower in the virtual container. The highest entry in the virtual container is first assigned the desired LSP and thus accorded priority. The above ensures LSP request Prioritization.

Step 4: The architecture of fiber links for the pure optical network for functionality demonstration of TGA is given in Figure 2.3. Figure 2.3 fiber link architecture shows that Node 1 is linked to Node 2, Node 3 and Node 4 with 12 fiber connections each, resulting in a total of 36 fiber connections emanating from Node 1. The central PCE controller receives the DFSI information and generates a 'Node wise Fiber State Information' for every optical node. Let us assume the Node wise fiber state information for Node 1 in the schematic of Figure 2.7 be given at Table 2.3.

Table 2.3: Node wise Fiber State Information/Node.

Destination Node	Number of Fibers **Class A**	Number of Fibers **Class B**	No of Fibers **Class C**
2	03	07	02
3	02	06	04
4	04	05	03

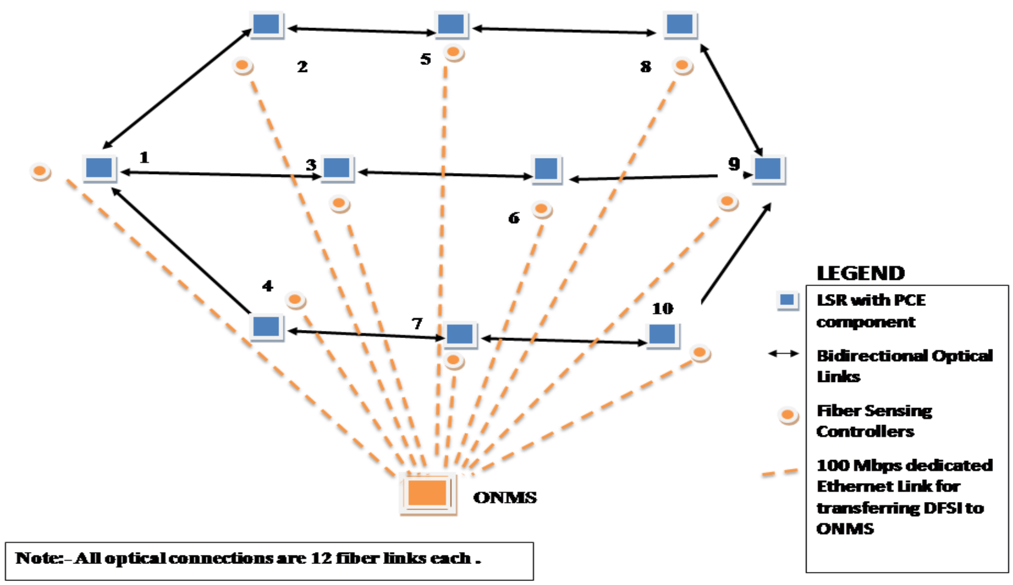

Figure 2.7: Schematic of Optical Fiber

We should note that the Class C Fiber is of an inferior quality and all the links allocated to this grade of optical fiber will ensure dropping of LSPs, which will increase the connection blocking probability of the network.

Step 5: Table 2.2 derived out of Step 3 which is termed as the ‘Prioritized Queuing Table’ (for every node), and Table 2.3 derived out of Step 4 which is termed as ‘Node wise Fiber State Information’, would be utilized for allotment of LSPs by the central PCE controller for every hop of the total route. The highest row entry in the Table 2.2, allocates the best grade of optical fiber from Table 2.3 for the end point node, if obtainable; else an inferior grade of optical fiber which is obtainable in that hop is assigned. If there are no obtainable optical fibers, the request for the LSP will be unsuccessful. The above procedure runs through again for the next row entry of Table 2.2, until no row entries are available in Table 2.2. Step 5 individually processes for every optical node in the optical network.

The logic for assigning weights for each LSP request is as follows:

Let X(a-b)be the value of a parameter X for node pairs a to b

Then WLSP(a-b)< WLSP(a-c),

if CLSP(a-b)< CLSP(a-c)and

DLSP(a-b)< DLSP(a-c)and

HLSP(a-b)< HLSP(a-c)

2.4.4.5.3Priority Assignment

The priority of the LSP request is inversely proportional to the weight assigned by the above step.

i.e, PLSP(a-b)> PLSP(a-c)

if WLSP(a-b)< WLSP(a-c)

2.4.4.5.4 Constraints

The following constraints are utilized in the simulation process:

(a) Data Rate constraint: The data rate requested for each LSP should be less than or equal to the maximum data supported for each link which is MD.

i.e. DLSP(a-b)< = MD

(b) Hop constraint: The number of hops requested for each LSP should be less than or equal to the maximum number of hops as calculated by OSPF-TE which is the routing algorithm used in the simulation process.

i. i.e. HLSP(a-b)< = MH

(c) Wavelength constraint: The wavelength can be assigned in each link only if the following condition satisfies

i. WALSP(a-b)= 1 iff AWLSP(a-b)> 0, else

ii. WALSP(a-b)= 0.

where,

AW is the number of wavelengths available and WA is a Boolean value indicating wavelength assignment for a fiber link. The above expression implies that the wavelength assignment is not successful if no wavelength is available in the fiber link.

2.4.4.5.5 Complexity of the Algorithm

The computational complexity of the equation (2.1) in Step 2 is of the order O(1), which is minimal. The computational complexity of the entire algorithm from Step 1 to Step 5 is equal to O(nlog(n)) + O(1) ~ O(nlog(n)), where n is the input size in units of bits needed to represent the input. The TGA has incorporated additional components such as FSC, ONMS, CoS Quantizer, LSP Priotizer and Ethernet links for the implementation of the algorithm in the standard GMPLS architecture. These components can be easily implemented on the existing hardware or as add-on hardware for implementation of the TGA. The cost factor for the implementation of the above components is not substantial; however, it optimizes the utilization of network resources substantially, to ensure more services being provisioned on the existing network. The above is aptly demonstrated in the simulation and their results in Section 2.5.

2.5 Simulation Results and Analysis

The simulation architecture of TGA [38] using dynamic RWA in PCE based architecture is demonstrated as the optical network of the Indian sub-continent in Figure 2.8. The optical network comprises of ten LSRs (optical nodes), linked via eleven bi-directional connections to create an architecture which is meshed in nature. Each bidirectional optical link incorporates twelve fiber strands, with every fiber strand using four wavelengths each. There is one central PCE controller in the architecture which is linked to every other LSR in conjunction with PCC component via a PCECP communication connection so as to ensure that the control signals are transmitted from the central PCE controller to every other PCC on the control plane. There is a provision of FSC at each LSR, whose primary job is to update the DFSI for all fibers branching out from the LSR in regular intervals of 5 ms via the 100 Mbps Ethernet Link destined to the ONMS. The ONMS in turn revises this new DFSI every 5 ms via the 1 Gbps Ethernet Link destined to the central PCE controller. The central PCE controller is connected with a routing controller whose primary job is to run the routing protocol to find the optimum path for every LSP request. OSPF-TE is used as the routing protocol for computation of the optimum path for each LSP request. The LSRs are also interlinked to a signaling controller for transmission of control information to the other signaling controllers and also the central PCE controller on the control plane. RSVP-TE is the signaling protocol which is incorporated in the GMPLS architecture to establish the LSPs. Further, it is also clarified that there are 2000 packets generated per node and each packet attempts to get an independent connection in the simulation. There are a total of 10 nodes, each node generates 2000 packets per simulation and all these packets attempt to establish a connection. A connection is either successful or failed, and a failed connection is dropped and does not try to reconnect, thereby resulting in the overall increase in the Blocking Probability (BP). This work enhances and details the initial work by the authors [38-39] by analysing the performance of algorithm on the following issues:

(a) Analysing the relative improvement of BP for TGA and non-TGA cases by increasing the wavelengths per optical link.
(b) Analyzing the effect of TGA on each CoS and also comparing it with TGA and non-TGA cases.
(c) Incorporating Dynamic Routing and comparing the performance of TGA with non-TGA case.
(d) Analyzing the improvement in Network Resource Utilization in comparison with BP on incorporating TGA in the optical network.
(e) Inference from above analysis is also highlighted in this work.

2.5.1 Simulation Details

The simulations have been carried out in INET Framework in the OMNET++ open source simulating environment [51]. The network architecture of Figure 2.8 has been simulated in INET Framework and the TGA has been incorporated in each of the 10 optical nodes as a software code. Each node generates 2000 packets to each of the nine other nodes. The number of packets lost in the entire network is found out and the BP is plotted with respect to the increasing Traffic Intensity (TI).

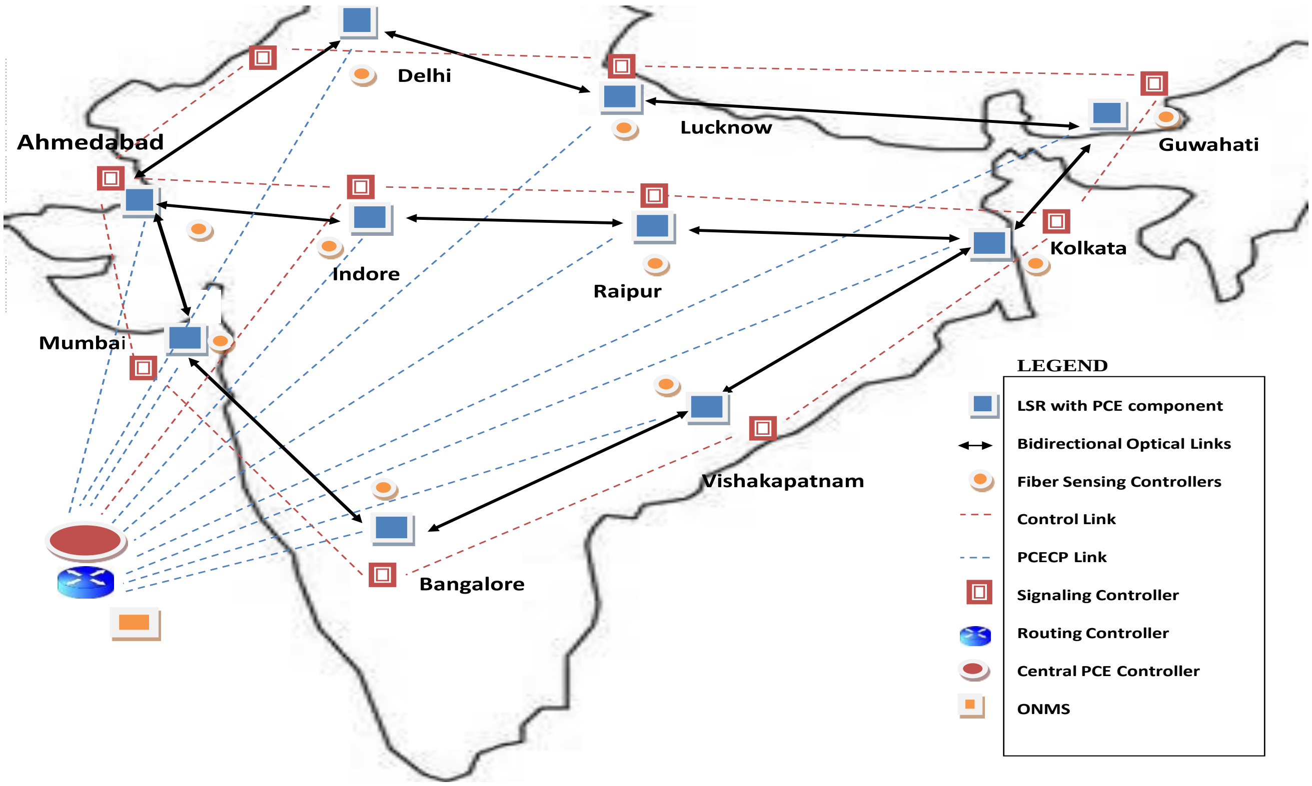

Figure 2.8: Architecture for simulation of TGA in an Indian optical network.

The assumptions made for the TGA [38] are enumerated below:

(a) The nature of requests for LSP creation is random and is Poisson distributed. The arrival times between two successive LSP creation requests has an exponential distribution.

(b) The highest data rate capability of every optical connection is 10 Gbps. The lowest data rate requirement for a connection is kept at 500 Mbps. Additional requests for LSPs should be in bundles of 500 Mbps.

(c) The packets are generated randomly for all realizable origin to end-point links and a LSP request will not be realizable if the network resources are not available.

(d) Plotting of simulation results has been with BP in comparison to expanding TI for four wavelengths, each in a linear scale. The quantum of users in the optical network is directly related to the TI. The number of packets lost in the network is directly related to the BP.

(e) The number of packets generated per LSR in the optical network gradually increases to 2000 packets, which directly increases the TI of the network.

(f) OMNET++ (version 4.2.2) with INET framework has been incorporated for the simulation process.

(g) Incorporation of IP/MPLS routers has been done in the simulation of TGA. Suitable coding has been ensured in these routers in the simulation in order to groom the traffic before transmitting information to the next router on the optical link. The use of RSVP-TE routing protocol for control plane signalling has been ensured. To cater for route calculation OSPF-TE has been implemented in the routing controller.

(h) Node failures have ensured to simulate real network scenarios and further convergence of the network. Node Indore in the simulation architecture of Figure 2.8 is failed and then recovered in the simulation every 5 secs to create real network scenarios.

Various parameters utilized in the simulation are provided in Table 2.4.

Table 2.4: Simulation Parameters

S. No.	Simulation Parameter	Value used in simulation
01	Number of optical nodes	10
02	Number of Bi-Directional Links	11
03	Number of Wavelengths in each Link	4
04	Link Capacity of Bi-Directional Link	10 Gbps
05	Minimum Data Rate request unit for an LSP	500 Mbps
06	Number of Packets generated by each node	2000
07	Maximum number of Hops	4
08	Step Size of the Simulation	0.005
09	Batch Processing Time	5 ms
10	Confidence Interval	95%

The simulation has been carried out in five phases as described below:

2.5.2 Phase 1

In the first phase, the functionality and performance of TGA algorithm is evaluated in isolation, without incorporating any routing algorithm. Simulations have been carried out in the Indian optical network architecture as given in Figure 2.8, in two parts. In the first part, the network is simulated with ordinary traffic (without any traffic grooming or incorporating traffic engineering algorithm). In the second part, the simulation in the Indian optical network of Figure 2.8 has been carried out incorporating the proposed TGA algorithm. The relative BP has been plotted with respect to increasing TI for single wavelength. The simulation is next carried out with two, three, and four wavelengths in each of the bidirectional optical links.

The simulation plots of relative BP with respect to TI for two, three, and four wavelength links for both ordinary traffic and groomed traffic (with TGA algorithm) is shown as a composite figure in Figure 2.9

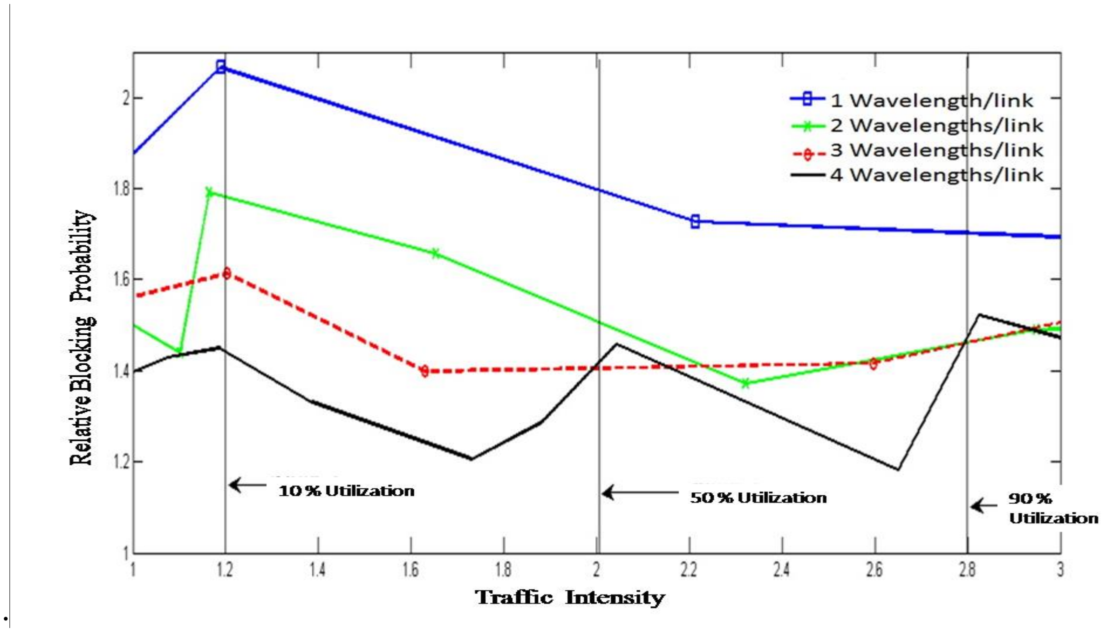

Figure 2.9: Comparison of BP v/s TI curves for 1/2/3/4 wavelengths/links of non-TGA with TGA normalized to X- Axis.

From Figure 2.9, following can be inferred:

(a) In Figure 2.9, the TGA curve has been kept in the X-Axis that is given a value of 1, and the non-TGA curves are plotted with respect to this normalized TGA case (X-Axis). Hence, there are four curves for wavelengths ranging from 1 to 4.

(b) The improvement can be seen as how many times the Relative BP of non-TGA case is higher than TGA case kept at a value of 1 for increasing wavelength values of 1, 2, 3 and 4 for each link in the simulation architecture.

(c) It is observed that when there is 1 wavelength/link the non-TGA case has nearly 2 times higher relative BP than TGA case. Further, for 2 wavelengths/link, the non-TGA case has nearly 1.8 times higher Relative BP than TGA case. For 3 wavelengths/link, the non-TGA case has nearly 1.6 times higher Relative BP than TGA case and for 4 wavelengths/link the improvement in Relative BP value comes down to 1.4.

(d) There is a substantial improvement in the connection BP performance of the network while incorporating TGA algorithm. The improvement due to the TGA algorithm is most effective when a single wavelength is used in each link. The improvement reduces as the number of wavelengths increase in each link. This is in accordance with the established fact, that TE is less effective when the network is underutilized.

Further to analyze the proposed TGA, one wavelength per bidirectional optical link was simulated and BP for increasing TI, in the logarithmic scales for non-TGA case, TGA case, Class-1 Traffic, Class- 2 Traffic, Class-3 Traffic was plotted and the results are given in Figure 2.10.

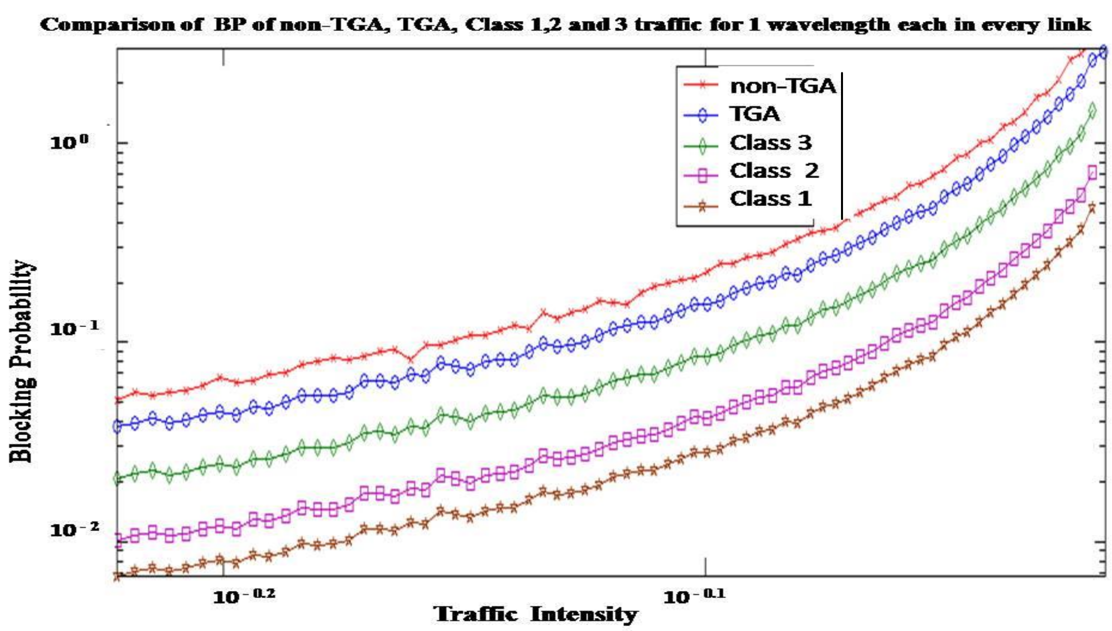

Figure 2.10: Comparison of BP of non-TGA, TGA, Class 1, 2, 3 traffic for one wavelength/optical link.

From Figure 2.10, following can be inferred:

(a) TGA case has a substantially lower BP than non-TGA case.

(b) Further in the TGA case, if we analyze the BP for each class of traffic we observe that Class-1 traffic has 18 % BP, Class-2 traffic has 27 % BP and Class-3 Traffic has 55% BP as compared to the complete TGA case, which includes all the three classes of traffic as per equation (2.1) in sub-section 2.4.4.5.

(c) Hence, we can visualize as to how TGA incorporates the BP of each class of traffic in terms of increasing TI.

Further to analyze the network resource utilization in terms of BP for the network when TGA is incorporated and without TGA being incorporated is given in Figure 2.11.

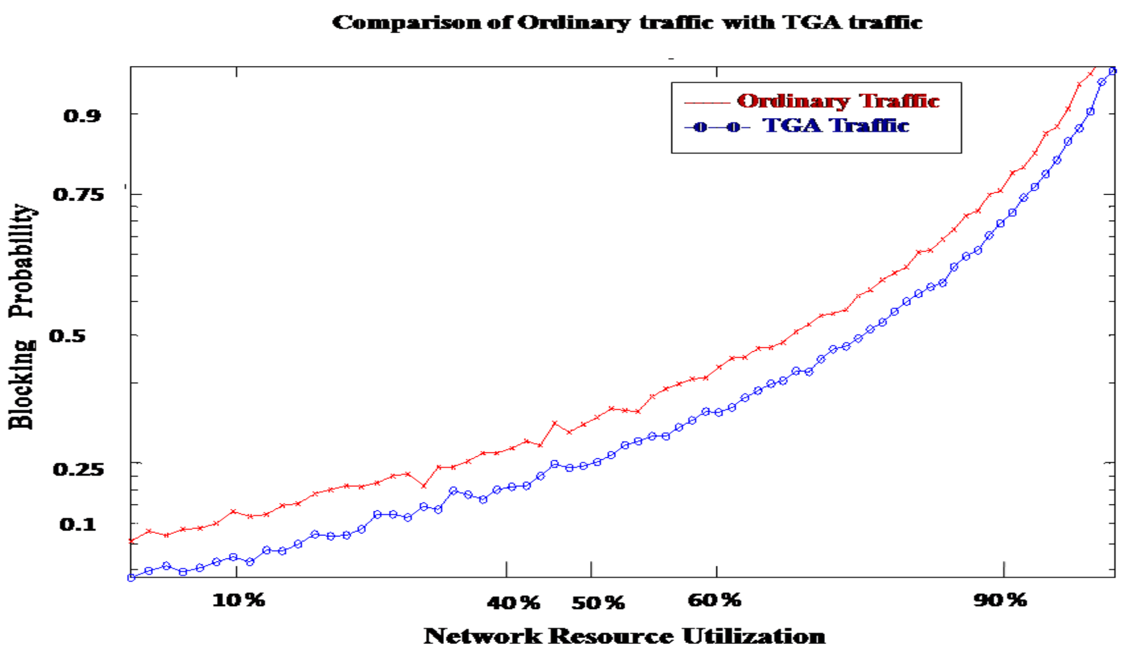

Figure 2.11: Comparison of Network Resource Utilization with BP for TGA Traffic and Ordinary Traffic.

From Figure 2.11, following can be inferred:

(a) The BP becomes substantially higher as the network resource utilization is increased.

(b) The performance of TGA is substantially better in terms of BP compared to ordinary traffic (non-TGA case).

2.5.3 Phase 2

In the second phase, the TGA has been combined with dynamic OSPF-TE routing algorithm and its performance evaluated by comparing it with a dynamic OSPF-TE routing model without TGA.

The BP has been plotted with respect to increasing TI for four wavelengths, both in linear scales, and the result is shown in Figure 2.12.

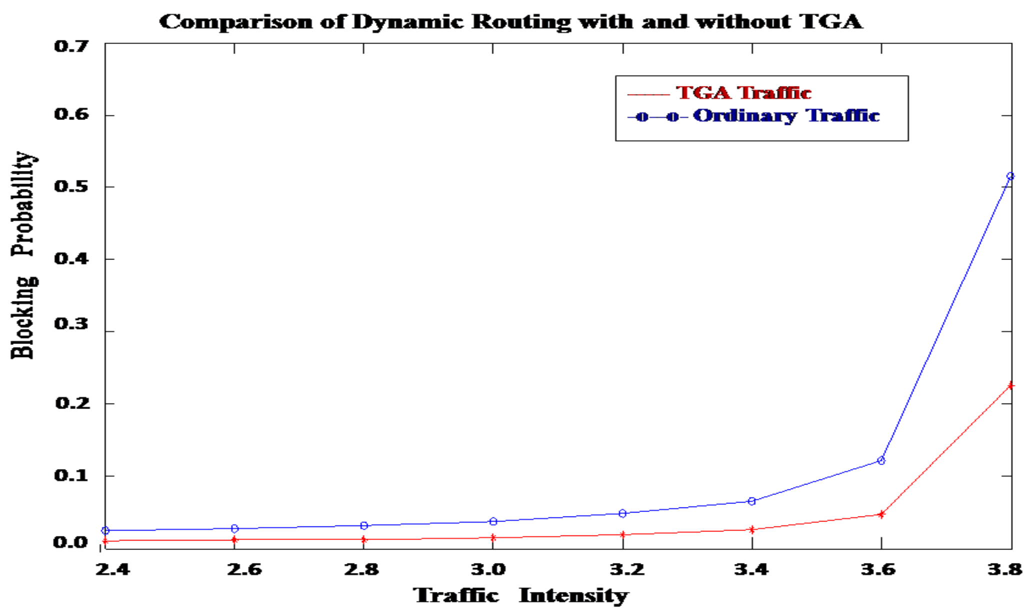

Figure 2.12: Comparison of Dynamic Routing with and without TGA, BP v/s TI for four wavelengths.

From Figure 2.12, following can be inferred:

(a) Dynamic routing (OSPF-TE) incorporating TGA has a better performance in terms of connection BP when compared to dynamic routing with ordinary traffic (without TGA). There is a substantial improvement in connection BP using TGA algorithm.

(b) The improvement in connection BP is most effective when the network is loaded with greater than 90% of input user traffic.

2.5.4 Phase 3

In the third phase, the dynamic routed (OSPF-TE) TGA was combined with two of the existing optimum WA techniques. In the first part of simulation process Random Fit (RF) WA technique was used and in the second part First Fit (FF) WA technique was used. The simulation result comparing the performance of dynamic routed (OSPF-TE) TGA combined with RF-WA and FF-WA techniques are shown in Figure 2.13. The connection BP has been plotted with respect to increasing TI for four wavelengths, in linear scales.

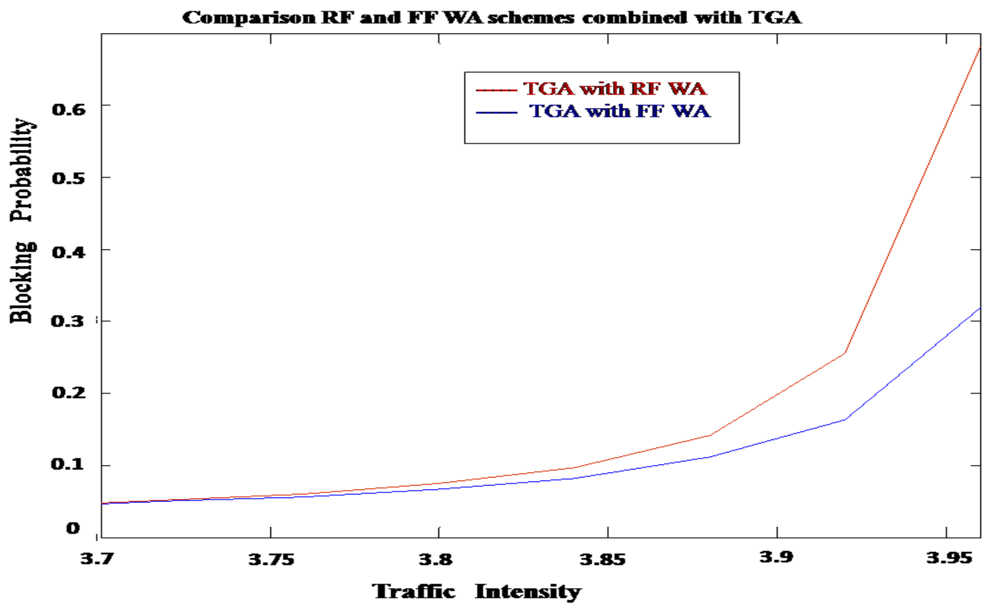

Figure 2.13: Comparison of Dynamic Routing with TGA using RF and FF WA schemes, BP v/s TI for four wavelengths**.**

From Figure 2.13, following can be inferred:

(a) FF-WA scheme has lower connection BP than RF-WA scheme at higher input traffic load in the network. Hence, we see that for the same value of TI, BP is lower for FF-WA when compared with RF-WA scheme.

(b) This is due to the fact that RF-WA scheme increases discontinuous wavelength fragmentation, and thus degrades the forward blocking probability in succeeding hops, during WA.

(c) It is to be noted that the scope of this research work has been to evaluate the performance of TGA with the existing well researched dynamic WA schemes [26].

2.5.5 Phase 4

The simulation in the phase four validates the rendition of TGA when dynamic routing is combined and the result is validated with the Priority Based Algorithm (PBA) [24]. The result is given in Figure 2.14.

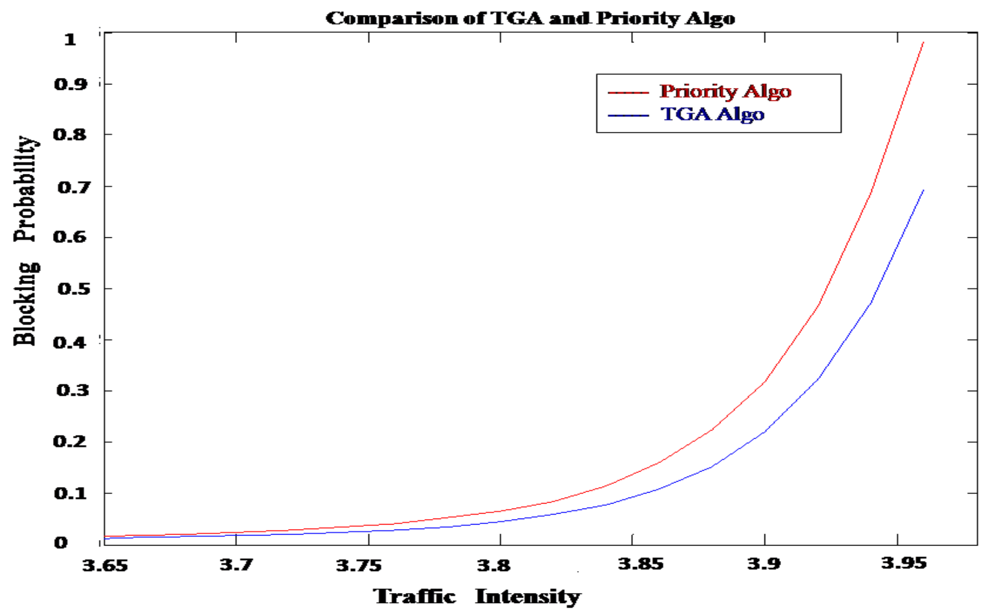

Figure 2.14: Comparison of TGA and Priority Based Algorithm.

The inferences from the above result are enumerated below:

(a) The rendition of TGA is considerable in comparison to PBA. This is due to the fact that four parameters are imbibed by TBA. The four parameters being CoS, quantum of spans, data rate, and DFSI to compute priority for LSP as enumerated in sub-section 2.4.4.5.

(b) The PBA on the other hand imbibes only two parameters. These parameters are quantum of spans and data rate of lightpath request to assign priority to every LSP.

(c) On analysis of PBA, for the parameter for data rate, it is noticed that greater priority to LSP requests which demand higher quantum of data rate is provisioned. The above draws to lower quantum of LSPs provisioned in the optical network.

(d) On the contrary, LSP requests which demand lower quantum of data rate are provided greater priority in the TGA. Thus, conclusively TGA ends up servicing more quantum of LSP requests. The above, makes the performance of TGA superior in comparison to PBA [24]. Additionally, DFSI capability in TGA greatly enhances BP of the optical link at times of failures of LSRs and connections in the network.

2.5.6 Phase 5

In Phase 5, which is the final phase of the simulation, PBA interlinked with WA schemes and TGA interlinked with WA schemes have been evaluated and their performance compared. Initially PBA and TGA have been interlinked with RF-WA scheme and the result is shown in Figure 2.15.

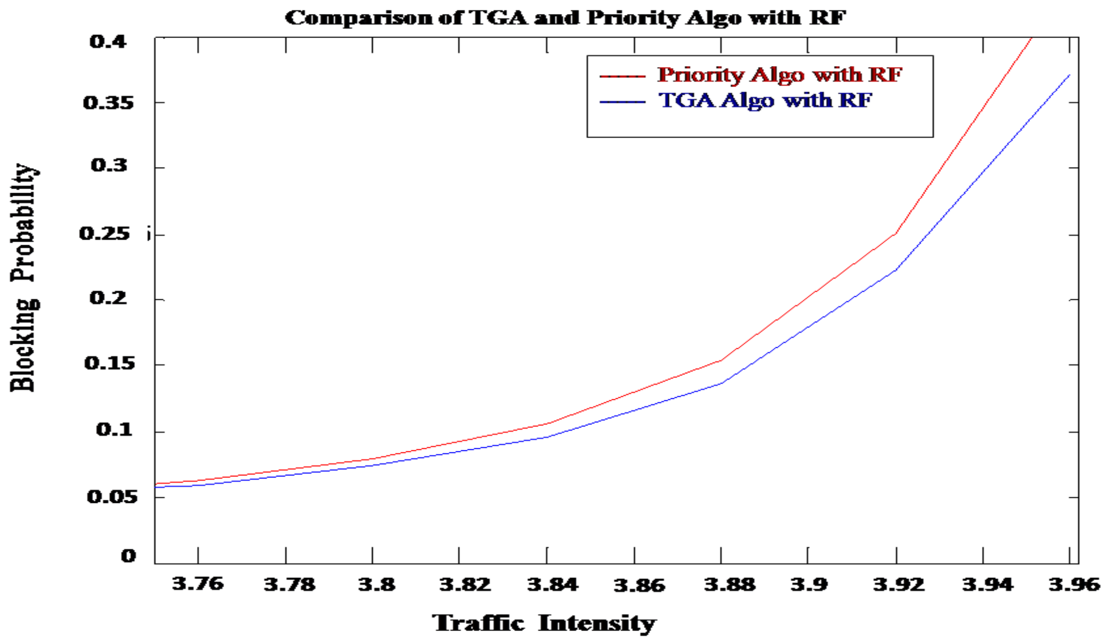

Figure 2.15. Comparison of RF-WA scheme combined with TGA and PBA, BP v/s TIfor four wavelengths

From Figure 2.15, following inferences are drawn:

(a) TGA when interlinked with RF-WA outperforms PBA interlinked with RF-WA scheme. The performance is substantial when the quantum of load of information from users is greater than 80 %.

(b) On analysis we conclude that greater the quantum of load of information from users, network congestion escalates and in such a scenario, TGA being the superior algorithm, ensures smaller BP in the network.

Hereafter, PBA and TGA have been interlinked with FF-WA scheme. The validation of PBA interlinked with FF-WA and TGA interlinked with FF-WA scheme has been done and the result is shown in Figure 2.16.

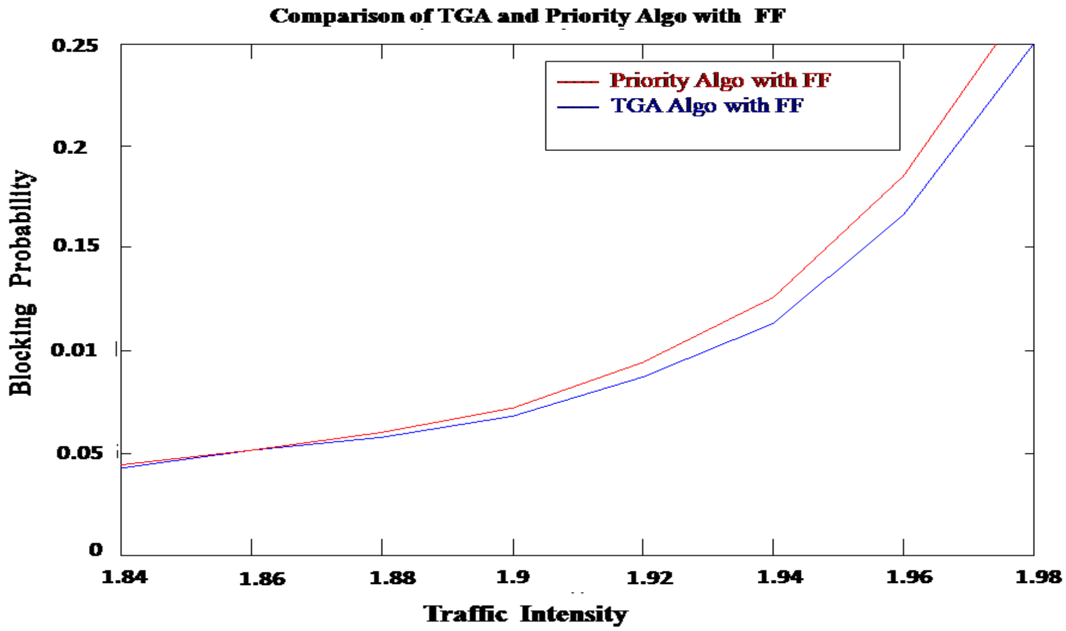

Figure 2.16: Comparison of FF-WA scheme combined with TGA and PBA, BP v/s TI for four wavelengths

From Figure 2.16, following inferences are drawn:

(a) TGA when interlinked with FF-WA outperforms PBA interlinked with FF-WA scheme. The performance is substantial when the quantum of load of information from users is greater than 88 %.

(b) Additionally, greater the quantum of load of information from users, network congestion escalates and in such a scenario, TGA being the superior algorithm, ensures smaller BP in the network.

2.5.7 Effectiveness of the TGA

The network operators in a developing nation and price driven markets like India usually do not under load their networks. The network infrastructure is always planned so as to cater for 100 % utilization and at times to overload the network to earn greater revenue. Due to exponential growth in the telecom user base, the network operators will face capacity problems in the near future that will make QoS algorithms like TGA a good tool to implement at a minimal cost. On the other hand upgrading the existing optical nodes to WDM systems or DWDM systems is a higher investment cost, in terms of new hardware procurement. The proposed TGA can even be incorporated as a software upgrade on existing WDM systems to further substantially improve the number of users supported by these existing WDM systems. Finally laying new fibers is an expensive option and requires huge investments in network planning, permissions including multiple clearances, and therefore is seldom done for large optical networks. TGA can improve the user density in the existing laid fibers substantially for nearly loaded present day optical networks.

TGA is a software based algorithm with the computational complexity of the order O(nlog(n)). There are no costly upgrades in the hardware and only software update is needed for TGA implementation in the present optical networks. Further, the FSCs required for fiber sensing and health measurements of all optical links in a network are already incorporated in the present day optical networks [52]. Therefore, incorporating TGA effectively optimizes the use of existing optical network infrastructure, providing better QoS, and enhanced connection establishment at a minimal cost.

2.5.8 Limitations of Research Work

The TGA algorithm can be easily ported to each optical node assuming the proprietary software allows porting of the algorithm and scheduling of traffic at each optical node. Further, the ONMS database for the entire optical network should be available real-time in at every optical node in order to choose the best suited fiber for each traffic type.

2.6. Summary

Intelligent optical networks (GMPLS with intelligent control plane) are the future of backbone telecommunication networks. These optical networks are the important backbone interconnecting constituents, of various emerging high data rate wireless networks, which are seen as future of mobility networks. The data rate requirements of the end user of modern telecommunication era are ever increasing. With applications like video-conferencing and video transfers the end user has become data-rate/bandwidth hungry. With the induction of optical technology in the backbone telecommunication networks, a massive jump has been achieved in data-rate/bandwidth transport capabilities. However, with more and more end users consuming the backbone bandwidth, the massive bandwidth offered by optical networks may soon become inadequate given the increasing trends of user traffic in various access networks.

Hence, there is an inherent requirement to develop very fast and proficient routing and wavelength assignment techniques to utilize the optical resources (wavelengths) optimally. These proficient routing and wavelength assignment techniques will provide an enhanced virtual bandwidth, over and above the basic bandwidth of optical networks, which reduce the connection blocking probability of telecommunication networks. TE is an important aspect in management of these telecommunication networks for maximum utilization of optical resources. Hence, there is an imminent requirement to implement various traffic engineering methodologies combined with efficient dynamic routing and wavelength assignment techniques.

The proposed TGA combined with dynamic RWA in PCE based architecture imbibes traffic scheduling to optimize pure backbone optical networks. The results in Section 2.5, proves that the TGA improves network performance by reducing BP of pure optical networks. As a result, the utilization of network resources improves greatly for pure optical networks, while using the existing hardware. The proposed TGA has better connection blocking performance than the PBA which uses only two variables viz. number of hops and data rate of requested service as compared to TGA which incorporates four variables viz. class of service, number of hops, data rate and fiber state to calculate priority for each service request. Hence, the proposed TGA effectively optimizes the use of existing optical network infrastructure, providing better QoS and enhanced connection establishment at a minimal cost.

In the next chapter, the research contributions made on the access network are detailed.

Chapter 3

Channel Sounding for Wireless Networks

Telecommunication networks are ever-evolving and can be categorized in to two separate segments namely backbone network and access network [2]. The backbone network comprises of high date rate pure optical highway rings and meshes which use state-of-the-art dense wavelength division multiplexing techniques to substantially enhance the data carrying capability of the existing optical fibers [3]. As a standby media, point-to-point microwave radio links are also used at critical portions of the backbone network segment. The access network segment of the telecommunication networks earlier comprised of copper cable links from the nearest access point to the end user as the last mile connectivity. Due to the advancements in the wireless technologies and successful implementation of LTE protocol [5] and future implementation planning of Fifth Generation (5G) cellular technologies, the access network is mostly wireless. LTE as an implemented protocol is already delivering data rates of 100 Mbps in the access network, whereas LTE Advanced promises download data rates of upto 1 Gbps [7] thereby, replacing all the copper links in the last mile connectivity. Future wireless protocols like 5G and beyond will provide such high data rates at multipath fading environments. Further, these future wireless networks will have small cell sizes to increase capacity in the form of pico and micro cells which need to be implemented in various terrains which have unique multipath fading characteristics in terms of Signal to Noise Ratio (SNR), Received Signal Strength (RSS) and Delay Spread (DS).

A microcell is a cell serviced by a low powered eNodeB in an LTE network, covering a limited area such as a mall, a hotel, or a transportation hub. A microcell is usually larger than a picocell. A microcell uses power control to limit the radius of its coverage area. Typically the range of a microcell eNodeB is less than two kilometers radius, whereas a typical macrocell eNodeB in an LTE network may have ranges up to tens of kilometers in radius.

A picocell on the other hand is a small eNodeB, typically covering a small area, such as in-building. In cellular networks, picocell eNodeBs are typically used to extend coverage to indoor areas where outdoor signals do not reach well, or to add network capacity in areas with very dense mobile density, such as train stations or stadiums. Picocell eNodeBs provide coverage and capacity in areas difficult or expensive to reach using the more traditional macro cell approach. A picocell eNodeB may have a coverage radius of 200 meters or less.

3.1 Channel Sounding Concepts

3.1.1 Channel Sounding

Mobile communication is a specialized type of communication which differs drastically from a typical microwave link which is classified as point-to-point communication link. A mobile communication environment is not characterized as Line of Sight (LoS) communication but largely depends on refracted, diffracted, and scattered copies of the original signal transmitted by the eNodeB of an LTE network or any legacy cellular standard to the UE. The UE does not see the eNodeB as direct LoS, but receives highly attenuated copies of original signal from various paths through reflection, diffraction, and scattering. These copies of original signal are time delayed as they traverse different paths in the mobile environment and suffer relative phase differences as they reach the UE. Due to the difference in the phases of the multiple copies received at the UE, constructive and destructive interferences occur at the UE at any instant leading to large variation of received signal strength at the UE. This effect is called small scale fading in the mobile environment or the multipath effect [53], which is largely detrimental to the received signal quality in a mobile environment.

Channel sounding is a technique that evaluates the radio environment for wireless communication. To minimize or use the multipath effect, engineers use channel sounding to process the multidimensional spatial-temporal signal and estimate channel characteristics. This helps simulate and design wireless systems. Channel sounding for a multipath channel is the process of analyzing and understanding the behavior of a channel for a specific band of frequency for duration of measurement. An impulse is transmitted through the channel and consequently the response of the channel to the impulse is measured. This process is carried out for multiple times. The above measurements are thereafter analyzed to ascertain distortion in amplitude and phase of the transmitted signal by the channel in that duration. Further, the transceivers are designed for a specific band so as to minimize the effect of channel distortion.

These transceivers incorporate equalizer circuits, which will undo the effect of the channel distortion in the amplitude and phase during channel sounding process.

3.1.2 Channel Sounding Parameters

Various parameters are utilized to analyze the channel measurements during the channel sounding and the same are enumerated below:

(a) Signal to Noise Ratio (SNR) It is defined as the ratio of the received signal power (P_R) to the noise power (P_N) in a multipath channel environment as

$$\text{SNR (dB)} = 10\log_{10}(P_R/P_N) \qquad (3.1)$$

(b) Received Power (P_R) It is a measure of power received at the receiver during the channel sounding process.

(c) Delay Spread (σ_τ) Mean excess delay ($\bar{\tau}$) and the rms delay spread (σ_τ) are multipath channel parameters that can be determined from a power delay profile (τ). $\bar{\tau}$ is the first moment of the τ, whereas σ_τ is the square root of the second moment of τ and defined as:

$$\sigma_\tau = \sqrt{\overline{\tau^2} - \bar{\tau}^2} \qquad (3.2)$$

The maximum excess delay (X dB) of the power delay profile is defined to be the time delay during which the multipath energy falls to X dB below the maximum value observed.

(d) Coherence Bandwidth (B_c): Analogous to the delay spread parameters in the time domain, coherence bandwidth is used to characterize the channel in the frequency domain. The rms delay spread and coherence bandwidth are inversely proportional to each other. B_c is defined as a statistical measure of the range of frequencies over which the channel can be considered flat. It is defined for a bandwidth over which the frequency correlation function is above 0.9 as

$$B_c = 1/50\sigma_\tau \qquad (3.3)$$

(e) Doppler Spread (B_D): It is a measure of the spectral broadening caused by the time rate of change of the mobile radio channel and is defined as the range of frequencies over which the received Doppler spectrum is non-zero. This phenomenon happens primarily due to the relative movement of eNodeB and UE in a mobile environment. When a signal of frequency f_c is transmitted, the received signal spectrum, called the Doppler Spectrum, will have components in the range f_c - f_d to f_c + f_d, where f_d is the Doppler Shift. The amount of spectral broadening depends on f_d, which is a function of the relative velocity of the mobile, and the angle between the direction of motion of the mobile and direction of arrival of the scattered waves.

(f) Coherence Time (T_C): It is the time domain dual of Doppler spread and used to characterize the time varying nature of the frequency dispersiveness of the channel in the time domain. The Doppler spread (f_m) and T_C are inversely proportional to one another and is given as:

$$T_C = 1/f_m \tag{3.4}$$

where $$f_m = v/w \tag{3.5}$$

and v is the velocity of relative motion and w is the wavelength of operation of the signal. Coherence time is a statistical measure of the time duration over which the channel impulse response is essentially invariant. If the Coherence time is defined as the time over which the time correlation is above 0.5, then it can be expressed as:

$$T_C = \frac{9}{16} \pi f_m \tag{3.6}$$

3.1.3 Channel Models

There are a variety of channel models available for calculating the P_R in a wireless environment. The models are specific to the frequency of operation and also to the type of terrain under which the transmitter and receiver are deployed. The following popular models have been considered in this research work for analysis with the real channel measurements:

(a) Okumura-Hata Model: The model [53] is designed for large cells for frequency ranges between 150-1500 MHz. The path loss (PL) is calculated as

$$PL = A + B \log(d) + C \tag{3.7}$$

where A,B and C are factors that depend on frequency and antenna height, and

$$A=69.55 + 26.16\log(f_c) - 13.82\log(h_b) - a(h_m) \quad (3.8)$$

$$B= 44.9 – 6.55\log(h_b) \quad (3.9)$$

where f_c is given in MHz and d in km. The function $a(h_m)$, h_b and factor C depend on the environment, and are detailed in [54].

(b) <u>COST 231-Welfish-Ikegami Model:</u> It is an extension of Hata model for small distances between BS and MS, and their relative lower heights and further frequency of operation upto 2 GHz. The PL for LOS is calculated as given in eq (3.10).

$$PL= 42.6 + 26\log(d) + 20 \log(f_c) \quad (3.10)$$

where f_c is the carrier frequency in MHz and d is the distance between the transmitter and receiver in km. The PL for non-LOS case is also given in [54, 55].

(c) <u>COST 207 Model:</u> The model gives normalized scattering functions as well amplitude statistics for four classes of environment: Rural, Urban, Semi-urban and Hilly terrains. The values of the delay spread for each of the terrains is given in [54].

(d) <u>Stanford University Interim (SUI) Model:</u> The model can be used for frequency ranges around 2 GHz for forest, hilly and flat terrains. It accounts for a variety of Doppler spreads, delay spread and LoS/ NLoS conditions that are typical of a country like the United States [56].

(e) <u>3GPP Channel model</u> The model can be used for wide frequency ranges for macro and micro cellular urban, sub-urban and rural areas. It has both SISO and MIMO antenna configurations. The values of the delay spread for different terrains are given in [57].

The above models have been developed for specific frequencies, locations and terrains, and can give an estimate of the received power levels and delay spreads on operation of wireless links at

specified parameters. The popular COST 207, SUI and 3GPP channel models have been considered in this research work for comparison with real channel measurements for various terrains in the Indian Subcontinent. Recent work on performance analysis of wireless protocols on COST 207 channel model [55] [58], and on SUI channel model [59-60] are available.
COST 207, SUI and 3GPP channel models have been considered in this research work for comparison with real channel measurements for various terrains.

3.1.4 Related Work

Measurements of channel parameters and analysis of indoor radio channels has been undertaken in [61-62]. Channel measurements on wideband radio and their analysis are discussed in [63]. Work on channel measurements for ultra wideband channels has also been done [64-65]. Channel sounding on WiFi 802.11b has been adequately researched in [66-67]. There has been substantial amount of work in channel sounding for wideband in and around 60 GHz [68-69]. Though research on channel measurements for indoor environments for protocols like WiFi has been undertaken, and also for 60GHz bands, however, channel sounding and measurements for LTE and future wireless protocols for sub-1, 2 and 3 GHz bands for different real terrains for pico cell sizes has not been undertaken to the best of author's knowledge. In this thesis channel sounding and measurements at indoor and field conditions for sub-1, 2 and 3 GHz bands and for five different terrains namely Urban, Semi-urban, Forest, Rural and Desert terrains to effectively cover varied deployments of future wireless networks in pico cell size.
Recent work on performance analysis of wireless protocols on COST 207 channel model [58] [70], and on SUI channel model [60] are available.

In view of the above fast changing scenarios in the access segment of the telecommunication networks, there is an urgent need to carry out channel sounding measurements for pico cell sizes in multiple bands and in various terrains for doing Channel Impulse Response (CIR) analysis in the Indian Sub-continent. This CIR analysis can be used in HetNets cellular network [71] having various pico cells. This will enable design of efficient transceivers for future wireless technologies which are band specific and perform optimally in various terrains of deployment in the Indian Subcontinent.

The purpose of this research work is to undertake channel sounding and measurements at both indoor and field conditions for sub-1, 2 and 3 GHz bands, and for five different terrains namely Urban, Semi-Urban, Forest, Rural and Desert terrains to effectively cover varied deployments of future wireless networks in pico cell sizes. These results can form a basis for designing transmitters and receivers for pico cells at the above bands and further facilitate optimum deployment of such transceivers for operation of future wireless networks.

3GPP channel model for pico cells for LTE standard with different terrains is not available as per our knowledge. However, 3GPP channel models for micro and macro cells are available for various terrains and have been considered in this research work for comparison.

In the measurement, Single Input Single Output (SISO) antenna configuration is used. It is observed from the measurement that for all the terrains, there is a single path between transceiver because of low bandwidth (20 MHz) signal and short distance (100m).The channel is Rician faded because of LoS condition. Further, no threshold for multipath selection was incorporated; all reflections/multipath within receiver sensitivity range are captured.

For receiver sensitivity calculation, the following formula is used:

$$\text{DANL} + 10 \log (\text{RBW}) \qquad (3.11)$$

(Say at 1 GHz, DANL is -165 dBm/Hz; for 20 kHz RBW;

Sensitivity = -165 dBm/Hz + 43 dB = -122 dBm)

3.2 Channel Measurement Setup

In order to undertake channel sounding and thereafter measurement of the multipath channel conditions, the measurement setup as given in Fig. 3.1 is incorporated. The Lab setup is shown in Fig. 3. 2.

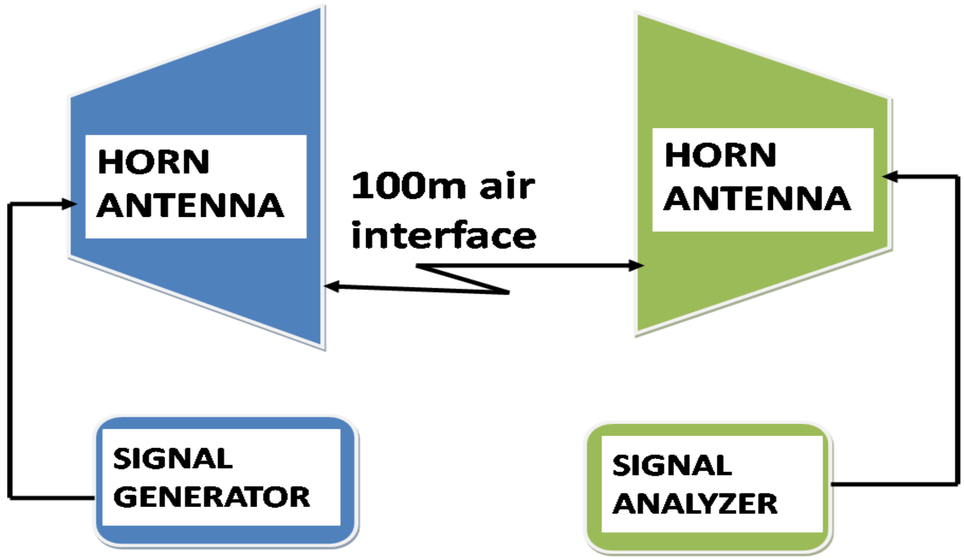

Fig. 3.1: Block diagram of measurement setup for channel sounding and measurement.

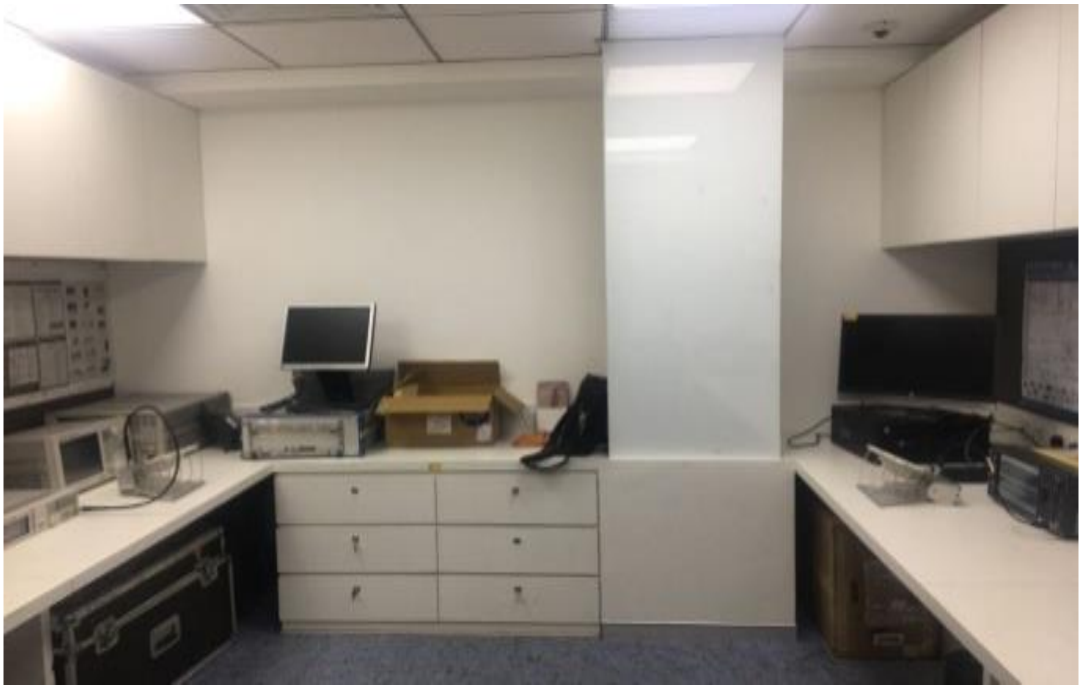

Fig. 3.2: Lab measurement setup for channel sounding and measurement.

The channel measurements are undertaken by transmitting an impulse from a Signal Generator (Keysight Signal Generator Model No: MXG N5182B) which is coupled to a horn antenna for better impedance matching. Horn antennas are wideband so it facilitated to cover the entire range of frequencies incorporated in the measurement process. The antenna effect has been properly eliminated in the reported results.

The signal traverses 100m to realize an average pico-cell size and is received by a horn antenna coupled to a Signal Analyzer (Keysight Signal Analyzer Model No: PXA N9030B). The received signal is analyzed by the above Signal Analyzer.

The important parameters from the data sheets for Signal Analyzer and Signal Generator are given in Table 3.1 and Table 3.2 respectively.

Table 3.1: Data Sheet of Signal Analyzer

Parameter	Value
Frequency	2Hz to 50GHz
Frequency Options	3.6, 8.4, 13.6, 26.5, 43, 44, 50 GHz, Mixers to 1.1 THz
Maximum Analysis Bandwidth	510 MHz
Bandwidth Options	25 standard, 40, 85, 125, 160, 255, 510 MHz
Maximum Real-Time Bandwidth	510 MHz
Real-Time Bandwidth Options	85, 160, 255, 510 MHz
DANL @1 GHz	-174 dBm
Phase Noise @1 GHz (10 kHz offset)	-136 dBc/Hz
Phase Noise @1 GHz (30 kHz offset)	-136 dBc/Hz
Phase Noise @1 GHz (1 MHz offset)	-146 dBc/Hz
Overall Amplitude Accuracy	±0.19 dB
TOI @1 GHz (3rd Order Intercept)	+22 dBm
Maximum Dynamic Range 3rd Order @1 GHz	118 dB

Table 3.2: Data Sheet of Signal Generator

Parameter	Value
Output Power @1 GHz	-144 dBm to +26 dBm
Phase Noise @1 GHz (20 kHz offset)	-146 dBc/Hz
Frequency Switching	≤ 800 μs
Harmonics @1 GHz	<-35 dBc
IQ Modulation BW Internal/External	160 MHz to 200 MHz
Non-Harmonics @1 GHz	-96 dBc
Sweep Mode	List, Step
Baseband Generator Mode	Waveform Playback & Real-Time
Frequency Modulation-Maximum Deviation @1 GHz	4 MHz
Frequency Modulation-Rate @100 kHz Deviation	DC to 7 MHz
Phase Modulation-Maximum Deviation in Normal Mode	0.5 rad to 8 rad

As per the signal measurements which have been done in the lab and outdoor conditions, the numbers of Frequency Points used are 409601.The technique used for all measurements is based on transmitting a known waveform through the channel and comparing the received signal with the reference signal to calculate the channel metrics. The above technique does not rely on external synchronization or clocks so that the time scale of the impulse response trace is relative to the largest peak, and Doppler metrics are not computed.

In principle, the system operates as follows:

(a) The signal generation software generates a specially-coded waveform, which is then filtered by a band-pass filter.

(b) This waveform is played out on a Keysight Vector Signal Generator and transmitted over the air using appropriate horn antenna.

(c) The signal is received by one or more antennas connected to Keysight Signal Analyzer running Keysight VSA 89601B software.

(d) The Channel Sounding plug-in for the 89600 VSA then computes channel sounding traces and metrics. The signal can be digitally filtered first, to remove unwanted spectral components.

The sounding signal is generated at specified symbol rates and length. The symbol rate determines the bandwidth to be sounded, and the length of the coded signal determines the maximum time delay (and hence distance) between first and last of reflections that can be faithfully resolved.

The Vector Signal Analyzer displays the Impulse Response, Power Delay Profile (PDP), channel frequency response and additional sounding metrics for each channel.

For better impedance matching Horn antennas are utilized. Horn antennas are wideband so it facilitated to cover the entire range of frequencies incorporated in the measurement process.

Further, it has been observed from the measurements that for all the terrains, there is a single path between transmitter and receiver because of the low bandwidth (20 MHz) signal and limited range (100m). Hence, effect of multipath has not been observed in the measurements.

The measurements have been undertaken in five different terrains in order to effectively cover varied deployments of LTE-Advanced and other future wireless networks in pico cells in the Indian sub-continent and are given below:

(a) Urban Terrain

(b) Semi-urban Terrain

(b) Forest Terrain

(c) Rural Terrain

(e) Desert Terrain

The graphical details of the locations of measurements undertaken in the Indian sub-continent for the five different terrains are enumerated in Fig. 3.3.

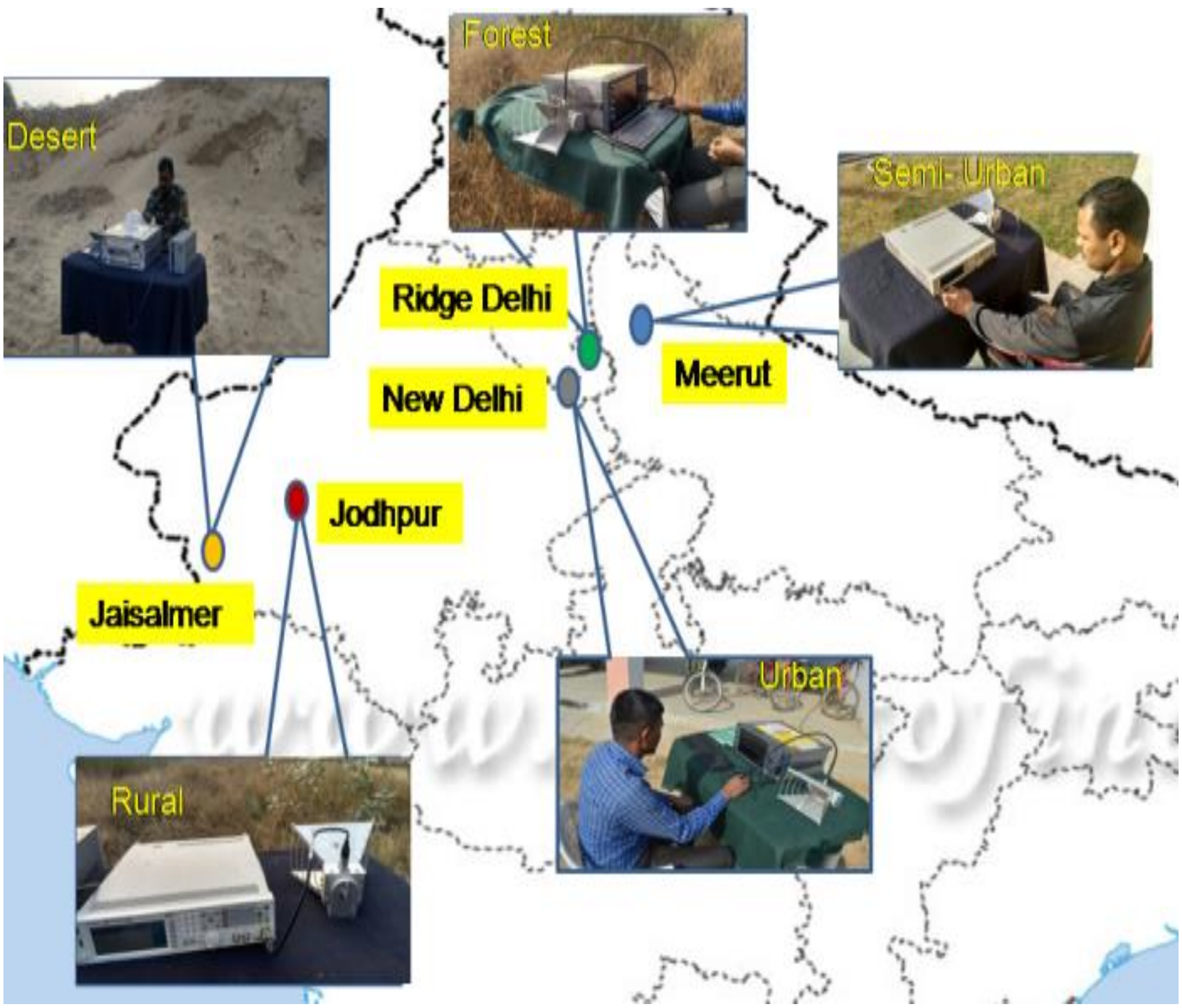

Fig. 3.3: Details of the terrains and the locations of measurements undertaken in India.

3.3 Channel Measurement for Various Terrains in Multiple Bands

The channel measurements have been undertaken to facilitate design and development of future wireless transceivers operating in various terrains, for pico cell sizes, and for the following three bands to ensure entire coverage of LTE and other future wireless standards:

(a) Sub 1 GHz - 700 MHz

(b) Sub 2 GHz - 1.850 GHz

(c) Sub 3 GHz - 2.350 GHz

A typical screenshot of the measurement setup as captured by the Keysight Signal Analyzer Model No: PXA N9030B is given in Fig 3.4.

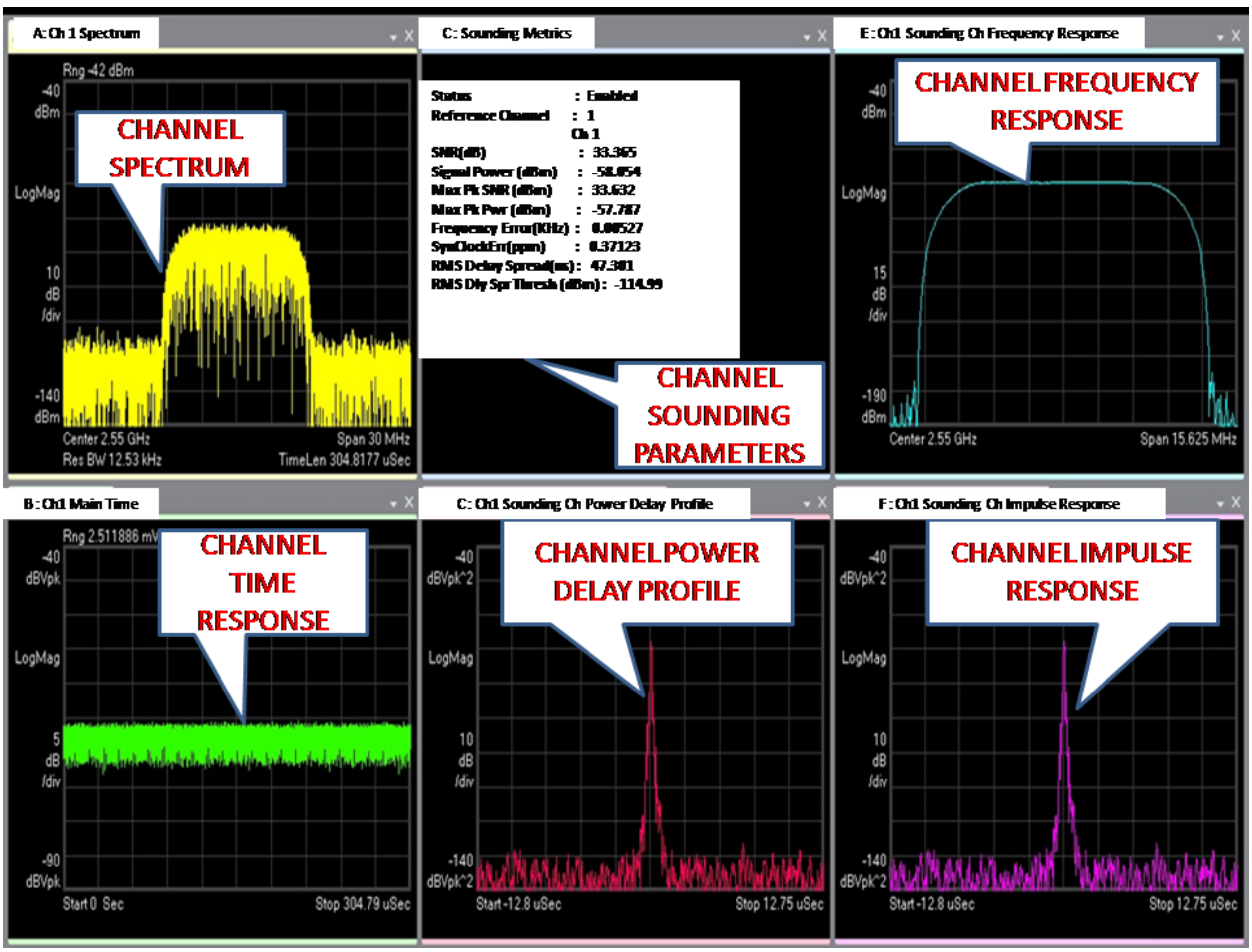

Fig.3.4: Typical screenshotof the channel measurement setup.

The channel measurements have been done in three phases as given below:

3.3.1 Phase-1(Sub-1GHz)

In the first phase, the channel measurements for Sub 1 GHz - 700 MHz and 20 MHz bandwidth for five different terrains of the Indian Subcontinent has been undertaken. The measurement values of SNR, Receive Power and Delay Spread for 700 MHz with 20 MHz bandwidth, 100 meter distance between transmitter and receiver at -10 dBm transmitter power are presented in Table III. The calculated values of delay spread from COST-207 model, 3GPP macro and micro-cell channel model are compared with the measured values of the delay spread in the Table 3.3

Table 3.3: Parameter Measurements for 700 MHz

Terrain	SNR (dB)	Rx Power (dBm)	Delay Spread (ns)	Delay Spread (ns) COST-207	Delay Spread (ns) 3GPP Microcell	Delay Spread (ns) 3GPP Macrocell
Urban	25.81	-66.59	23.32	1250	500	920
Semi-urban	37.67	-52.71	22.56	1650	500	920
Forest	14.27	-77.36	27.96	4300	-	-
Rural	33.93	-47.8	17.21	150	-	140
Desert	35.87	-45.91	15.65	-	-	-

3.3.2 Phase-2 (Sub-2 GHz)

In this phase, the channel measurements for Sub 2 GHz - 1.850 GHz bandwidth 20 MHz for the five different terrains of the Indian Subcontinent have been undertaken. The measurement values of SNR, Receive Power and Delay Spread for 1.850 GHz with 20 MHz bandwidth, 100 meter distance between the transmitter and receiver at -10 dBm transmitter power are tabulated in Table IV. The calculated values of delay spread from COST-207 model, 3GPP macro and micro-cell channel model are compared with the measured value of the delay spread in Table 3.4.

Table 3.4 Parameter Measurements for 1.850 GHz

Terrain	SNR (dB)	Rx Power (dBm)	Delay Spread (ns)	Delay Spread (ns) COST-207	Delay Spread (ns) 3GPP Microcell	Delay Spread (ns) 3GPP Macrocell
Urban	5.645	-72.954	27.542	1250	500	920
Semi-urban	13.72	-58.717	23.583	1650	500	920
Forest	2.348	-83.074	29.091	4300	-	-
Rural	16.178	-53.253	19.75	150	-	140
Desert	19.997	-52.142	16.146	-	-	-

3.3.3 Phase-3 (Sub-3 GHz)

In the final phase of channel measurement, the channel measurements for Sub 3 GHz -2.350GHz band for five different terrains of the Indian Sub continent has been undertaken. The measurement values of SNR, Receive Power and Delay Spread for 2.350 GHz with 20 MHz bandwidth, 100 meter distance between transmitter and receiver, and -10 dBm transmitted power are presented in Table V. The calculated values of delay spread from SUI-1(C) model, 3GPP macro and micro-cell channel models are also compared with the measured delay spread in Table 3.5.

Table 3.5: Parameter Measurements for 2.350 GHz

Terrain	SNR (dB)	Rx Power (dBm)	Delay Spread (ns)	Delay Spread (ns) SUI-1(C)	Delay Spread (ns) 3GPP Microcell	Delay Spread (ns) 3GPP Macrocell
Urban	4.213	-75.1	28.575	112.5	500	920
Semi-urban	12.503	-64.37	25.898	112.5	500	920
Forest	-3.331	-86.587	32.015	112.5	-	-
Rural	14.953	-58.782	24.384	112.5	-	140
Desert	18.209	-54.097	22.954	-	-	-

3.4 Channel Measurement Analysis

It is observed that the calculated values of delay spread from COST-207 channel model, 3GPP macro and micro-cell channel models in Tables III, Table IV and the SUI channel model, 3GPP macro and micro-cell channel models in Table V are substantially higher than their respective measured values. The reasons for the same could be that as per these models the BS should be at around 30m or higher, and the distance between BS and MS should be greater than 5 km.

Contrary to the above scenarios, in our measurement setup the height of BS is at 1.5m and the distance between BS and MS is 100m, as we are addressing deployments of pico-cells of LTE-Advance and future wireless networks. It is also observed from measurements in Table III, IV and V that the delay spread is less than 100 ns. The delay spread for pico-cells has been observed to be less than 100 ns as measured by the Eccentro-Scattering model in [72].

Hence, it ensures that the measured values of delay spread for different types of terrains of pico-cell based on LTE standard are in consonance. Further, it is observed from the measurements that for all the terrains, there is a single path between transmitter and receiver because of low bandwidth (20 MHz) and limited distance (100m) signal and the channel is Rician faded because of line of sight.

In addition, graphical representations of the channel measurements for Sub 1 GHz - 700 MHz bandwidth 20 MHz for five different terrains of the Indian Subcontinent are given in Fig. 3.5.

The graphical representations of the channel measurements for Sub 2 GHz - 1.850 GHz bandwidth 20 MHz for five different terrains are given in Fig. 3.6.

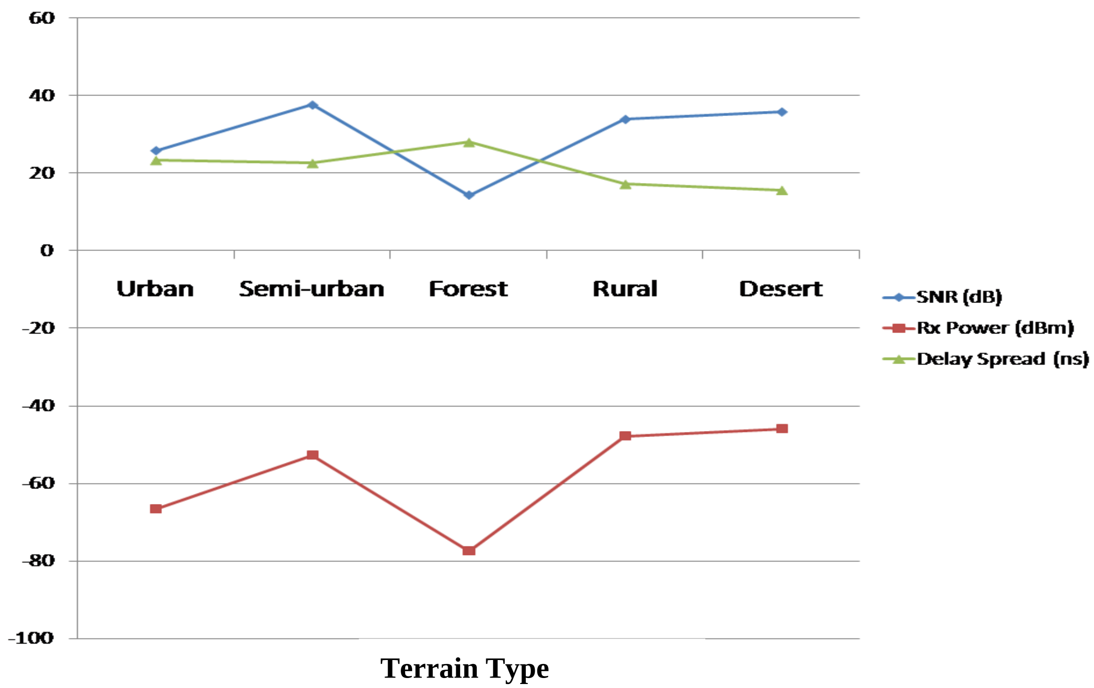

Fig. 3.5**:** Analysis of measurement results for 1 GHz-700 MHz band with 20 MHz for five different terrains.

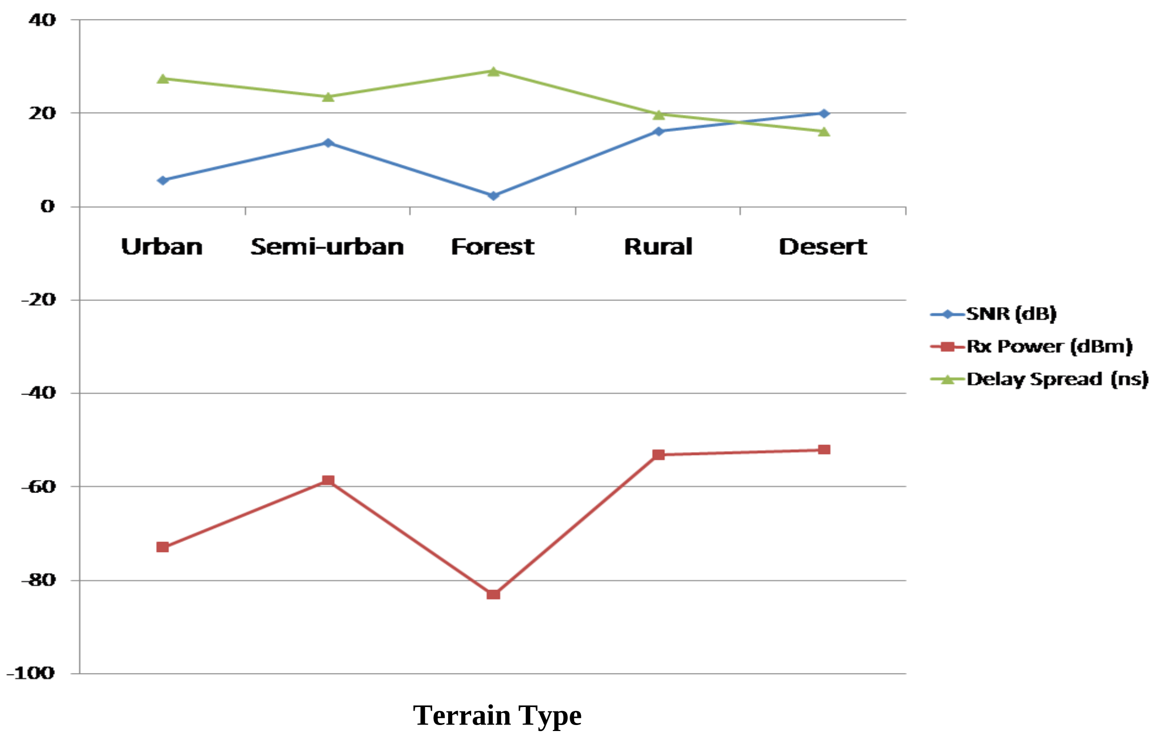

Fig.3.6**:** Analysis of measurement results for Sub-2 GHz-1.850 GHz band with 20 MHz for five different terrains.

The graphical representations of the channel measurements for Sub 3 GHz -2.350 GHz bandwidth 20 MHz for five different terrains are given in Fig. 3.7.

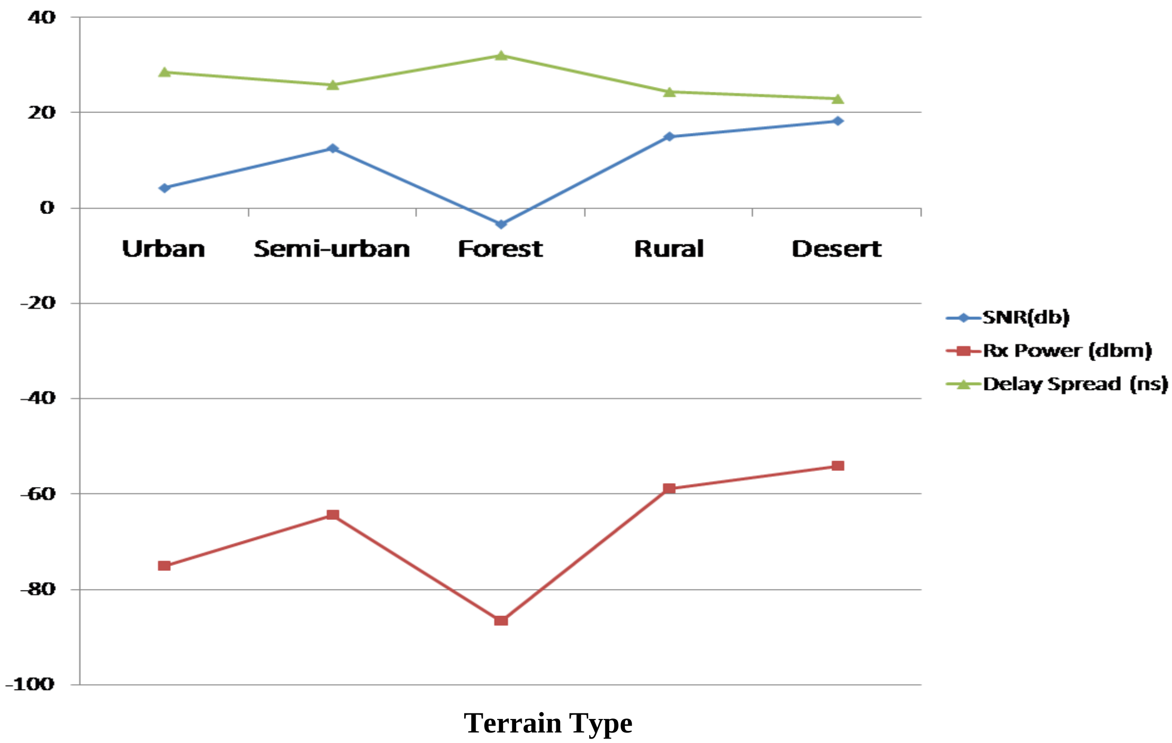

Fig. 3.7**:** Analysis of measurement results for Sub-3 GHz -2.350 GHz band with 20 MHz for five different terrains.

It can be inferred from Fig3.5 to 3.7 that the SNR (in dB) and the Receive Power (in dBm) increases from Urban terrain to Semi-urban terrain due to decrease in building density, however drops significantly for Forest terrain due to foliage losses as absorption is observed. The above parameters further increase substantially for Rural Terrain, as spread of structures increases. Further, the parameters marginally increase for Desert terrain as it offers obstruction free propagation.

On the other hand, graph for delay spread (in ns) decreases from Urban terrain to Semi-urban terrain due to decrease in building density but increases for Forest terrain due to foliage losses and absorption. The graphs further decreases for Rural Terrain, as spread of structures increases and thereafter marginally decreases for Desert terrain as it offers obstruction free propagation.

3.5 Limitations of the Research Work

The test setup range of 100m has been fixed due to the limitation of the test equipment. Due to the above, the multi-path effect has not been substantial in the measurements. Further, due to the above limitations, the results are only suited for pico-cell deployments.

3.6 Summary

The telecommunication access network is fast migrating to high data rate wireless networks which incorporate LTE and LTE-Advance standards and in near future will augment 5G and other future wireless standards. Pico-cell deployments will be favored to increase capacity of these future wireless networks. Small sized easy to deploy eNodeBs are the optimal choices for future deployment of LTE and 5G mobile networks in various terrains. These networks are prone to multipath fading conditions due to higher bands of operation and use of high data rates.

For the first time channel sounding measurements and analysis have been undertaken in multiple bands and in various terrains namely Urban, Semi-Urban, Forest, Rural and Desert terrains of the Indian Subcontinent. Lessons learnt from the measurements can be brought out in a way that the measurements can effectively show the behavior of the channels at sub-1, 2 and 3 GHz bands, and for five different terrains. The graphs clearly bring out the behavior of the three crucial channel parameters like SNR, Received Power and Delay Spread for different bands and five different terrain types.

This research works clearly characterizes the behavior of the above channels by detailed channel measurements and analysis for deployment of present and future wireless networks in pico-cells in the five different terrains of the Indian Subcontinent. This measurement and analysis will enable optimum design and deployment of future wireless transceiver technologies in varied terrains for pico-cells in the Indian Subcontinent.

Chapter 4

Traffic Scheduling in Defence Wireless Mesh Networks

WMN are self-configured and self-organized dynamic networks, automatically establishing an ad hoc network with the nodes in the network and also maintains connectivity in the mesh. Mesh routers and mesh clients are the type of nodes which comprises WMNs [4].Because of multi-hop communications; a mesh router achieves more coverage with the transmission power which is much lower. Multiple wireless interfaces which are made using the different access technologies or the same, are provided to a mesh router in order to improve the tractability of networking in mesh. Because of the minimal mobility, mesh routers constitute mesh backbone which is needed by the mesh clients. Though the mesh clients for mesh networking can also act as a router, simple and easy platform either software or hardware is needed for mesh clients than that for mesh routers. The advantages offered by WMNs are easy network maintenance, low up-front cost, reliable service coverage, robustness, etc. Mesh router's function of behaving as bridge/gateway results in desegregation of WMNs with many other type of networks. Mesh routers are also responsible for networking in a mesh amidst mesh clients and mesh routers [4].Wireless Network Interface Cards (NICs) are used by the established nodes to get connected to WMNs directly through wireless mesh routers.

4.1 Characteristics of Wireless Mesh Networks

WMNs have undergone and are also undergoing rapid commercialization in many other application scenarios such as community networking, metropolitan high speed area networks, building automation, enterprise networking and broadband home networking. However, significant efforts in research are still required, for WMNs to be all it can be. For example, scalability is the issue in the present routing and MAC protocols; increase in number of nodes or hops in WMNs results in decrease in throughput [4]. Thus, the protocols which are presently available necessitate re-inventing or enhancing in case of WMNs. In order to improve networking in WMNs, protocols' design of present wireless networks are being revisited by the researchers and same is the case with wireless sensor, ad-hoc and especially of IEEE 802.11 networks. WMNs' new specifications are currently under discussion by IEEE 802.15, IEEE 802.11, and IEEE 802.16 which are the industrial standard groups.

4.1.1 Network Architecture of WMN

It is necessary to discuss architecture of a network as to provide highly efficient bandwidth usage over specified area of coverage and also cost effectiveness in a network. The network architecture of WMNs has been categorized into backbone architecture and hybrid architecture as discussed below.

4.1.1.1 Backbone/Infrastructure WMN

The clients' infrastructure is built by mesh routers as shown in Figure 4.1.

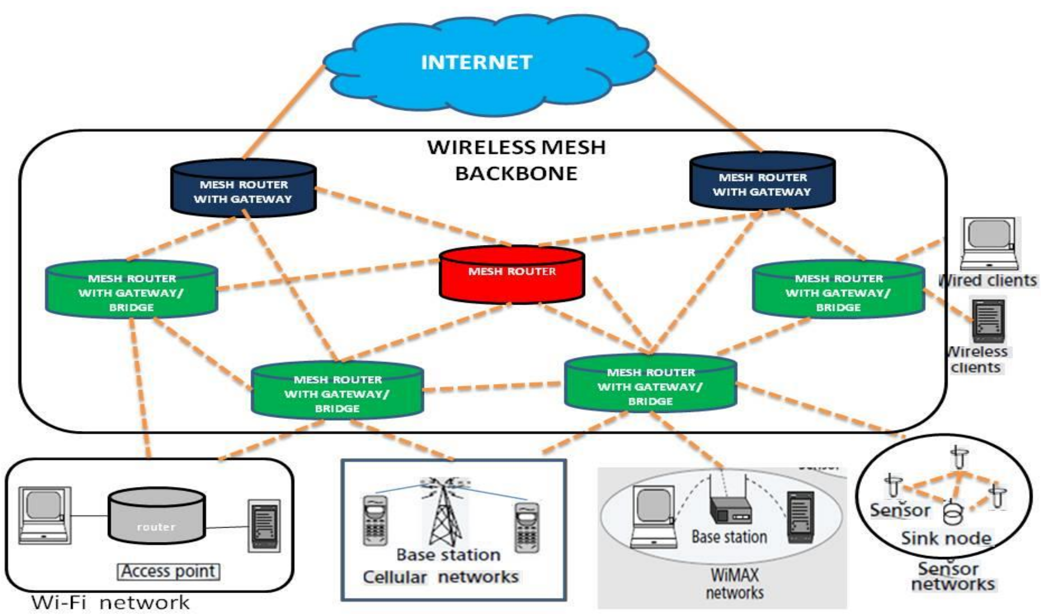

Figure 4.1: Infrastructure/backbone WMNs.

Here solid lines, depicts wired links and dashed lines depicts wireless links [4].IEEE 802.11 technologies and several other radio technologies are usually used to form WMN backbone/infrastructure. A mesh of links which are self-healing and self-configuring is formed by the mesh routers amongst themselves. Internet connectivity can be gained by mesh routers with gateway functionality. Infrastructure meshing approach uses mesh router's functionalities of bridge/gateway for desegregation of WMNs with other networks and also conventional clients are furnished with a backbone using this approach.

4.1.1.2 Hybrid WMN

As depicted in Figure 4.2 client and infrastructure meshing are combined in the hybrid architecture. Network can be accessed directly by mesh clients using mesh routers and also hybrid clients by the usage of meshing [4]. While the connectivity to other type of networks for example Wi-Fi, cellular, the Internet, sensor networks and WiMAX, is provided by the infrastructure, client's routing capabilities provide coverage and improved connectivity inside WMNs.

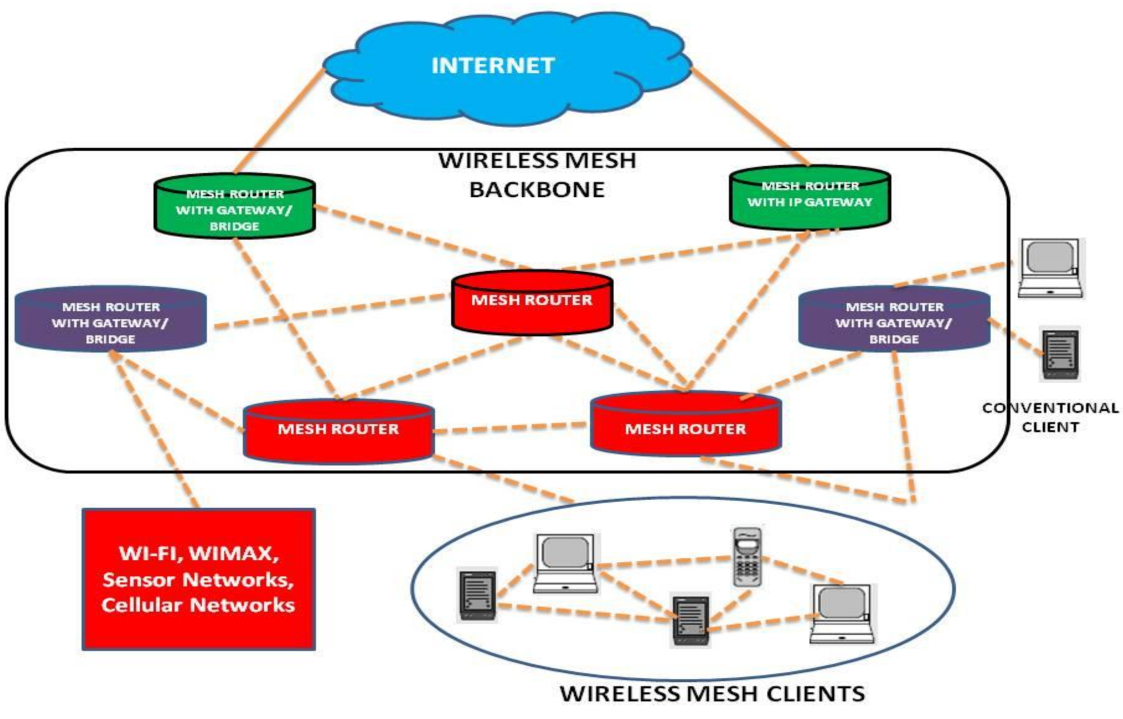

Figure 4.2: Hybrid WMNs.

4.1.2 Characteristics of WMN

As complete advantages are combined by hybrid architecture, therefore, considering this the WMN architecture's characteristics are given below [4]:

(a) WMNs have the capability of self organization, self healing, self-forming and support ad-hoc networking.

(b) WMNs are also referred to as multi-hop wireless networks, where the mesh routers provide a wireless backbone/infrastructure.

(c) Mesh routers perform configuration and dedicated routing, which significantly reduces the load of mesh clients and other end nodes and also mesh routers have minimal mobility.

(d) Wireless infrastructure supports mobility of end nodes easily.

(e) Multiple types of network access is present in WMNs as mesh routers desegregate heterogeneous networks, which includes both wireless and wired.

(f) Constraints of power consumption are different for mesh clients and mesh routers.

(g)WMNs are interoperable and compatible with other wireless networks, and are not stand-alone.

Therefore, WMNs instead of being another type of AN, diversify the potentialities of AN. These additional potentialities require new algorithms and also design principles for the realization of WMNs.

4.1.3 Critical Design Factors of WMN

The critical factors by which WMN's performance gets influenced are described below [4].

(a) <u>Radio Techniques</u> In recent years many approaches have been proposed to enhance capacity and flexibility of wireless systems. Typical examples are multi-channel/multi-radio systems, smart and directional antennas, and Multiple Input Multiple Output (MIMO) systems.

(b) <u>Scalability</u> Scalability is a vital requirement of WMNs. The network performance degrades significantly without the help of this feature, as network size increases. For example, transport protocols connections may be lost, a reliable routing path may not be found by the routing protocols, and substantial throughput reduction may be experienced by MAC protocols. All protocols starting from the MAC layer to the application layer need to be scalable to ascertain the scalability in WMNs.

(c) Connectivity in Mesh Many advantages of WMNs are because of its mesh connectivity. To ascertain reliable connectivity in mesh, topology control and network self-organization algorithms are required. Routing protocols and topology-aware MAC can significantly enhance the performance of WMNs.

(d) QoS and Broadband Most applications of WMNs require heterogeneous QoS such as broadband services which is quite different from that of classical ad-hoc networks. Thus, in addition to fairness and end-to-end transmission delay, various performance metrics, such as packet loss ratios, per-node and aggregate throughput, and delay jitter, must be considered by communication protocols.

(e) Security In recent years for wireless LANs, many schemes for security have already been proposed, but the proposed schemes are still not fully relevant for WMNs. For example, because of the distributed system architecture in a WMN for distribution of a public key centralized trusted authority is not present. For WMNs adoption of the already proposed security schemes for ad-hoc networks is generally done. However, majority of the solutions for security in ad-hoc networks are not mature enough to be applied practically. Moreover, ad-hoc networks and WMNs possess different network architectures which usually provide a solution for ad hoc networks inefficient in WMNs.

(f) Easy Usage Design of Protocols should be such that the network can be as independent as possible. In addition, development of network management tools is required to expeditiously monitor the performance, the parameters configuration in WMNs and the operation maintenance. Using these network management tools, along with the independent mechanisms in networking protocols helps in deployment of WMNs rapidly.

(g) Inter-operability and Compatibility Both conventional and mesh clients should be able to access the network, is the basic requirement in WMNs. Hence backward compatibility of WMNs with conventional client nodes is required. As a result mesh routers should be capable of desegregating heterogeneous wireless networks.

4.2 Typical requirements of Defence Mesh Networks

The inherent requirement for defence networks is to be reliable, flexible, mobile and should be able to transport real time voice, data and video services. Further, due to tactical communication requirements of defence operations, the network should be adaptive to changes in the defence operations and should be established in no time [39]. Due to the above, WMN based defence networks are the ideal networks for deployment in defence communication. To support high data rates, the WMN based defence networks incorporate futuristic technologies. Such networks can provide reliable and failsafe communication for defence networks. However, during the time of actual operations we may find overloading of user traffic in these networks and these networks may be prone to congestion in certain subnets.

The primary aim of WMN based defence networks is to ensure that these networks deliver at critical junctures of defence operations and to optimally utilize the bandwidth during overloaded traffic conditions. Further, there is an inherent requirement of WMN based defence networks to prioritize traffic according to the requirement of defence operations, which may be a problem dynamic in nature. The Typical requirements of Defence Networks have been tabulated in Table 4.1.

Table 4.1: Typical Requirements of Defence Networks

Ser No	Requirements of Defence Networks
1.	Reliable, Flexible and Mobile in nature
2.	Transport Real-Time Voice, Video and Data services
3.	Adaptive to changes in Defence Operations
4.	Established in No-Time
5.	Incorporate State-of the Art/ Futuristic Technologies
6.	Provide Reliable and Failsafe Communications in times of War/ Operations
7.	Deliver at Critical Junctures of Defence Operations
8.	Optimally utilize existing Bandwidth during Overloaded Traffic Conditions
9.	Prioritize traffic according to the requirement of Defence Operations

Defence WMNs are ever evolving and incorporating state of the art technologies to improve performance of the network in terms of throughput, and also ensuring QoS. LTE is a well established protocol in the telecommunication world today and hence, LTE based Defence Mesh Networks (DMN) will be the future of Defence Networks [75].

4.3 Scheduling of Defence Mesh Networks

LTE provides high DR services [5] to the end user and fulfils the expectations of defence users of today. It is evident that LTE based DMN will provide robust, reliable, and fail-safe communication in tactical battle area. However, with high DR services being handled by LTE based DMN, these networks will be prone to congestion and require a mechanism to prevent large packet losses. Further, it is important to understand and appreciate that any telecommunication network will be designed and implemented with only 40 to 50 % of peak traffic load statistically. This makes the network practical and economical to implement. However, in the event of active operations or a situation of full-fledged war, the defence users of LTE based DMN will start to transmit voice, data and video traffic continuously to inform their respective headquarters of the impending situation. This will lead to total blocking of the network or partial failure of certain subnets of the LTE based DMN. Hence, in such situations, it is necessary to classify traffic and prioritize traffic according to type of service (voice, video and data), area of origin in the network, amount of network resource utilization the service desires and delay tolerable by the service. The above prioritization enables important traffic to reach the headquarters or command centres, in order to facilitate real-time decision making in times of active operations or full-fledged war, and further dropping of low priority traffic to decongest subnets of the LTE based DMN.

Hence, a priority scheduling algorithm is required to be proposed which is both efficient and of low complexity. The incorporation of this algorithm in DMN will ensure lower packet loss in the network and substantially improve the QoS in the LTE based DMN.

4.4 Priority Scheduling Algorithm in DMN

LTE based DMN provides robust, redundant and reliable communication to the defence users. The LTE based DMN also facilitates the defence users to transport bandwidth heavy service like video transfers and video conferencing from edge of the battlefield in forward areas to the defence headquarters located in the hinterland through a mesh of high data links in the LTE based DMN. However, typically these telecommunication networks are planned, designed and implemented for a maximum of 40 to 50 % of peak loads [5]. During an event of active operations or full-fledged war, each defence user starts pumping bandwidth heavy traffic into the LTE based DMN in order to ensure that his higher headquarters gets the real-time information of the impending situation in its area of responsibility. Thus, the entire network or certain subnets of network gets congested and results in denial of service to the defence users of the LTE based DMN.

On the other hand, it is pertinent to understand that the headquarters, in the hinterland may be concentrating on information being originated from certain subnet or circle of LTE based DMN which is in contact with the enemy. On the other hand, information from other subnets may not be important to the headquarters during that phase of the battle. In the light of the above viewpoint, the headquarters, which requires real-time information to take immediate decisions that may shape the direction of battle in own favour, will like to drop traffic from low priority circles which are unnecessarily congesting the network. Further, higher priority should be given to traffic originating or destined to affected or active circles in the event of active operations or full-fledged war.

4.4.1 Problem Statement and Related Work

4.4.1.1 Problem Statement

A Priority Scheduling Algorithm (PSA) is proposed in this research work which assigns weights to each connection request for every wireless node in the LTE based DMN. Every connection request is classified into three different classes thus ensuring differentiated services. The number of hops and data rate requested by each service request is adequately utilized with the class of service to calculate weight for each connection request. The weights thus assigned to each connection request on the basis of above connection parameters are arranged in a fashion that the lighter requests are given higher priority and are assigned a better quality of wireless link for transmission. The incorporation of the proposed PSA ensures lower packet loss in the network and substantially improve the QoS in the LTE based DMN as discussed in the research work.

The above requirement can be fulfilled by incorporating a new traffic scheduling algorithm which should optimally utilize the limited bandwidth of WMN based defense networks. The proposed PSA in this research work effectively incorporates class of service quantization of connection requests and prioritization of service requests to ensure lesser blocking probability in WMN based defense networks. A brief overview of traffic scheduling in WMN is given in the next section for completeness.

4.4.1.2 Related Work

In this section, we present an overview of related work for traffic scheduling in LTE based WMN. Traffic grooming algorithms in WMN have been adequately researched and a survey of traffic scheduling in WMN is available [4]. Various algorithms for traffic scheduling in WMN are proposed in [76-81]. There has been substantial amount of work in the field of traffic scheduling in LTE based wireless networks Traffic scheduling for disjoint multipath based routing networks is discussed in [82]. Delay-aware QoS scheme for mixed traffic flow in LTE networks is researched [83]. Further performance evaluation of mixed traffic scheduling algorithm in LTE network [84], and analysis of scheduling policies for VoIP traffic in LTE-Advanced network [85] has been done. Experiments in fair scheduling for 4G networks are available [86]. Hierarchical taylor-made scheduling for data traffic with prioritization in LTE networks [87] and delay based scheduling algorithm for video traffic in LTE networks [88] has been researched. Delay scheduler with throughput-fairness in LTE wireless networks is available [89]. TCP-aware scheduling in LTE networks is also available [90]. Scheduling with channel quality indicator for real-time traffic in LTE networks has been done [91]. Ensuring QoS in LTE networks by traffic scheduling has been adequately researched [92-94]. Further, priority based traffic scheduling and utility optimization for smart grids [95] have shown that priority based traffic scheduling is an imminent requirement to optimize available bandwidth. Though, initial study of priority based algorithms for traffic grooming in wireless defense networks have recently been undertaken by authors [39] [95-100], however, the issue of giving weightage to information originating from important areas and for important class of user in the LTE based DMN has not been explored previously.

4.4.2 Priority Scheduling Algorithm Functionality

LTE based DMN requires an efficient traffic scheduling algorithm to ensure that high priority packets are dropped less in comparison to low priority packets. Various parameters affecting the performance of PSA and the various steps of the algorithm are described in details, followed by the proposed PSA architecture. The functionality of PSA is presented below:

A. Class of Service Quantization of Traffic

The PSA prioritizes the information from the users into multiple schemes of service so as to assure QoS. This division of information into multiple schemes of service is essential to ensure that a higher scheme of information from the user is not neglected during clogging of portions of the network during peak hour conditions in the LTE based DMN. To support the above, the PSA divides information from the users into the following schemes:

(a) Real Time Information (RTI) (S = 3): for voice and live video applications.

(b) Non-Real Information (NRI) traffic (S = 2): for compressed video information.

(c) Delay Tolerant Information (DTI) (S = 1): for movement of files.

This division of information into schemes of service is done by “Request Handler”, located at every wireless node in the LTE based DMN.

B. Prioritization of Sector

The LTE based DMN is organized into five sectors and one control headquarters for better command and control. In the scenario of active operations or full-fledged war, the traffic in the LTE based DMN increases substantially and the inter-sector traffic will experience high congestion. Further, any active operation or a full-fledged war is concentrated to a particular sector. Hence, the sector in which concentration of active operations or full-fledged war takes place at the moment is the Active Sector and the traffic generated from the Active Sector will be of utmost importance for the national security. Hence, the packets originating from the Active

Sector needs to be given the highest priority and should be the last ones to be dropped in case of congested wireless links.

In the simulations, without loss of generality it is assumed that the active operations or a full-fledged war is concentrated in Sector-A. Therefore, Sector-A is designated as the Active Sector. Sector-B is the adjacent sector and therefore is given second priority as it is assumed that this sector is going to have an impact on the operations in Sector-A (being the Active Sector). Sector-C has been given the last priority as it is assumed for the simulation process that the activities in the sector has little or no impact in the operations in Sector-A. In view of the above assumptions, each packet originating from a certain sector is given a Sector Priority (SP) value as given below:

(a) Packets from Sector-A (Active Sector) : SP = 1.

(b) Packets from Sector-B : SP = 2.

(c) Packets from Sector-C : SP = 3.

C. Algorithm Framework

The constituents of the framework for an LTE based DMN are Request Handler, Request Prioritizer, bidirectional wireless links and control links [39]. The described framework of the constituents of a LTE based DMN for application of PSA is given in Figure 4.3.

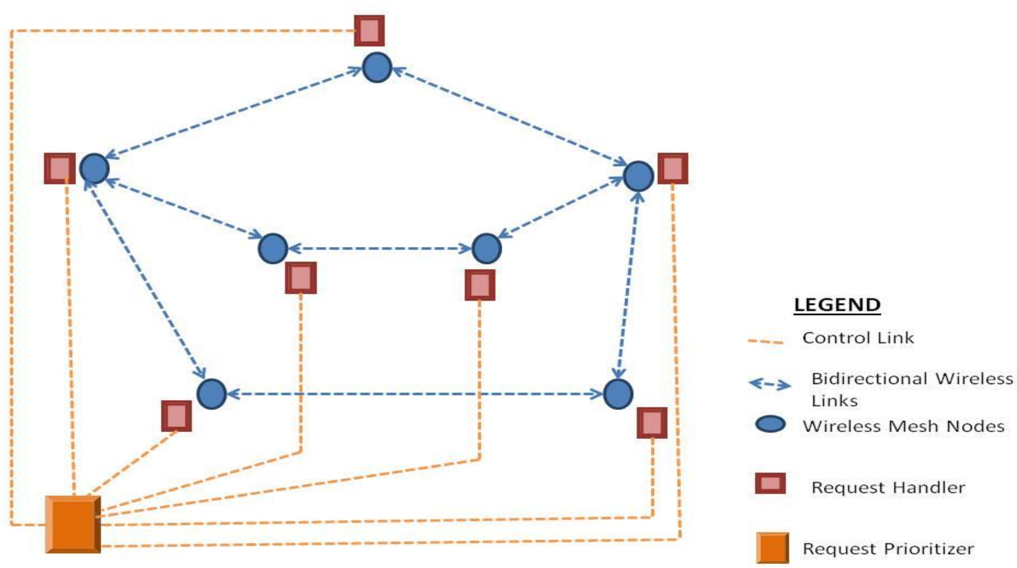

Figure 4.3: Framework for PSA.

D. Algorithm Functionality

PSA aims to enhance the delivery of packets which either carry important information or carry information which is originated from an important sector of the LTE based DMN. The above can be implemented by ensuring that these important packets are transferred first (in priority) in the LTE based DMN during an event of clogging of portions of the network during peak hour conditions. PSA incorporates processes of handling of user information [75] as described below:
Extraction of parameters from connection requests:

PSA needs to extract important parameters from the user connection requests and process it centrally. These important parameters are extracted by the 'Request Handler' positioned at every wireless node of the LTE based DMN. Further, every Request Handler forwards these important parameters to a central Request Prioritizer for processing the information as per the steps of the PSA algorithm. After processing at the central Request Priotizer, the weighted results are forwarded to the respective Request Handlers for processing and transmission of the respective packets in order of their assigned weights. The various important parameters extracted from the user connection requests are enumerated below:

(a) Hop Count (H): The source eNodeB number and destination eNodeB number are extracted from information bearing packet received by the serving eNodeB of the LTE based DMN. The above eNodeB numbers are used to calculate the route of the information carrying packet in the LTE based DMN utilizing Djikstra algorithm. Number of Hops in the LTE based DMN is extracted from the above.

(b) Tolerable Delay (D): The time delay in millisecs, an information carrying packet can withstand in the LTE based DMN, without any deterioration in end user service is extracted from the Request Handler.

(c) Required Data Rate (DR): The data speed required by the service requests throughout all links in the LTE based DMN is provided by the Request Handler.

(d) Service Priority (S): This division of information into multiple schemes of service generated by the user in the LTE based DMN. The different division of informations into multiple schemes are given in Section 4.4.2.A.

(e) Sector Priority (SP): This is the priority of the packet according to its sector of origin and takes values as highlighted in Section 4.4.2.B.

It is observed that the parameters (b), (c) and (d) are extracted from the service request of the user by the Request Handler and provided to the central Request Prioritizer on the control link. The parameters (a) and (e) are extracted from the system architecture by the central Request Prioritizer. The above five metric parameters are utilized for further processing at the central Request Prioritizer according to following steps:

Step-1: Generation of a schema for connection demand for every eNodeB in the LTE based DMN is given in Table 4.2.

Table 4.2: Connection Demand Schema

S. No	Source Id	Destination Id	No of Hops (H)	Data Rate Required (DR) (in Mbps)	CoS Requ-ired (S)	Tolerable Delay (D) (in msec)	Sector Priority (SP)
1	001	003	2	0.2	2	0.45	1
2	002	005	3	0.3	1	0.30	3
3	001	004	3	0.4	3	0.50	1
4	002	006	4	0.5	2	0.40	3
5	003	006	3	0.6	2	0.35	2
6	005	002	3	0.7	1	0.25	2

Note: The figures in Schema are random to elaborate PSA steps.

Step-2: After creating the connection demand schema, the Request Prioritizer derives the weight (W) for each connection demand by using (1) below:-

$$W = H/H_{max} + 1/S + DR / M_d + D + SP \qquad (4.1)$$

The weight derived from (4.1) indicates the portion of communication assets that the connection demand will be required for successful delivery of the packets to the destination. The logic of each term in of (4.1) is enumerated below:

(a) First term of (4.1) – is a relative of Hop Count (H) to the highest number of hops (H_{max}), the links span in the LTE based DMN. H_{max} is assumed to take a value of '4' as per the architecture in Figure 4.4.

(b) Second term of (4.1) – is a relative of Service Priority (S) to the maximum value of S possible, which is incidentally '3' as brought out in Section 4.4.2.A.

(c) Third term of (4.1) – is a relative of the data speed required (DR) by the service requests throughout all links in the LTE based DMN to the highest value of data speed (M_d), designed in the LTE based DMN which is incidentally 7 Mbps.

(d) Fourth term of (4.1) – The time delay in millisecs, an information carrying packet can withstand in the LTE based DMN, without any deterioration in end user service.

(e) Fifth term of (4.1) – gives the priority of a packet depending on the sector of origin. Packets from Sector-A (Active Sector) have been given the highest priority, packets from Sector-B (adjacent sector to the Active Sector) next priority and packets from Sector-C have been given the least priority. The value of the parameter assigned to each packet is as given in Section 4.4.2.B.

At each eNodeB, the derived service demand packets are stacked in queue in such a way that packets which have been stamped with greater value of weights are positioned first in order of transmission in every eNodeB of the LTE based DMN. The Weight (W) figures for all service demands for all rows of the connection demand schema in Table 4.2 are derived and a weighted demand schema is generated as given in Table 4.3.

Table 4.3: Weighted Demand Schema

S. No	Source Id	Destination Id	No of Hops (H)	Data Rate Required (DR) (in Mbps)	CoS Requ-ired (S)	Tolerable Delay (D) (in msec)	Sector Priority (SP)	Weight (W)
1	001	003	2	0.2	2	0.45	1	2.47
2	002	005	3	0.3	1	0.30	3	5.09
3	001	004	3	0.4	3	0.50	1	2.62
4	002	006	4	0.5	2	0.40	3	4.97
5	003	006	3	0.6	2	0.35	2	3.68
6	005	002	3	0.7	1	0.25	2	4.10

Note: H_{max} is chosen to be 4 hops as per algorithm architecture of Figure 4.4 and M_d is kept at 7 Mbps.

<u>Step-3</u>: The rows in the in weighted demand schema in Table 4.3 is reoriented in such a way that lower valued Weights (W) are on top and higher valued W are below. This new reoriented schema is called the Prioritized Queuing Schema and is given in Table 4.4.

Table 4.4: Prioritized Queuing Schema

S. No	Source Id	Destination Id	No of Hops (H)	Data Rate Required (DR) (in Mbps)	CoS Requ -ired (S)	Tolerable Delay (D) (in sec)	Sector Priority (SP)	Weight (W)
1	001	003	2	0.2	2	0.45	1	2.47
3	001	004	3	0.4	3	0.50	1	2.62
5	003	006	3	0.6	2	0.35	2	3.68
6	005	002	3	0.7	1	0.25	2	4.10
4	002	006	4	0.5	2	0.40	3	4.97
2	002	005	3	0.3	1	0.30	3	5.09

Step-4: The Prioritized Queuing Schema (derived for every eNodeB in a LTE based DMN), Table 4.4 from Step 3 deduces to the sequence of transmission of information carrying packets for every eNodeB of the LTE based DMN. The above deduction takes place at the central Request Prioritizer and communicated to the respective Request handlers of the LTE based DMN. The arrangement is repeated for the every row of Table 4.4 till there are no connection demands remaining in Table 4.4. Step-4 ensues for all the eNodeBs in the LTE based DMN.

E. Computational Complexity

The computational complexity of PSA as given in equation (4.1) of Step 2, is of the order O(1), which is minimal. The computational complexity of the entire algorithm from Step 1 to Step 4 of sub-section *D* is equal to O(nlog(n)) + O(1) ~ O(nlog(n)). The PSA is implemented as software in existing hardware of the LTE architecture (eNodeB) and the cost factor for the implementation is not substantial; however, it optimizes the utilization of network resources substantially, to ensure more services being provisioned on the existing network. The above is aptly demonstrated in the simulation and their results in Section 4.5.

4.5 Simulation Results and Analysis

The architecture considered for simulation of PSA in LTE based DMN is given in Figure 4.4. The DMN has been divided into 5 sectors, each having 2 nodes each, and a Control Headquarters with 2 nodes for better command and control. The voice, video and data sensors are connected to these nodes and the information is passed through inter and intra sector links to reach the destination at the Control HQs. The architecture consists of 12 wireless nodes and 20 bidirectional wireless links.

On the control plane, the architecture consists of a Request Handler collocated at each wireless node. A central Request Prioritizer handles all control functions for the DMN. The Request Handlers collocated at each wireless node are connected to the central Request Prioritizer by a control link. The Routing Controller is responsible for running the proposed PSA and routing of information in the LTE based DMN of Figure 4.4.

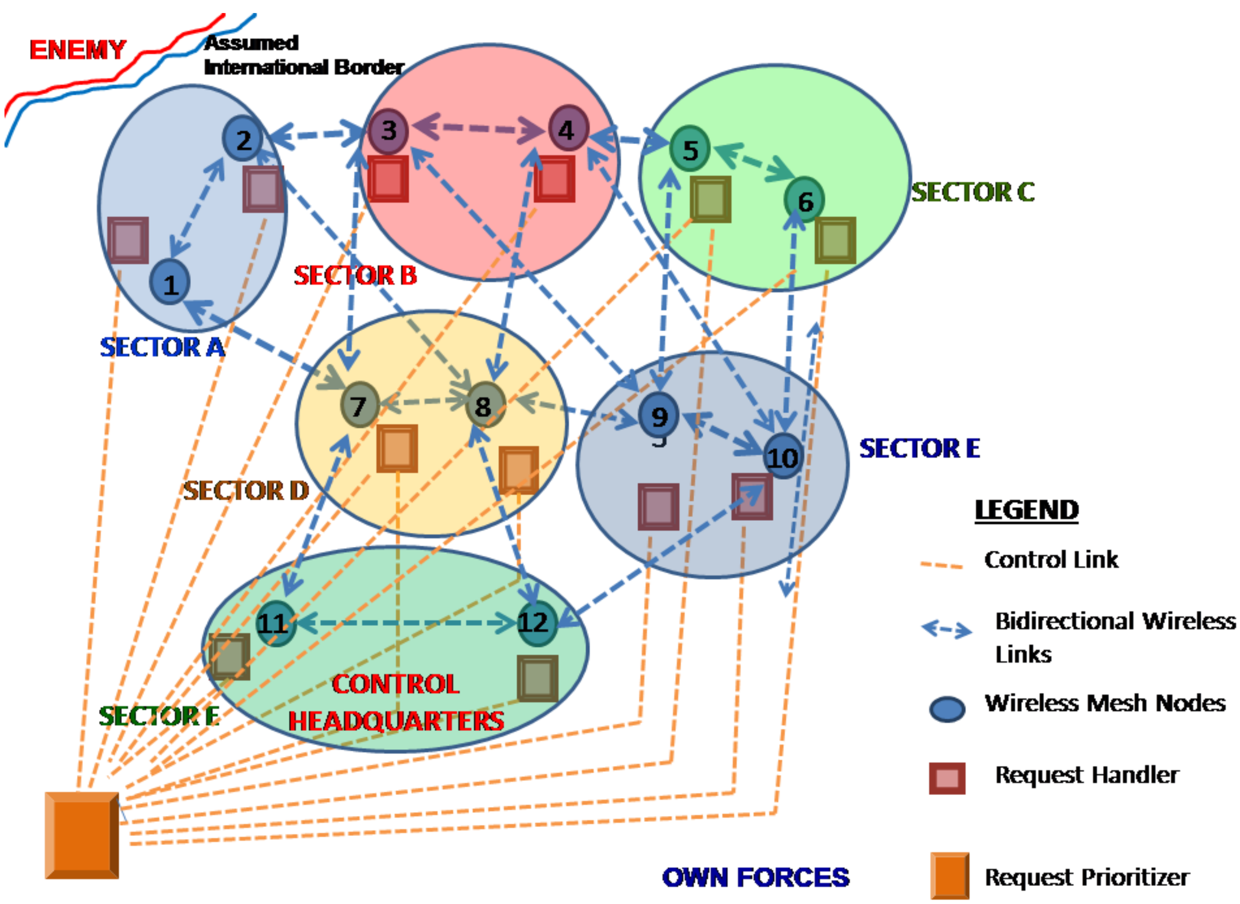

Figure 4.4: Simulation Architecture for PSA in LTE based DMN

The simulation has been done in OMNET++ framework [51]. The simulation has been carried out in OMNET++ (version 4.2.2), which is a discrete event simulating environment. INET framework has been used inside the OMNET++ environment, which facilitates simulation of the algorithm in LTE based DMN. The conjecture based on which the evaluation of PSA has been done is given below:

(a) The requests for channels/connections are random in nature. The stochastic behaviour of the random request follows a Poisson distribution. Further, the time of arrival between two events (two connection requests) of connection requests in succession, follow a distribution which is exponential in nature.

(b) The largest value for data rate of every wireless channel is kept at 7 Mbps. The increments of requests in data rate thereafter are in multiples of 100 Kbps.

(c) The data units/ packets are inducted arbitrarily amidst all originating and destined wireless eNodeBs. A channel demand is spoken to be not availed or denied in case the requisite bandwidth is not allocated in any of the intermediate links.

(d) The consummation of PSA is quantified in quantum of Packet Loss (PL) wherein; the more diminished the PL, finer the performance of network. Packet Increase (PI) is commensurate to accrual in cardinal of service users in the LTE based DMN.

(e) The quantum of data units developed by every eNodeB in the LTE based DMN is gradually increased for the evaluation and analysis of PSA to a value of 11,000 data units.

The evaluation and analysis of PSA is conducted in three phases as enumerated in following sub-sections:

A. Phase-1

In the first phase of the simulation, the functionality and performance of PSA algorithm is evaluated in the simulation architecture of Figure 4.4. The traffic in terms of voice, video and data packets have been generated from all wireless sensor nodes connected to each wireless node of LTE based DMN. The simulation result of number of dropped packets with increasing number of input packets in the simulation architecture of Figure 4.4is shown as Figure 4.5.

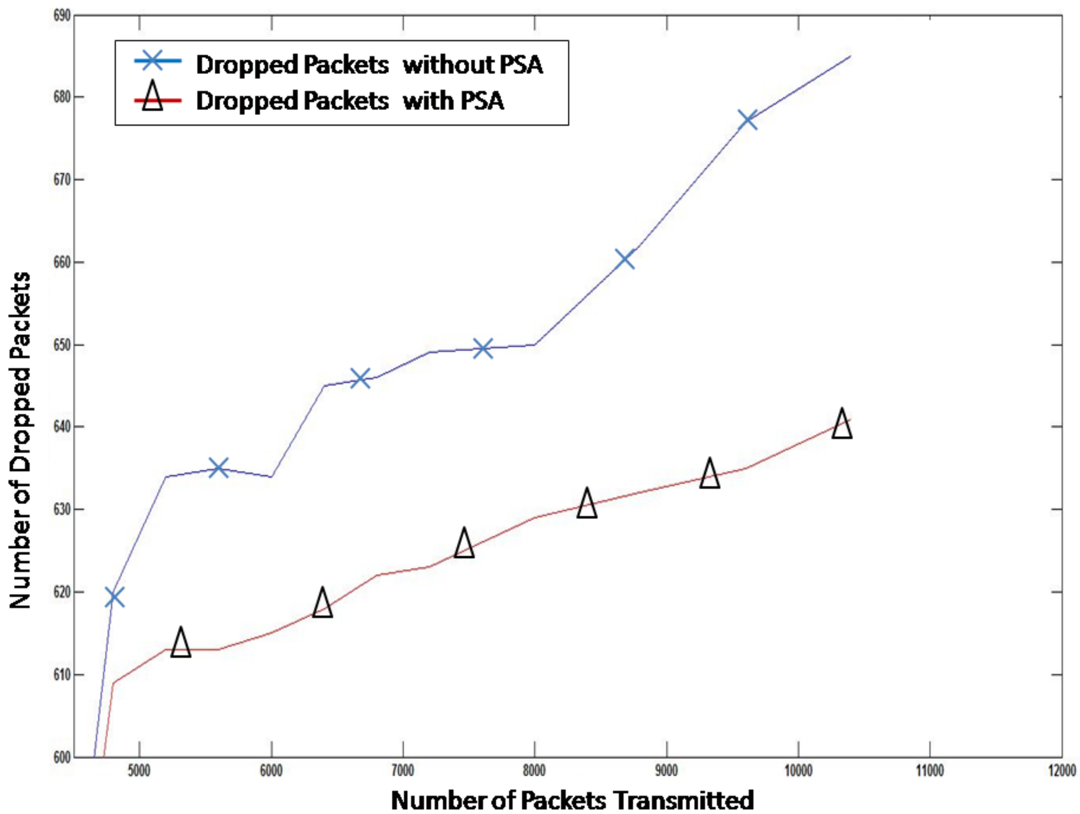

Figure 4.5: Performance of PSA.

From Figure 4.5, the number of dropped packets have reduced substantially (around 50 packets for 10,000 packets input in the network) on incorporating the PSA. Hence, we can infer that there is good amount of enhancement in the overall throughput of the network by associating PSA in the LTE based DMN. The improvement increases drastically as the more number of packets are entering the network.

B. Phase-2

In the next phase of simulation, the dropped packets of each sector have been analyzed and the simulation result is given in Figure 4.6.

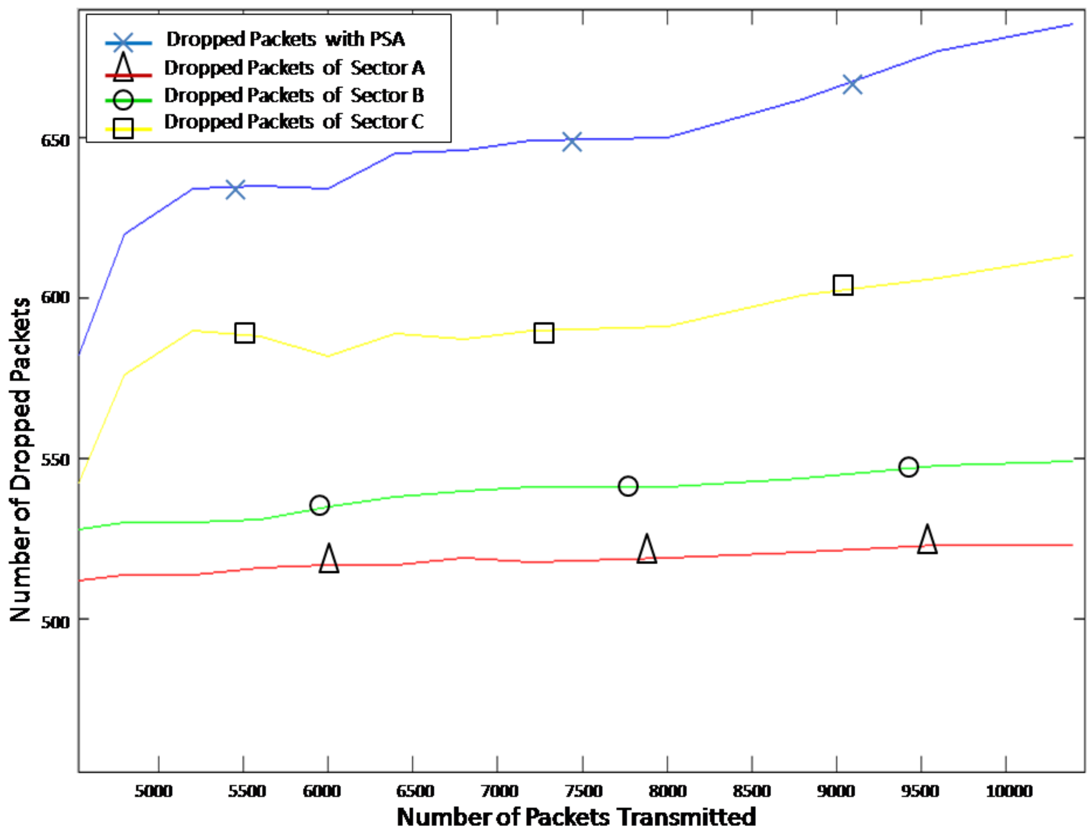

Figure 4.6: Sector wise Packet Loss Analysis

From the Figure 4.6, following inferences are deduced:

(a) Number of dropped packets of Sector A is minimum, Sector B has relatively more dropped packets and Sector C has maximum dropped packets.

(b) The above is due to the fact that the PSA in the simulation architecture of Figure 4.4 has assigned packets from Sector A with the highest priority, packets from Sector B with lower priority and packets from Sector C have been assigned the lowest priority.

Therefore, we infer that by the incorporation of PSA in the LTE based DMN has resulted that the minimum number of packets are dropped from high priority sector which is the "Active Sector" for the Control HQ. These results are shown during active operations or full-fledged war, since most important packets from the Active Sector (which is at the helm of operations) are rarely dropped and given the highest priority to reach the Control HQ. This facilitates fast and effective decision making in the interest of national security.

Further, the combined figure, showing class-wise number of dropped packets in different sectors has been simulated and are shown in Figures 4.7, 4.8 and 4.9 for Sectors A, B and C respectively.

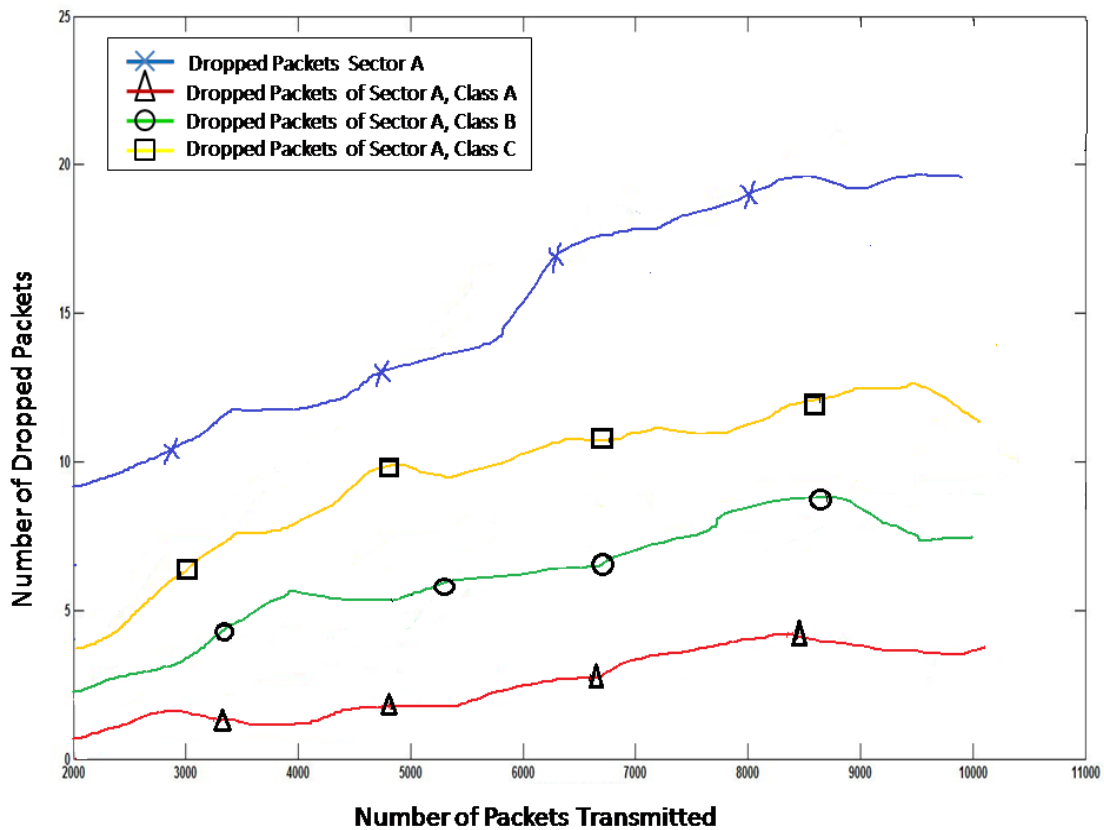

Figure 4.7: Class-wise Packet Loss Analysis of Sector A.

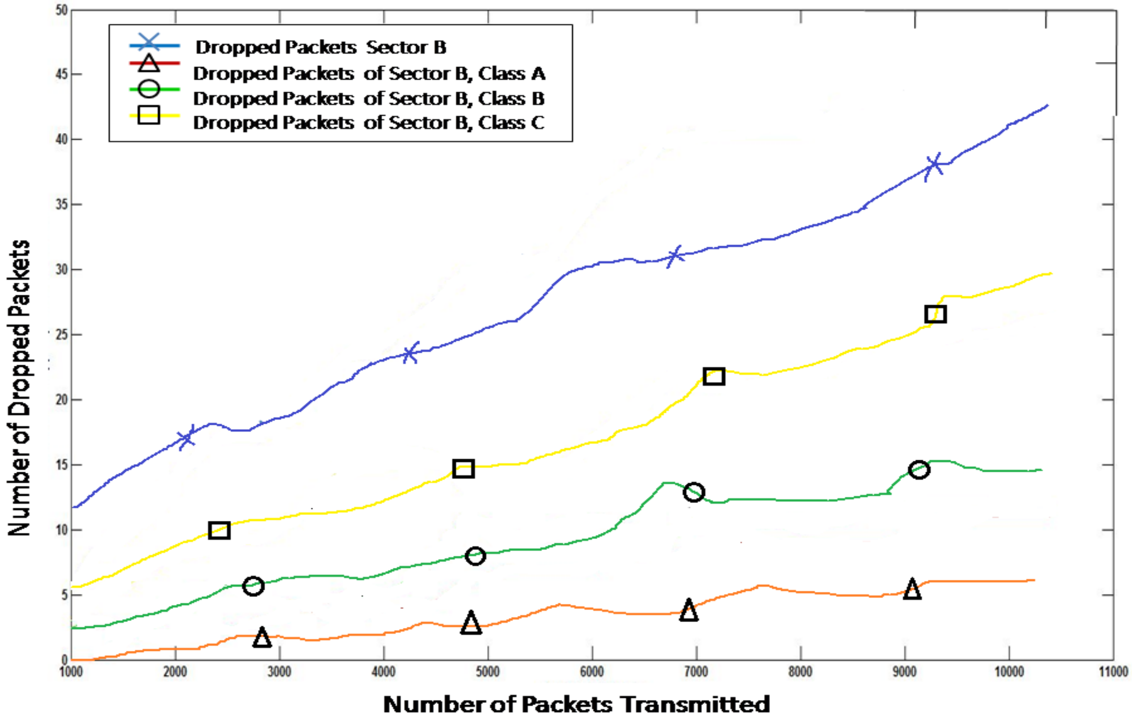

Figure 4.8: Class-wise Packet Loss Analysis of Sector B.

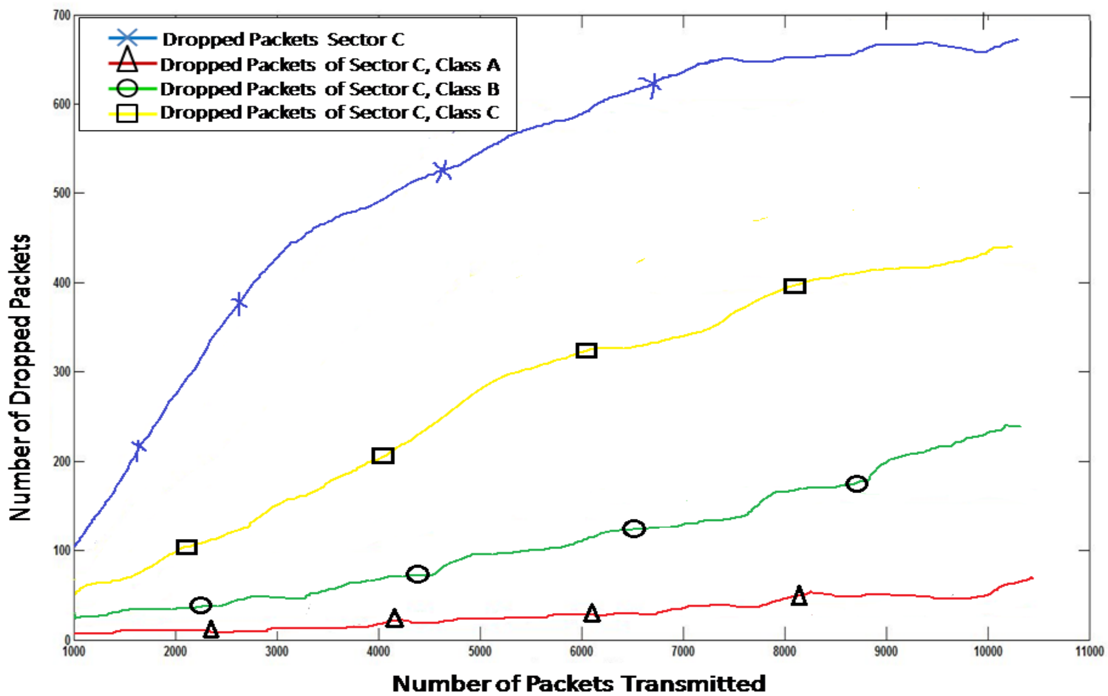

Figure 4.9: Class-wise Packet Loss Analysis of Sector C.

Further, in order to analyze the percentage (overall average) of Dropped Packets belonging to different classes in different sectors the results have been tabulated in Table 4.5.

Table 4.5: Sector-wise Percentage of Dropped Packets for different Classes

Ser No	**Type of Traffic**	**Percentage of Dropped Packets**
Sector A		
01	Class A	5.6 %
02	Class B	26.8 %
03	Class C	67.6 %
Sector B		
04	Class A	7.4%
05	Class B	30.1%
06	Class C	62.5%
Sector C		
07	Class A	13.5%
08	Class B	32.7%
09	Class C	53.8%

C. Phase 3

In the third phase of simulation, the class-wise packet analysis for LTE based DMN architecture of Figure 4.4 has been done and the results are given in Figure 4.10.

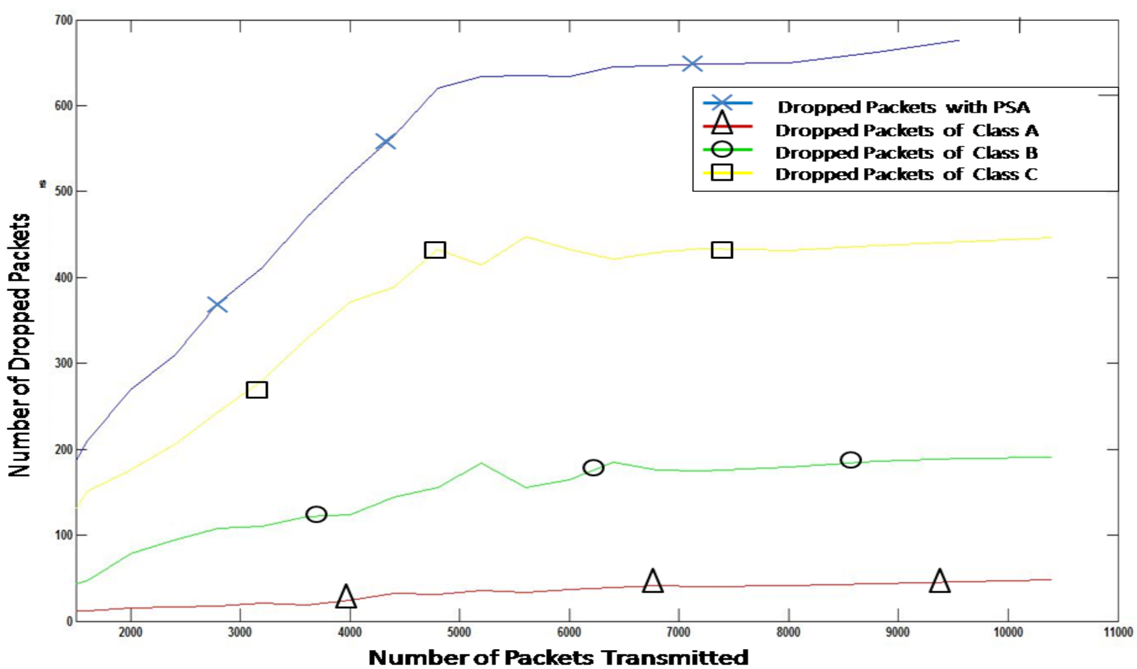

Figure 4.10: Class-wise Packet Loss Analysis of all Three Sectors in LTE based DMN

From Figure 4.10, we can infer that the packets of Class A have the highest priority, followed by packets of Class B and the packets of Class C have the minimum priority for the entire network. Hence, Class A packets attain the highest throughput in the entire network in comparison to other classes of traffic. The above is in accordance with the prioritization of packets done by PSA in the simulation architecture of Figure 4.4.

The PSA primarily incorporates two levels of prioritization i.e. CoS prioritization and Sector-wise prioritization in the simulation architecture of LTE based DMN of Figure 4.4. We have seen in all the above simulation results that the number of dropped packets during the time of congestion in the network (at times of active operations or full-fledged war) have been drastically reduced for packets of high priority class and packets originating from high priority sector which is the "Active Sector". The reduction of packet loss (thereby reducing the need to retransmit) in critical time (during active operations) is highly desirable in DMN.

A Summary of Initial Requirements Of Defence Networks and the corresponding results achieved by incorporation of PSA is given in Table 4.6.

Table 4.6: Typical Requirements of Defence Networks

Ser No	**Requirements of Defence Ntworks**	**Results Achieved**
1.	Reliable, Flexible and Mobile in nature	Yes
2.	Transport Real-Time Voice, Video and Data services	Yes
3.	Adaptive to changes in Defence Operations	Yes
4.	Established in No-Time	Depends on Actual deployment
5.	Incorporate State-of the Art/ Futuristic Technologies	LTE/ LTE-A is future ready
6.	Provide Reliable and Failsafe Communications in times of War/ Operations	Yes
7.	Deliver at Critical Junctures of Defence Operations	Capable to deliver
8.	Optimally utilize existing Bandwidth during Overloaded Traffic Conditions	Yes
9.	Prioritize traffic according to the requirement of Defence Operations	Yes

4.6 Limitations of Research Work

The PSA algorithm can be easily ported to each DMN node assuming the military proprietary software allows porting of the algorithm and scheduling of traffic at each DMN node, as these military hardware are generally customized to suit the military requirements of ruggedness and performance at extreme temperature ranges. Further, the parameters of Tolerable Delay and Sector Priority have to be available in real-time at each DMN node for effective employment of the PSA in a DMN.

4.7 Summary

Future Wireless Networks (FWNs) are anticipated as a convergence of various kinds of technologies which are wireless, for example cellular technologies, Wireless Metropolitan Area Networks (WMANs), Wireless Local Area Networks (WLANs), Wireless Sensor Networks (WSNs), and conventional wired networks. Though the users are unknown to the particular underlying network which is being utilized by the users' applications, the networks must be capable of providing the resource (bandwidth) with assured QoS. The users must be capable of moving smoothly among different networking technologies, e.g., among WiMAX, Ethernet, 2G/3G/4G and WLANs, with rigorous requirements of QoS. As the bandwidth becomes a critical network resource that needs to be optimized because of bandwidth hungry services that integrates voice, video and data, several techniques need to be developed.

LTE based DMN is the solution for current and future defence networks. Due to high traffic inflow in the LTE based DMN at times of active operations or full-fledged war, the LTE based DMN experiences high congestion in the wireless links resulting in high packet loss of critical information from the Active Sector. The proposed PSA improves the packet loss in the network and incorporate QoS in the network, which improves the packet throughput from high priority sector and for high priority class. The same has been validated from the simulation results and their analysis in Section 4.5

Chapter 5

Traffic Scheduling in Long Term Evolution based Wireless Mesh Networks

LTE is the name given to a 3GPP for UTRAN evolution to meet the needs of future broadband cellular communications [5]. This project can also be considered as a milestone towards 4G standardization, and also referred as Long Term Evolution of the UMTS.

5.1 Third Generation Partnership Project standard for LTE

LTE standard for advanced cellular communications is an emerging standard being embraced by commercial carriers. It holds the promise of an interoperable network based on non-proprietary, commercially available technology. LTE embodies a vision of wireless access that assumes a path-breaking transition towards a packet switched only system that is distinctly non-hierarchical, and which makes wide use of IETF protocols and practices. LTE is further designed to be interoperable with legacy UMTS systems and offers support for seamless mobility through non-3GPP wireless accesses including WiMAX and Wi-Fi.

5.1.1 Background

The LTE access network incorporates state-of-the-art air interface technologies including OFDMA and advanced antenna techniques to maximize the efficient use of RF spectrum. It also accommodates several options for frequency bands, carrier bandwidths and duplexing techniques in order to effectively utilize the different portions of unused spectrum available in different countries and geographies. Additionally, and significantly, the LTE network architecture evolves to all IP architecture, enabling the seamless delivery of applications and services over what were previously two separate and distinct networks, while QoS options which allow for real time packet data services like VoIP and live video streaming.

As a wireless network which improves spectral efficiency, simplifies deployment of all-IP real-time services, facilitates integration with non-wireless networks and supports interworking with legacy wireless technologies, LTE is strongly positioned to lead the evolution in the communications industry for several years. It achieves all of the above issues through a flat, scalable architecture which is designed to manage and maintain QoS in a mobile environment. The fine granularity (180 KHz Resource Block times 1millisecond Transmission Time Interval) afforded by LTE allows for packing efficiency and exploitation of time/frequency channel selectivity through opportunistic scheduling, thus enabling higher user throughputs. Thus packet scheduling is an important aspect of LTE.

5.1.2 Overview of Physical Layer Technologies

The requirements standards for LTE specified envisage high peak data rates, low latency, increased spectral efficiency, scalable bandwidth, flat all-IP network architecture, optimized performance for mobile speed, etc. In order to fulfill this extensive range of requirements several key technologies have been considered for LTE radio interface of which the most important are briefly described in succeeding sub-sections.

5.1.2.1 Orthogonal Frequency Division Multiplexing

The LTE radio interface is based on the frequency division multiplexing technique. OFDMA is used in the downlink direction whereas Single Carrier Frequency Division Multiple Access (SC-FDMA) is used in the uplink direction [7]. Its advantage lies in dealing with frequency selective fading and inter-symbol interference with high spectral efficiency, whereas its disadvantage is high peak to average power ratio as well as sensitivity to Doppler shift and to frequency synchronization. OFDM also provides some additional benefits relevant for LTE:

(a) OFDM provides access to the frequency domain, thereby enabling an additional degree of freedom to the channel-dependent scheduler compared to time-domain-only scheduling used in major 3G systems.

(b) Flexible transmission bandwidth to support operation in spectrum allocations of different size is straight forward with OFDM, at least from a baseband perspective, by varying the number of OFDM subcarriers used for transmission.

5.1.2.2 Frequency Division Duplex and Time Division Duplex

LTE supports both FDD (Frequency Division Duplex) and TDD (Time Division Duplex) duplexing schemes. In FDD mode, the uplink and downlink transmission happens in separate frequency bands, whereas the TDD mode uses timeslots of the same frequency band for downlink and uplink transmission. The frequency band varies between 1.4 and 20 Mhz. Modulation schemes used for uplink and downlink are QPSK, QAM-16 and QAM-64.

5.1.2.3 Multi-Antenna Configurations

Multi-antenna techniques can be seen as a joint name for a set of techniques with the common theme that they rely on the use of multiple antennas at the receiver and/or the transmitter, in combination with more or less advanced signal processing. Multi-antenna techniques can be used to achieve improved system performance, including improved system capacity (more users per cell) and improved coverage (possibility for larger cells), as well as improved service provisioning – for example, higher per-user data rates.

The availability of multiple antennas at the transmitter and/or the receiver can be utilized in different ways to achieve different aims. Multiple antennas at the transmitter and/or the receiver can be used to provide additional diversity against fading on the radio channel. In this case, the channels experienced by the different antennas should have low mutual correlation, implying the need for a sufficiently large inter-antenna distance (spatial diversity), or the use of different antenna polarization directions (polarization diversity).

Multiple antennas at the transmitter and/or the receiver can be used to "shape" the overall antenna beam (transmit beam and receive beam respectively) in a certain way – for example, to maximize the overall antenna gain in the direction of the target receiver/transmitter or to suppress specific dominant interfering signals.

The simultaneous availability of multiple antennas at the transmitter and the receiver can be used to create what can be seen as multiple parallel communication "channels" over the radio interface. This provides the possibility for very high bandwidth utilization without a corresponding reduction in power efficiency or, in other words, the possibility for very high data rates within a limited bandwidth without a disproportionately large degradation in terms of coverage. This is called spatial multiplexing often also referred to as MIMO antenna processing.

5.1.3 LTE Architecture

In parallel to the work on the LTE radio-access technology in 3GPP, the overall system architectures of both the Radio-Access Network (RAN) and the Core Network (CN) were revisited, including the split of functionality between the two network parts. This work was known as the System Architecture Evolution (SAE) [7] and resulted in a flat RAN architecture, as well as a new core network architecture referred to as the Evolved Packet Core (EPC). Together, the LTE RAN and the EPC can be referred to as the Evolved Packet System (EPS).

5.1.3.1 Background

LTE uses a simplified flat network infrastructure that consists of only two nodes: the enhanced NodeB (eNodeB) and the Mobile Management Entity/serving gateway (MME/S-GW). This is also one of the main factors that LTE can achieve a reduced latency compared to UMTS/HSPA. A typical architecture of SAE is given in Figure 5.1.

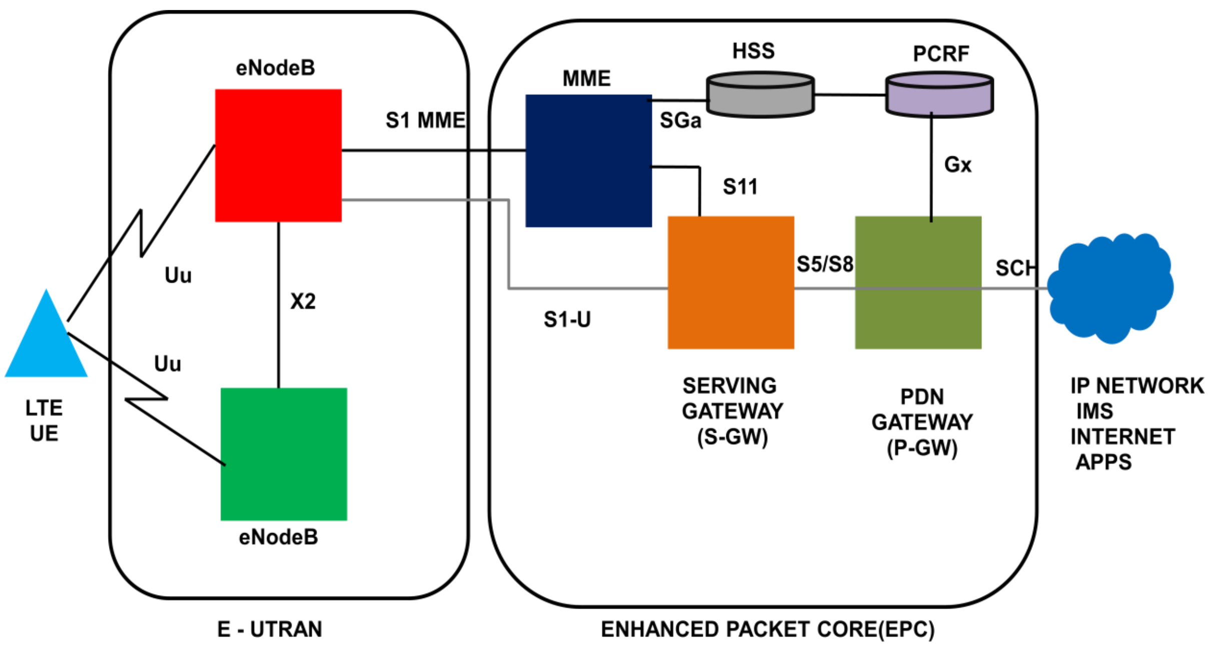

Figure 5.1: A typical SAE Architecture of LTE

The LTE radio access network consists of the enhanced eNodeB. The eNodeBs are connected with each other through the X2 interface and with the EPC through the S1 interface. An eNodeB may be served by more than one MME. The RAN is responsible for all radio-related functionality of the overall network including, for example, scheduling, radio-resource handling, retransmission protocols, coding and various multi antenna schemes.

The EPC consists of one control plane, which is called MME and two user plane nodes, which are called S-GW and Packet Data Network Gateway (PDN-GW). It is responsible for functions not related to the radio interface but needed for providing a complete mobile-broadband network. This includes, for example, authentication, charging functionality, and setup of end-to-end connections. Handling these functions separately, instead of integrating them into the RAN, is beneficial as it allows for several radio-access technologies to be served by the same core network.

The main components of an LTE network include eNodeB and different UEs. eNodeB is used to control the network core using different standard protocols. System 3G LTE employs Physical Resource Blocks (PRB) to transmit resources. PRBs comprises of frequency and time domain phases. eNodeB has got a specific amount of PRBs based on the assigned bandwidth, it also has the responsibility to distribute these PRBs constantly at each Transmission Time Interval (TTI) . General packet scheduling can be employed by the network operator in the UEs and eNodeBs in either the uplink or the downlink. The main issue is that there are no firm provisions that are set by the 3GPP for controlling the packet scheduling mechanisms and thus it’s an extensive area of research.

5.1.3.1 LTE Nodes\Interfaces

The various nodes/ interfaces of LTE architecture are enumerated in succeeding sub-sections

5.1.3.1.1 eNodeB- The Single E-UTRAN Node

The E-UTRAN OFDM-based structure is quite simple. It is only composed of one network element – the eNodeB. The 3G Radio Network Controller (RNC), inherited from the 2G Base Station Controller (BSC) has disappeared from E-UTRAN and the eNodeB is directly connected to the Core Network using the S1 interface. As a consequence, the features supported by the

RNC have been distributed between the eNodeB or the Core Network MME or Serving Gateway entities. The comparison of LTE architecture with a typical 3G cellular architecture is given in Figure 5.2.

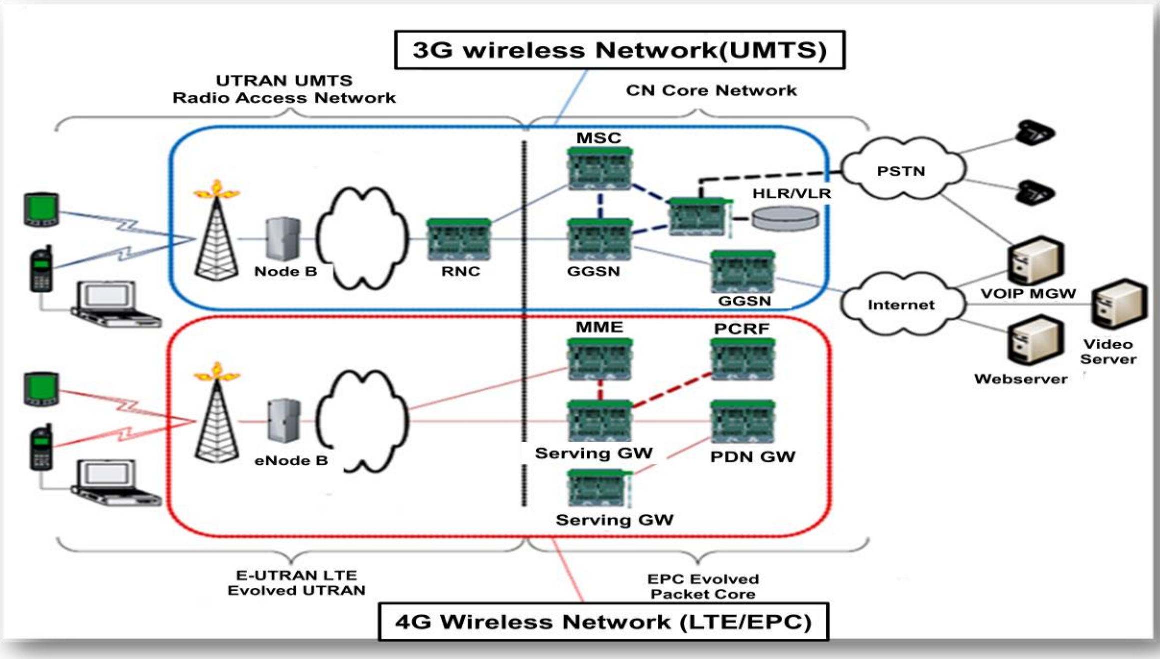

Figure 5.2: Comparison of LTE architecture with 3G cellular architecture

The functionalities of eNodeB are:

(a) Header compression and user plane ciphering.

(b) MME selection when no routing to an MME can be determined from the information provided by the UE.

(c) UL bearer level rate enforcement based on UE-AMBR and MBR via means of uplink scheduling (e.g., by limiting the amount of UL resources granted per UE over time).

(d) DL bearer level rate enforcement based on UE-AMBR.

(e) UL and DL bearer level admission control.

(f) Transport level packet marking in the uplink, e.g. setting the DiffServ Code Point, based on the QCI of the associated EPS bearer.

(g) ECN-based congestion control.

5.1.3.1.2 The X2 Interface

A new interface (X2) has been defined between eNodeB, working in a meshed way (meaning that all Node Bs may possibly be linked together). The main purpose of this interface is to minimize packet loss due to user mobility. As the terminal moves across the access network, unsent or unacknowledged packets stored in the old eNodeB queues can be forwarded or tunneled to the new eNodeB thanks to the X2 interface. From a high-level perspective, the new E-UTRAN architecture is actually moving towards WLAN network structures and Wifi or WiMAX Base Stations.

5.1.3.1.3 P-Gateway

The PDN Gateway is responsible for IP address allocation for the UE, as well as QoS enforcement and flow-based charging according to rules from the Policy Control and Charging Rules Function (PCRF). It is responsible for the filtering of downlink user IP packets into the different QoS-based bearers. This is performed based on Traffic Flow Templates (TFTs). The P-GW performs QoS enforcement for Guaranteed Bit Rate (GBR) bearers. It also serves as the mobility anchor for interworking with non-3GPP technologies such as CDMA2000 and WiMAX networks.

5.1.3.1.4 S- Gateway

All user IP packets are transferred through the Serving Gateway, which serves as the local mobility anchor for the data bearers when the UE moves between eNodeBs. It also retains the information about the bearers when the UE is in the idle state.

5.1.3.1.5 Mobile Management Entity

The Mobile Management Entity (MME) is a control node that processes the signaling between the UE and the CN. The protocols running between the UE and the CN are known as the Non Access Stratum (NAS) protocols.

5.1.3.1.6 Policy Control and Charging Rules Function

The PCRF is responsible for policy control decision-making, as well as for controlling the flow-based charging functionalities in the Policy Control Enforcement Function (PCEF), which resides in the P-GW. The PCRF provides the QoS authorization (QoS Class Identifier [QCI] and bit rates) that decides how a certain data flow will be treated in the PCEF and ensures that this is in accordance with the user's subscription profile.

5.1.3.1.7 Home Subscriber Server

The Home Subscriber Server (HSS) contains users' SAE subscription data such as the EPS-subscribed QoS profile and any access restrictions for roaming. It also holds information about the PDNs to which the user can connect. This could be in the form of an Access Point Name (APN) (which is a label according to DNS naming conventions describing the access point to the PDN) or a PDN address (indicating subscribed IP addresses). In addition the HSS holds dynamic information such as the identity of the MME to which the user is currently attached or registered. The HSS may also integrate the Authentication Center (AUC), which generates the vectors for authentication and security keys.

5.2 Packet Scheduling features in LTE standard

5.2.1 Background

LTE is a purely scheduled system in that all traffic with diverse QoS requirements needs to be scheduled. LTE supports sufficiently short turn-around latency allowing for some opportunistic scheduling even for delay sensitive traffic (with delay tolerance of few tens of milliseconds). The Packet Scheduling (PS) is an entity located in MAC sub layer which aims to utilize efficiently the downlink and uplink shared channel resources.

The main role of the PS is to multiplex the users in the time and frequency domains. Such multiplexing takes place via mapping of user to the available physical resources. The PS is able to perform mapping of users to the PRBs on a Transmission Time Interval (TTI) (1ms) basis and is therefore referred to as fast scheduling.

5.2.2 Need For Packet Scheduling

One of the key characteristic of mobile radio communication is the typically rapid and significant variations in the instantaneous channel conditions. There are several reasons for these variations. Frequency selective fading will result in rapid and random variations in the channel attenuation. Shadow fading and distance-dependent path loss will also significantly affect the average received signal strength.

Also, the interference at the receiver due to transmissions in other cells and by other terminals will also impact the interference level. Hence, to summarize, there will be rapid, and to some extent random, variations in the experienced quality of each radio link in a cell, variations that must be taken into account and preferably exploited.

Scheduling controls the allocation of the shared resources among users at each time instant. It is closely related to link adaptation and often scheduling and link adaptation is seen as one joint function. The PS entity thus allocates portion of the bandwidth that exhibit favourable channel conditions.

5.2.3 How is Packet scheduling different in LTE

What distinguishes packet scheduling in LTE from that in earlier radio access technologies such as High Speed Downlink Packet Access (HSDPA), is that LTE schedules resources for users in both the time domain and the frequency domain whereas HSDPA only involves the time domain. Because packet scheduling for LTE involves scheduling users in both TD and FD, various TD and FD schemes are available.

Let us assume that we have packets for N users waiting in the queue, and that resources can only be allocated at the beginning of a pre-defined time period known as the TTI or scheduling period. In TD, scheduling users from the total of N users are selected based on some priority metric. After the U users have been selected, appropriate subcarrier frequencies and Modulation and Coding Schemes (MCSs) are then assigned by the FD scheduler. Note that the metrics used for TD and FD scheduling can be different in order to provide a greater degree of design flexibility.

5.2.4 Channel-dependent scheduling

Channel-dependent scheduling in a mobile-communication system, deals with the question of how to share between different users (different terminals) the radio resource(s) available in the system to achieve an efficient resource utilization as possible. Typically, this implies minimizing the amount of resources needed per user and thus allowing for as many users as possible in the system, while still satisfying whatever QoS requirements that may exist. Closely related to scheduling is link adaptation, which deals with how to set the transmission parameters of a radio link to handle variations of the radio-link quality. Both channel-dependent scheduling and link adaptation try to exploit the channel variations through appropriate processing prior to transmission of the data. However, due to the random nature of the variations in the radio-link quality, perfect adaptation to the instantaneous radio-link quality is never possible.

Hybrid ARQ, which requests retransmission of erroneously received data packets, is therefore useful. This can be seen as a mechanism for handling variations in the instantaneous radio-link quality after transmission and nicely complements channel-dependent scheduling and link adaptation. Hybrid ARQ also serves the purpose of handling random errors due to, for example, noise in the receiver. In order to make good scheduling decisions, a scheduler should be aware of channel quality in the time domain as well as the frequency domain. Ideally, the scheduler should have knowledge of the channel quality for each sub-carrier and each user. In practice, due to limited signaling resources, sub-carriers in an OFDMA system are often allocated in groups.

5.2.5 Downlink scheduling parameters

Downlink scheduling decisions can be made on the basis of the following information for each user:

5.2.5.1 QoS Class Identifier

In the LTE architecture downlink data flows from a Packet Gateway (called PDN GW) to eNodeB and then to the UE (user). The PDN GW to eNodeB is an IP link and the eNodeB to UE is over the wireless link. When the logical link from the bearer to the UE is set up (called a bearer), a QCI is specified. This defines whether the bearer is guaranteed bit-rate or not, target delay and loss requirements, and so forth. The eNodeB translates the QCI attributes into logical channel attributes for the air-interface and the scheduler acts in accordance with those attributes.

5.2.5.2 Channel Quality Indicator

Channel Quality Indicator (CQI) is a four digit value sent to eNodeB by UE as a feedback for downlink channel. CQI informs eNodeB about the channel quality in downlink. This helps eNodeB to allocate proper MCS and PRB for UE. These reports contain the value of the Signal-to-Interference- and- Noise - Ratio (SINR) measured by the user. We denote by $\gamma i(t)$ the most recent wideband CQI value received by the eNodeB at or before time t for user i. The LTE system allows several reporting options for both wideband (over the system bandwidth) and sub band (narrower than the system bandwidth) CQI, with the latter allowing exploitation of frequency selective fading. It is an indication of the downlink mobile radio channel quality as experienced by this UE. Essentially, the UE is proposing to the eNodeB an optimum modulation scheme and coding rate to use for a given radio link quality, so that the resulting transport block error rate would not exceed 10%. 16 combinations of modulation schemes and coding rate are specified as possible CQI values.

The UE may report different types of CQI. A so-called wideband CQI refers to the complete system bandwidth. Alternatively, the UE may evaluate a sub-band CQI value per sub-band of a certain number of resource blocks which is configured by higher layers. The full set of sub-bands would cover the entire system bandwidth. In case of spatial multiplexing, a CQI per code word needs to be reported.

Sub-band CQI reporting can be either configured by higher layers or UE selective. The later means the UE divides the bandwidth in a number of sub bands estimates the channel quality for each of these sub-bands but reports only the best ones. How many RB forming a sub-band as well as how many sub-bands are reported depends on the overall system bandwidth. In terms of 5 MHz equals 25 RB the sub-band size is defined with 2, making it 13 sub bands, but only the top three of them are reported. For 20 MHz (100 RB) we have 25 sub-bands, only the best six are reported. The reported sub-band CQI values are relative to the estimated wideband CQI value and in that matter always better, but at least equal.

For higher-layer configures sub-band CQI reporting, the applied principle is modified in that way, that the sub-band size is increased (e.g. 20 MHz = 8 RB per sub-band), so that less sub-bands are need to be measured but all of them are reported. For some sub- bands the reported CQI value can be lower than the estimated wideband CQI value, which is in contrast to UE-selected sub-band reporting.

5.2.5.3 Pre-coding Matrix Indicator

It is an indication of the optimum pre-coding matrix to be used in the base station for a given radio condition. The Pre-coding Matrix Indicator (PMI) value refers to the codebook table. The network configures the number of resource blocks that are represented by a PMI report. Thus, to cover the full bandwidth, multiple PMI may be reported, but this depends on the configured reporting mode and transmission mode. PMI reports are required for closed loop spatial multiplexing, multi-user MIMO and closed-loop rank 1 pre-coding MIMO modes.

5.2.5.4 Buffer State

The buffer state refers to the state of the users' buffers, representing the data available for scheduling. We assume that for each user i, the queue length in (the beginning of) sub frame t, denoted by $qi(t)$ bits, and the delay of each packet in the queue, with $wi(t)$ ms denoting the delay of head-of-line packet, is available at the scheduler.

5.2.5.5 Phy ACK/NACK

At time t, ACK/NACK for all transmissions scheduled in sub frame $(t - 8)$ are known to the scheduler.

5.2.5.6 Resource Allocation History

Scheduling decisions can also be based on scheduling decisions in the past. For example, if a user was allocated multiple RBs over the past few sub frames, then its priority at the current sub frame may be reduced (even though ACKs/NACKs are still pending). A commonly used approach is to maintain the average rate, $xi(t)$ at which a user is served. The average rate is updated at every time t using an exponential filter as given in (5.1).

$$x_i(t) = (1 - \tau_i)_* x_i(t - 1) + \tau_i r_i(t), t = 1, 2, \ldots \quad (5.1)$$

where $ri(t)$ is the rate allocated to the *i*th user at time *t*, and $\tau i \in (0, 1)$ is a user specific constant; we refer to $1/\tau_i$ as *time-constant* for (rate averaging for) user i.

5.3 Packet Scheduling Algorithm in LTE based WMN

5.3.1 Background

4G cellular standards have incorporated both OFDM and MIMO techniques [5] to provide high Data Rates (DR) in their wireless networks. IEEEs WiMax was the first 4G technology which incorporated both OFDM and MIMO techniques to provide near wireline DR. Unfortunately, due to its incompatibility with legacy cellular technologies, WiMax could not obtain the acceptance of telecommunication industry [5]. The 3GPP under the aegis of International Telecom Union (ITU) standardized a 4G cellular protocol named LTE evolving from the UMTS commonly known as 3G. LTE is backward compatible with legacy cellular networks and hence has obtained wide acceptance from the telecommunication industry. LTE is a pure IP based protocol and can be easily integrated with existing wireline technologies. Further, all the mature routing protocols of IP networks are easily implemented in the backbone LTE networks. LTE based Cellular Networks (CN) are already being implemented or in the process of being implemented worldwide, and is looked upon as the cellular standard of the future. 3GPP also proposed LTE-Advanced which promises download DR up to 1 Gbps, which is at par with the DR provided by any of the copper or optical links as of today. The standardization of 5G technology is also in an advanced stage and some countries have also started testing 5G CN, which are expected to be launched around 2020 [101].

The wireless infrastructure of future telecommunication networks will be IP packet based which is also the case for 4G and 5G CN. The telecommunication users demand high quality and high definition display devices, and therefore utilize high DR services from the service providers. Due to the ever increasing traffic base of the users these CN are prone to congestion and need a mechanism to prevent large packet losses and incorporate QoS. QoS can be incorporated by classification of traffic in terms of real or non-real time services, prioritizing the traffic in terms of CoS and origin of traffic generation in the network, and ensuring high priority traffic is not dropped during congestion scenarios. To this end, a PSA is proposed which assigns weights to each connection request for every wireless node in the LTE based CN (LCN). The incorporation of the proposed PSA will ensure lower packet loss in the CN.

5.3.2 Problem Statement and Related Work

5.3.2.1 Problem Statement

CN of the present day and the future, need to provide high DR to the users and be reliable even at peak hours of operation. However, as a reality of the day, in many developing nations, we experience low DR and call dropping at peak hours due to congestion in various subnets of the CN, contrary to the SLA between users and the CN connection providers [7]. Further, at times of any emergency or natural calamity we experience near failure of the information carrying capability of the CN in the affected area. The above greatly affects the restoration and life-saving activities conducted by various government agencies in the affected area of CN. The information passed from the affected circle, which provides telecommunication services to the affected area, to the adjoining circles of the CN is of critical nature. The failure to deliver a message in any form during the above times of crisis from the affected area may be detrimental to the lives of people inhabiting the area of emergency or natural calamity. Hence, CN have to be designed and implemented in such a manner that these networks are fail safe even in the worst of the situations like an emergency or natural calamity.

The LCN are ideally designed in such a way that each eNodeB of the CN is connected to at least two other eNodeBs in the CN. Further, there may be a redundant eNodeB in the same location in case of a failure. The above architecture ensures that each node in the network is dual homed and dual plane. The CN are generally divided into Circles, for better organization and effective control of the CN architecture. The various Circles are interconnected with long range wireless links/optical links for intra-Circle traffic. The voice, video and data traffic through the various eNodeBs of the LCN are transported through inter and intra-circle links to reach the EPC for switching, routing and metering functionalities. The connectivity diagram of such an organized LCN is shown in Figure 5.3.

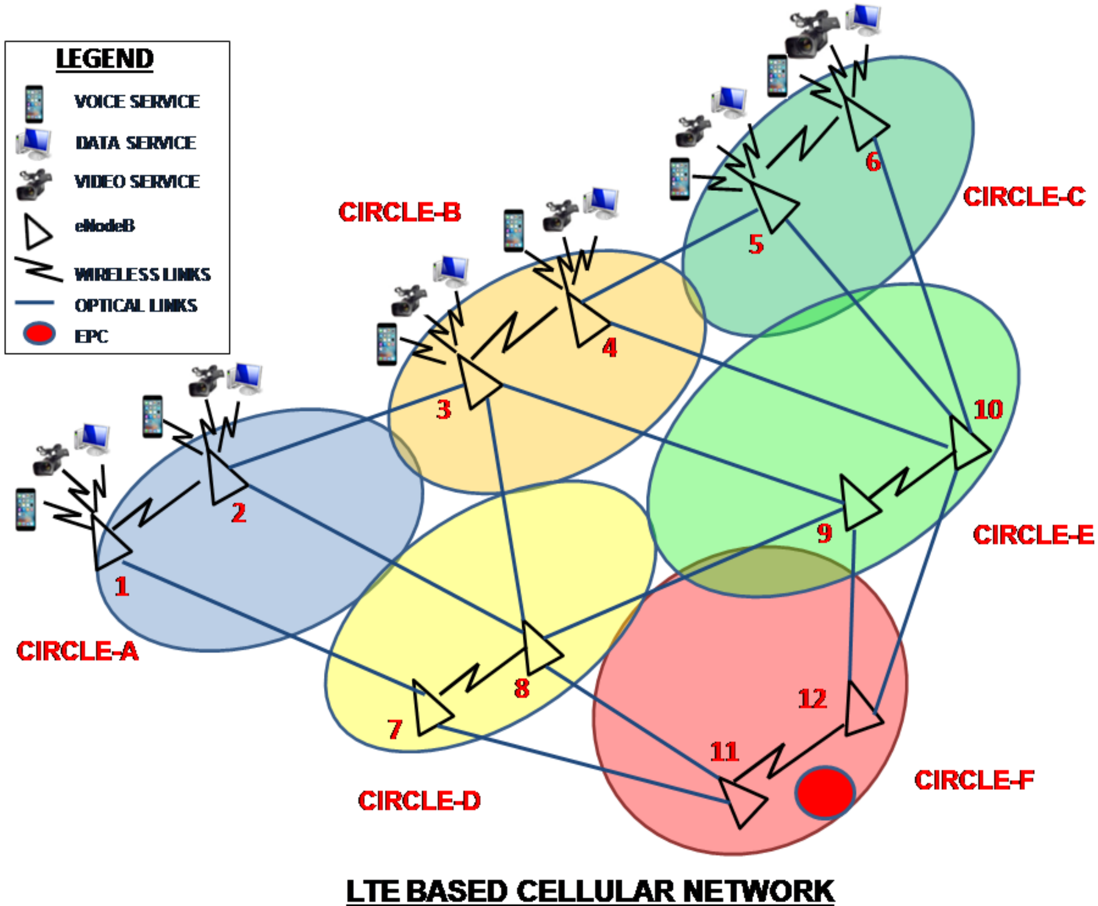

Figure 5.3: LTE based CN.

The architecture of the organized LCN of Figure 5.3 has 6 Circles, each having 2 eNodeBs each, and one EPC is collocated with an enodeB of one of the circles (eNodeB 12 of Circle in Figure 5.3) for switching, routing and metering functionalities for the entire LCN. Each eNodeB in the CN is in dual homed dual plane architecture, which means that each eNodeB has minimum two links connected to two other eNodeBs in the CN. This architecture ensures that there is no single point of failure in the CN architecture. There are a total of 12 eNodeBs and 21 wireless links in the LCN architecture of Figure 5.3.

The requirement for the architecture of the LCN of Figure 5.3, in the event of any emergency or natural calamity, is enumerated in succeeding paragraphs:

(a) The traffic generated in the CN is very high which leads to congestion in the critical inter-circle links and results in heavy loss of information packets. This in turn, is detrimental to the restoration and life-saving activities conducted by various governmental agencies in the affected area of CN.

(b) Due to high congestion in critical links, packets of data or voice are assigned with higher priority in comparison to video packets (as video packets consume higher DR). The above enables the high priority voice and data packets to reach the destination with higher probability. Hence, classification of various type of traffic into voice, video and data is of utmost importance and prioritization of the traffic is an inescapable requirement.

(c) In case of emergency or natural calamity occurring in a certain area, the circle of the LCN which provides cellular communication services to the area will be termed as an "Affected Circle". Further, traffic of the Affected Circle where emergency or natural calamity has occurred may be of higher priority than the others due to concentration of restoration and life-saving activities conducted by various governmental agencies in the Affected Circle. The traffic generated from this Affected Circle will be of paramount importance to the restoration and life-saving activities conducted by various government agencies, and should be given highest priority in the LCN. The traffic generated from the adjacent circles will be considered less important and should be given lower priority in the CN than the traffic originating from the Affected Circle.

In view of the above, there is a need to improve the throughput provided by the LCN by reducing the overall packet loss in the network. The above is achieved by incorporating the proposed PSA in LCN. Further, the PSA should also prioritize packets originating from different circles so as to ensure that the critical information from Affected Circle reaches the EPC and HQ of government agencies in times of emergency or natural calamity when the inter-circle critical links may be congested. The proposed PSA will incorporate prioritization of packets thus ensuring QoS in the CN at all times.

5.3.2.2 Related Work

A study of similar work for traffic scheduling in LTE based WMN is discussed in this section. Traffic grooming algorithms in WMN have been adequately researched [102-110]. Scheduling of traffic ensures important traffic being handled with priority in case of congestion in subnets, thus increasing throughput of important packets in the entire network. There has been substantial amount of work in the field of traffic scheduling in LTE based wireless networks. Delay-aware QoS scheme for mixed traffic flow in LTE networks is researched [111]. Moreover, traffic scheduling analysis in LTE network [112] and evaluation for traffic scheduling in VoIP services in LTE-Advanced network [113] have been done. Experiments in fair scheduling for 4G networks are available in [114]. Structural prioritized traffic scheduling for data-centric traffic in LTE networks [115] and delay based scheduling algorithm for video traffic in LTE networks [116] have been researched. Delay scheduler with throughput-fairness in LTE wireless networks is available in [117]. TCP-aware scheduling in LTE networks is also available in [118]. Traffic prioritization with channel indicators for quality in LTE networks has been analyzed in [119]. Ensuring QoS in LTE networks by traffic scheduling has been adequately researched in [120-130]. Further, Priority based traffic scheduling and utility optimization for smart grids [131] has shown that priority based traffic scheduling is an imminent requirement to optimize available bandwidth. Though studies for packet scheduling in wireless defense networks are available in [39], however, packet scheduling for LCN and its inherent problems is not researched well. This research work incorporates the above aspects in the proposed Packet Scheduling Algorithm discussed in Section 5.3.4.

5.3.3 QoS and Prioritization in LTE

LTE is the first cellular standard which aims to provide QoS and prioritization of user traffic as has been traditionally ensured in wireline networks [5]. The primary parameters incorporated in LTE downlink scheduling protocol, which ensure prioritization of user traffic and QoS assurance are enumerated below.

5.3.3.1 QoS Class Identifier

It is incorporated in the downlink data drift in LTE structure from a PDN GW to eNodeB [5], and further down to the UE. On setting up of a virtual channel from the eNodeB to the UE, a QCI is specified. The above will quantify the guarantee of the wireless link. Moreover, delay in link and signal strength concerns are also indicated.

5.3.3.2 Channel Quality Indicator

CQI is a four digit value sent to eNodeB by UE as a feedback for downlink channel. CQI informs eNodeB about the channel quality in the downlink. This helps eNodeB to allocate proper MCS and PRB for UE. SINR measurements are included in the above notifications.

It can be clearly seen that the parameters of QoS in LTE which have been discussed above are effective only in the air-interface between user equipment and the eNodeB. However, there are no QoS mechanisms available in the LTE standard for the core LTE network [5] which can experience congestion and high packet loss during peak hours. In Section 5.3.4, a PSA for optimizing the LTE based backbone of a LCN is proposed.

5.3.4 Priority Scheduling Algorithm

In a CN to ensure that the throughput at peak traffic conditions is maximum incorporation of efficient packet scheduling algorithms is a key requirement. The different facets of priority scheduling algorithm are discussed in subsequent sections.

5.3.4.1 Traffic Differentiation for LTE based CN

Traffic differentiation is important to prioritize important traffic in a CN so as to ensure that this important traffic is not dropped during congestion scenarios in a CN. This traffic differentiation results in increase in throughput for important traffic in a CN affected by congestion in peak scenarios. Traffic differentiation is prevalent in wired networks, however is now being incorporated in wireless mesh networks due to limitation of bandwidth in them [108].

5.3.4.2 Classification of Traffic

The PSA will differentiate traffic and further prioritize connections in the LCN according to the three different classification of service as given below:

5.3.4.2.1 High Priority Traffic (HPT) (P=3): for voice and live video applications (video calls of members of government agencies (specific numbers) involved in restoration of emergency and live feed from surveillance cameras from the affected area).

5.3.4.2.2 Medium Priority Traffic (MPT) (P=2): for restricted video and data traffic.

5.3.4.2.3 Low Priority Traffic (LPT) (P=1): for file transport.

The classification of traffic varies from 1 to 3 as assigned above, the maximum priority being 3 and the minimum being 1. The handling of traffic in eNodeB of the LCN will be based on the above CoS and will be managed by a traffic classifier called "Request Handler" collocated with each eNodeB of the LCN.

5.3.4.3 Prioritization of Circle

The LCN is organized into six circles for structured control of the LCN as given in Figure 5.3. In the scenario of an emergency or natural calamity occurring in a certain area, the traffic in the Circle of the LCN providing cellular services to the affected area will increase substantially and the inter-circle traffic will experience high congestion. Further any emergency or natural calamity will be concentrated to a particular area within the LCN circle. Hence, the Circle which provides cellular services to the area, in which an emergency or natural calamity has taken place, is referred to as the Affected Circle. The traffic generated from the Affected Circle will be of upmost importance for the concentration of restoration and life-saving activities conducted by various governmental agencies. Hence, the packets originating from the Affected Circle needs to be given the highest priority and should be the last ones to be dropped in case of congested cellular links. From Figure 5.3 and for simulation, we have assumed that the emergency or natural calamity is concentrated in Circle-A. Therefore, Circle-A is the Affected Circle. Circle-B is the adjacent Circle and therefore has been given second priority as it is assumed for the simulation process that this Circle is going to have an impact on the concentration of restoration and life-saving activities conducted by various governmental agencies in Circle-A being the Affected Circle. Circle-C has been given the last priority as it has been assumed, for the simulation, that the activities in the Circle-C has little or no impact in the restoration activities in Circle-A. In view of the above assumptions, each packet originating from a certain Circle will be assigned a particular value for the Circle Priority (CP) as given below:

(a) Traffic from Circle-A (Affected Circle): CP = 1.

(b) Traffic from Circle-B: CP = 2.

(c) Traffic from Circle-C: CP = 3.

5.3.4.4 Algorithm Architecture

The constituents of the design for implementation of the algorithm are eNodeB, Request Handler, Request Prioritizer, EPC, wireless connections bidirectional in nature, optical connections and control connections. The structural design for PSA functionality is given in Figure 5.4(a) [39].

The logical flow of the proposed PGA incorporating various modules is shown in Figure 5.4(b).

Various processes of the proposed PSA of Figure 5.4(a) and (b) are enumerated below:

(a) Initial request for cellular service from the user is given to eNodeB. The eNodeB hands over the request first to the collocated Request Handler for classification of service request. The Request Handler classifies the service request as Class 1/2/3 as per the traffic classifications given in sub-section 5.3.4.2.

(b) The Request Handler then forwards the requests to the central Request Prioritizer through the control links of the algorithm architecture of Figure 5.4(a).

(c) The central Request Prioritizer uses the routing protocols (OSPF-TE) to find the optimum path for the service request in the LCN. The central Request Prioritizer also runs the PSA and assigns path to the lightest weighed request.

(d) The assigned optimum path by the central Request Prioritizer is sent as a response to the service request back to the requesting Request Handler through the control links of the algorithm architecture of Figure 5.4(a) and given to the servicing eNodeB.

(e) This process continues for each user request by every Request Handler collocated with the eNodeB in the LCN.

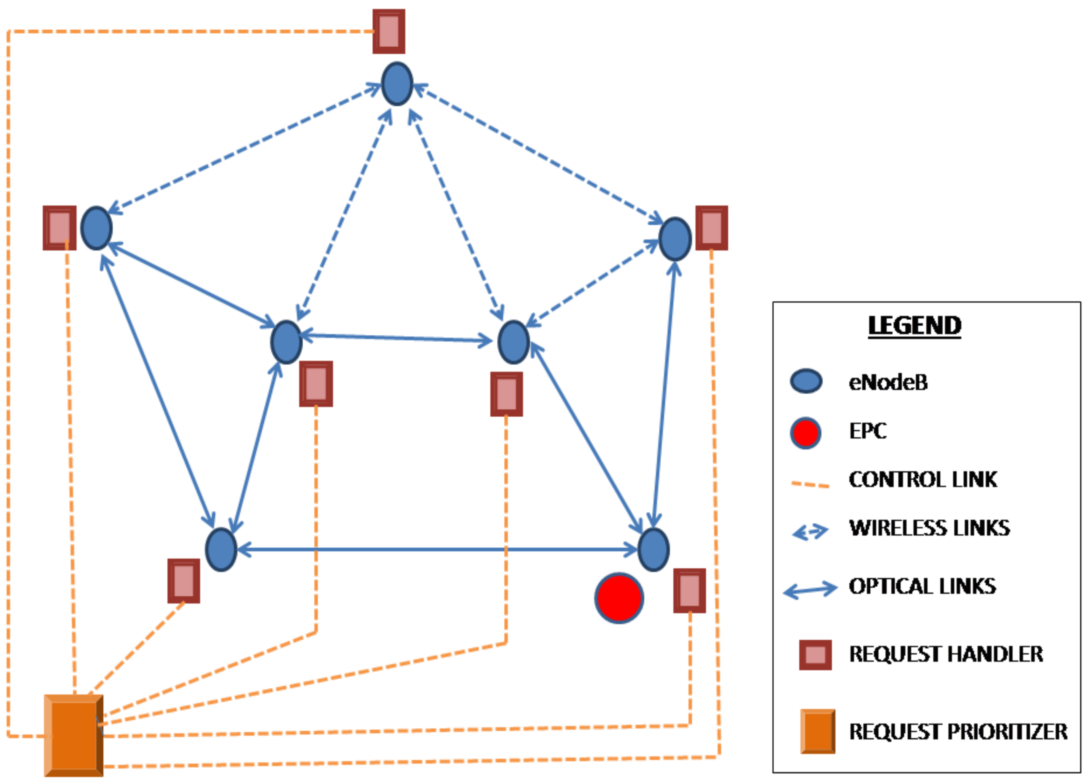

Figure 5.4(a): Algorithm Architecture for PSA.

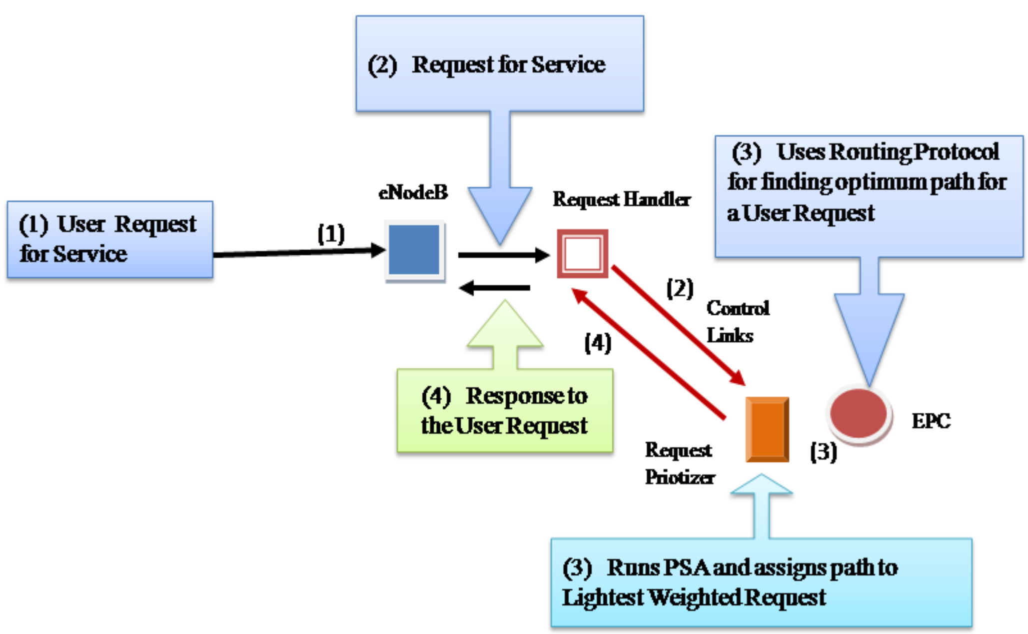

Figure 5.4(b): Logical Flow Diagram for PSA.

5.3.4.5 Algorithm Functionality

The PSA has been advocated to better the throughput of priority packets by traffic scheduling in LCN. PSA will incorporate the following parameters which will be drawn out from the connection requests by the Request Handler:-

5.3.4.5.1 Hop Span Computation (C) The length of hops the connection will span in the LCN from origin eNodeB to the destination eNodeB.

5.3.4.5.2 Delay Tolerance (T) The tolerance of delay (in milli-seconds) a connection can accommodate to be faithfully reproduced at the destination.

5.3.4.5.3 Data Transfer Rate (D) The amount of DR a connection desires for faithful transmission of the desired service in the LCN.

5.3.4.5.4 Connection Priority (P) The level of priority at which a connection desires to be treated in the LCN is termed as the priority. The schemes of connection priority are explained in sub-section 5.3.4.2.

5.3.4.5.5 Circle Priority (CP) This is the priority of the packet according to its Circle of origin and will take values as brought out in sub-section 5.3.4.3.

It is observed that parameters T, D, and P are provisioned to the cardinal Request Prioritizer on the control connection after being derived by the Request Handler from the connection request. The parameters C and CP are extracted from the system architecture by the central Request Prioritizer. The above five metric parameters are utilized for further processing at the central Request Prioritizer according to following processes:

Process-A: A connection request matrix is populated for all connection requests in each eNodeB of the LCN, as shown in Table 5.1.

Table 5.1: Connection Request

Ser No	Source Id	Destination Id	No of Hop Count (C)	Data Rate Required (D) (in Mbps)	CoS Requ-ired (P)	Tolerable Delay (T) (in msec)	Circle Priority (CP)
1	001	003	2	0.2	2	0.45	1
2	002	005	3	0.3	1	0.30	3
3	001	004	3	0.4	3	0.50	1
4	002	006	4	0.5	2	0.40	3
5	003	006	3	0.6	2	0.35	2
6	005	002	3	0.7	1	0.25	2

Figures used to populate the matrix are random to explain the operational procedure of PSA.

<u>Process-B</u>: On successful population of connection request matrix, W is computed by the Request Prioritizer for every connection as given in (5.2).

$$W= C/C_{max} + 1/P + D/ M_d + T + CP \qquad (5.2)$$

As per (5.2) the weightage of a connection will be higher for a connection requesting greater resources of the LCN and vice versa.

Further, each fraction of (5.2) has been analyzed below:

(a) <u>First Fraction</u> – Fraction of spans (C) encompassed by the connection in relation to the maximum spans in the LCN (C_{max}). C_{max} is assumed to take a value of ‘4’ as per the simulation architecture of PSA in Figure 5.5.

(b) <u>Second Fraction</u> – Inverse of Connection Priority (P) a connection is granted as enumerated in sub-section 5.3.4.2.

(c) <u>Third Fraction</u> - Fraction of Data Transfer Rate (D) used by the connection in relation to the highest data transfer rate available in the LCN (M_d), which is kept at 7 Mbps.

(d) The fourth and fifth values of (5.2) have already been detailed in the sub-sections 5.3.4.5.2and 5.3.4.5.5.

At every eNodeB of the LCN, the connection requests with appropriate weightage are organized in a sequence of expanding weightage in the framework of a stack and the connections with minimal weightage are transmitted ahead.

The W quantum for every value in the connection request matrix in Table 5.1 is computed and a fresh weighted connection request matrix is populated as shown in Table 5.2.

Table 5.2: Weighted Connection Request

Ser No	Source Id	Destination Id	No of Hop Count (C)	Data Rate Required (D) (in Mbps)	CoS Required (P)	Tolerable Delay (T) (in msec)	Circle Priority (CP)	Weight (W)
1	001	003	2	0.2	2	0.45	1	2.47
2	002	005	3	0.3	1	0.30	3	5.09
3	001	004	3	0.4	3	0.50	1	2.62
4	002	006	4	0.5	2	0.40	3	4.97
5	003	006	3	0.6	2	0.35	2	3.68
6	005	002	3	0.7	1	0.25	2	4.10

C_{max} is computed at 4 spans according to the architecture chosen for simulation at Figure 5.5 and M_d is kept at 7 Mbps so as to explain the operational procedure of PSA.

Process-C: In this process of PSA all values of the weighted connection request matrix at Table 5.2 are reorganized in increasing sequence of W, in a way that minimal weighted connections are placed on top of the Matrix and vice versa. This new reorganized Matrix is the Prioritized Matrix and shown as Table 5.3.

Table 5.3: Prioritized Matrix

Ser No	Source Id	Destination Id	No of Hop Count (C)	Data Rate Required (D) (in Mbps)	CoS Requ -ired (P)	Tolerable Delay (T) (in sec)	Circle Priority (CP)	Weight (W)
1	001	003	2	0.2	2	0.45	1	2.47
3	001	004	3	0.4	3	0.50	1	2.62
5	003	006	3	0.6	2	0.35	2	3.68
6	005	002	3	0.7	1	0.25	2	4.10
4	002	006	4	0.5	2	0.40	3	4.97
2	002	005	3	0.3	1	0.30	3	5.09

Process-D: The Prioritized Matrix for each eNodeB in the LCN from Process-C is utilized by the Request Prioritizer for allocation of connections in the LCN. The elite row of the Prioritized Matrix is first allocated a connection in the LCN if resources are available. This step is repeated for the next row of the Prioritized Matrix till there are no rows left in Prioritized Matrix. Process-D is repeated for all the eNodeBs in the LCN.

5.3.5 Complexity of the Algorithm

The computational complexity of PSA as given in (5.2) of Process B, as given in sub-section 5.3.4.5is of the order O(1), which is minimal. The computational complexity of the entire algorithm from Process A to Process D of sub-section 5.3.4.5is equal to O(nlog(n)) + O(1) ~ O(nlog(n)). The PSA is implemented as software in existing hardware of the LTE architecture (eNodeB) and the cost factor for the implementation is not substantial; however, it optimizes the utilization of network resources substantially, to ensure more services being provisioned on the existing network. The above is aptly demonstrated in the simulation results and their analysis in Section 5.4.

5.4 Simulation Results and Analysis

The structured schema for simulation of PSA is given as Figure 5.5. The LCN architecture of Figure 5.5 consists of 6 Circles, each having 2 eNodeBs each with a total of 12 eNodeBs and 21 bidirectional wireless/optical links which connect the eNodeBs of the LCN. There is only one Request Prioritizer in the architecture chosen for simulation of Figure 5.5. The Request Prioritizer is integrated via a communication channel to each Request Handler, structured around each eNodeB. The communication channel is utilized for sending of communication values destined to Request Handler originating from Request Prioritizer which also operates in the reverse direction. Each eNodeB is facilitated with a Request Handler, which routinely refreshes its content to the central Request Prioritizer through the communication channel. An EPC is structurally designed with the central Request Prioritizer for switching, routing, and metering functionalities.

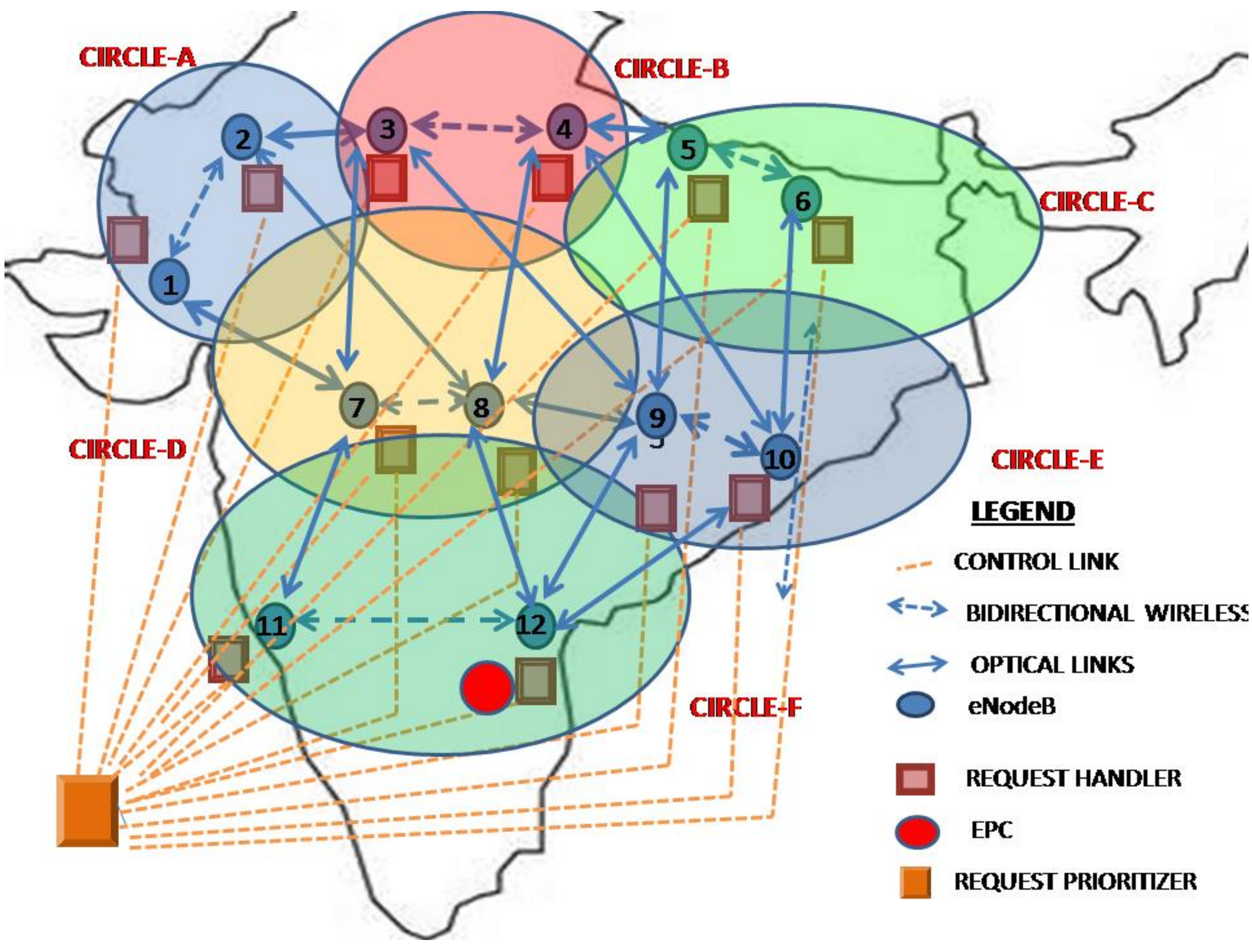

Figure 5.5: Simulation Architecture for PSA.

The simulations has been done in OMNET++ framework [51]. The simulation has been carried out in OMNET++ (version 4.2.2), which is a discrete event simulating environment. INET framework has been used inside the OMNET++ environment, which facilitates simulation of the algorithm in LCN architecture. The conjectures based on which the evaluation of PSA has been done are given below [132]:

(a) The requests for channels/connections are random in nature. The stochastic behavior of the random request follows a Poisson distribution. Further, the time of arrival between two events (two connection requests) of connection requests in succession, follow a distribution which is exponential in nature.

(b) 7 Mbps is the maximum supported data rate on every wireless channel. The increments of requests in data rate thereafter are in multiples of 100 Kbps.

(c) The data units/packets are inducted arbitrarily amidst all originating and destined wireless eNodeBs. A channel demand is spoken to be not availed or denied in case the requisite bandwidth is not allocated in any of the intermediate links.

(d) The performance of PSA is quantified in quantum of Packet Loss (PL) wherein; the lower the PL, better is the performance of the network. Packet Increase (PI) is commensurate to increase in value of service users in the LCN.

(e) The number of data units developed by every eNodeB in the LCN is gradually augmented for the evaluation and analysis of PSA to a value of 11000 data units. The above process will aftermath in greater quantum of PI in the LCN.

(f) The evaluation and analysis of PSA is conducted in four phases as enumerated in following sub-sections:

Various parameters utilized in the simulation are provided in Table 5.4.

Table 5.4: Simulation Parameters

S. No.	Simulation Parameter	Value used in Simulation
01	Number of eNodeBs	12
02	Allocated BW per eNodeB	10 MHz
03	Cell Capacity Downlink/ Uplink	100/400 Mbps
04	Number of Users supported by each eNodeB	200
05	Number of Bi-Directional Wireless Links	21
06	Data Rate of Each Wireless Link	7 Mbps
07	Minimum Data Rate request	100 Kbps
08	Number of Packets generated by each eNodeB	1000

5.4.1 Phase-1

In phase one of the evaluation and analysis of PSA, the performance and operational functionality of PSA was analyzed. The traffic in terms of voice, video and data packets have been generated from users connected to each node of a Circle in the LCN. The simulation has been carried out in the LCN architecture as shown in Figure 5.5.

The simulation result of number of dropped packets with increasing number of input packets in the LCN mesh of Figure 5.5 is displayed in Figure 5.6.

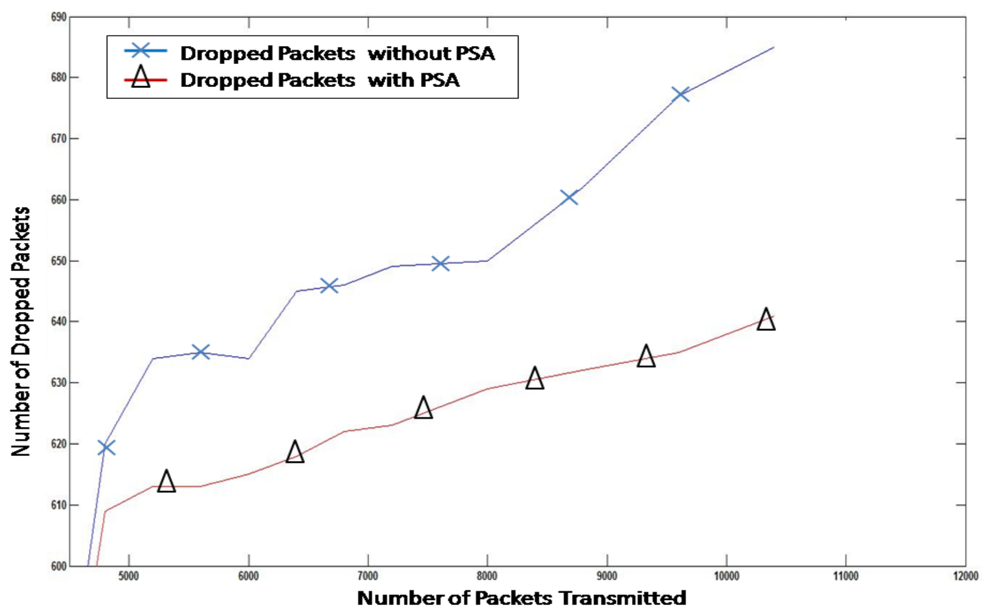

Figure 5.6: Performance of PSA in LCN.

From the Figure 5.6, we deduce that the number of dropped packets have reduced substantially (around 50 packets for 10000 packets input in the network) on incorporating the PSA in the LCN mesh. Hence, we can infer that there is considerable betterment in the overall throughput of the LCN by incorporating PSA. The betterment increases drastically as more number of packets are entering the network.

5.4.2 Phase-2

In the next phase of simulation, the dropped packets of each Circle has been analyzed and the displayed graph is given in Figure 5.7.

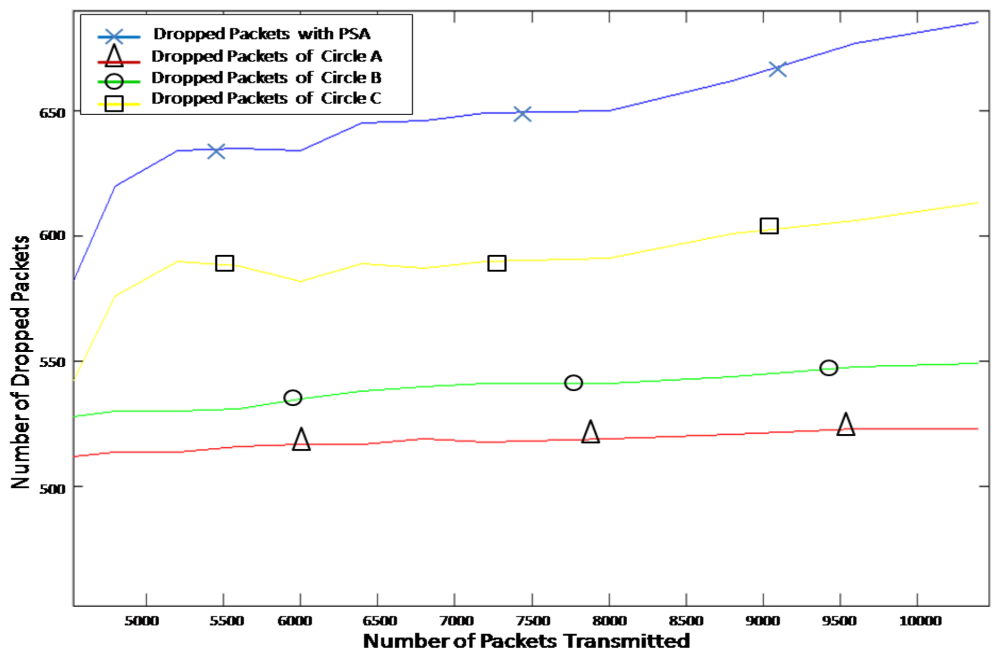

Figure 5.7: Circle wise Packet Loss Analysis.

From Figure 5.7 we deduce that:-

(a) Number of dropped packets of Circle A is minimum, Circle B has relatively more dropped packets and Circle C has maximum dropped packets.

(b) The above is due to the fact that the PSA in the simulation architecture of Figure 5.5 has assigned packets from Circle A with the highest priority, packets from Circle B with lower priority and packets from Circle C have been assigned the lowest priority.

(c) Therefore, we infer that by the incorporation of PSA in the LCN has resulted that minimum number of packets are dropped from high priority Circle which is the "Affected Circle" where an emergency or natural calamity has taken place.

5.4.3 Phase-3

In the third phase of simulation, the class-wise packets dropped have been analysed in each Circle. First the class-wise packets dropped have been analyzed in Circle A and the result is shown in Figure 5.8.

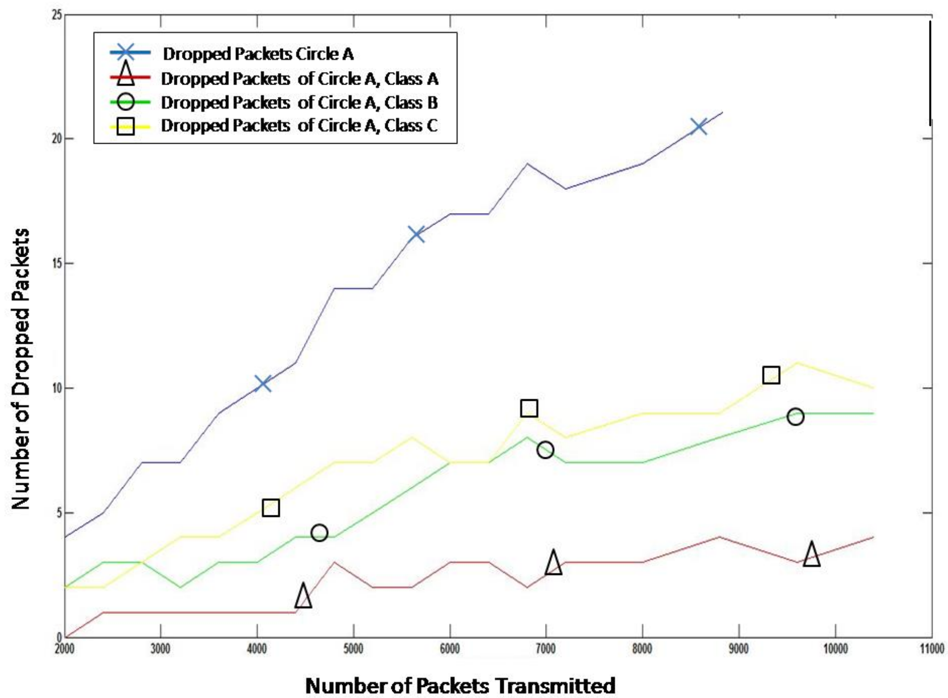

Figure 5.8:Class-wise Packet Loss Analysis of Circle A.

Next, the class-wise packets dropped have been analyzed in Circle B and the result is given in Figure 5.9.

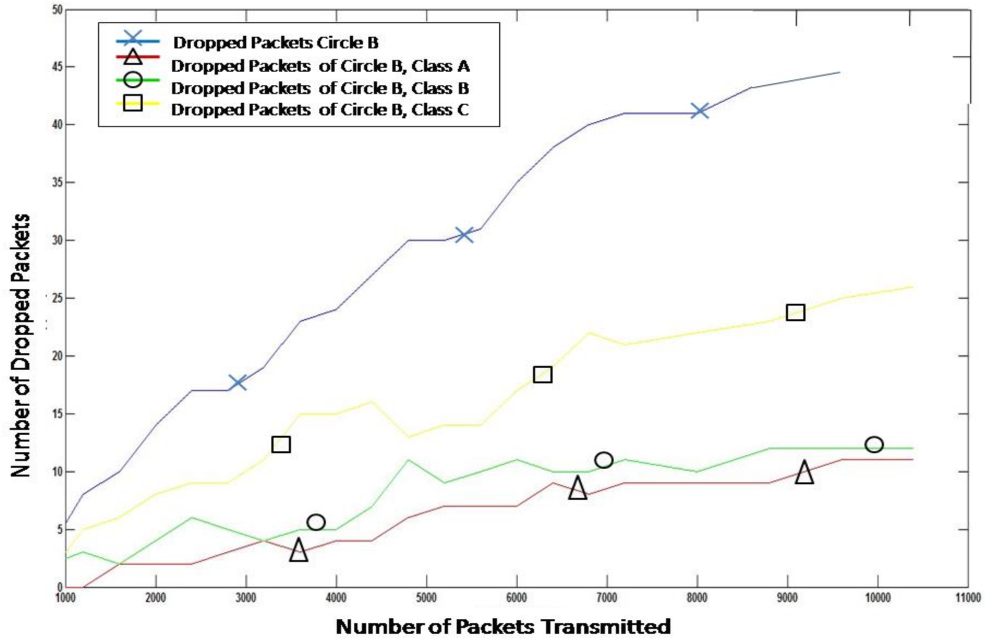

Figure 5.9: Class-wise Packet Loss Analysis of Circle B.

Finally, the class-wise packets dropped have been analyzed in Circle C and the result is given in Figure 5.10.

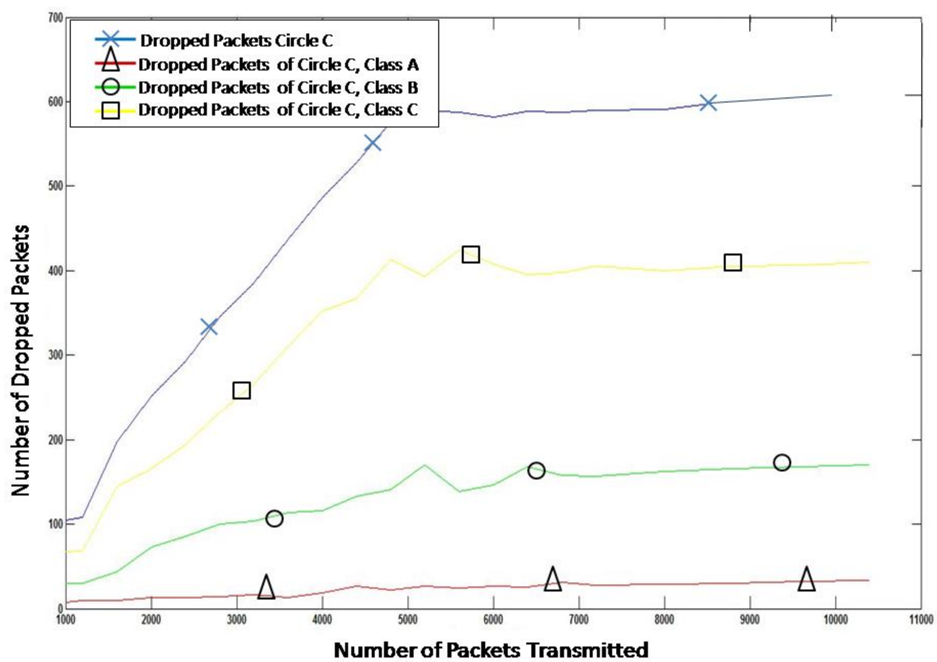

Figure 5.10: Class-wise Packet Loss Analysis of Circle C.

From the Figures 5.8 to 5.10, we deduce that:

(a) Number of dropped packets of Class A is minimum, Class B has more dropped packets and Class C has maximum dropped packets in all three Circles.

(b) Further, we observe that there are more dropped packets of Class A in Circle C than in Circle B and minimal in Circle A.

(c) The above is due to the fact that the PSA in the simulation architecture of Figure 5.5 has assigned packets of Class A with the highest priority, packets of Class B with lower priority and packets of Class C have been assigned the lowest priority in all the Circles.

5.4.4 Phase 4

In the fourth phase of simulation, the class-wise packet analysis, for all the three Circles has been done and the displayed graph is given in Figure 5.11.

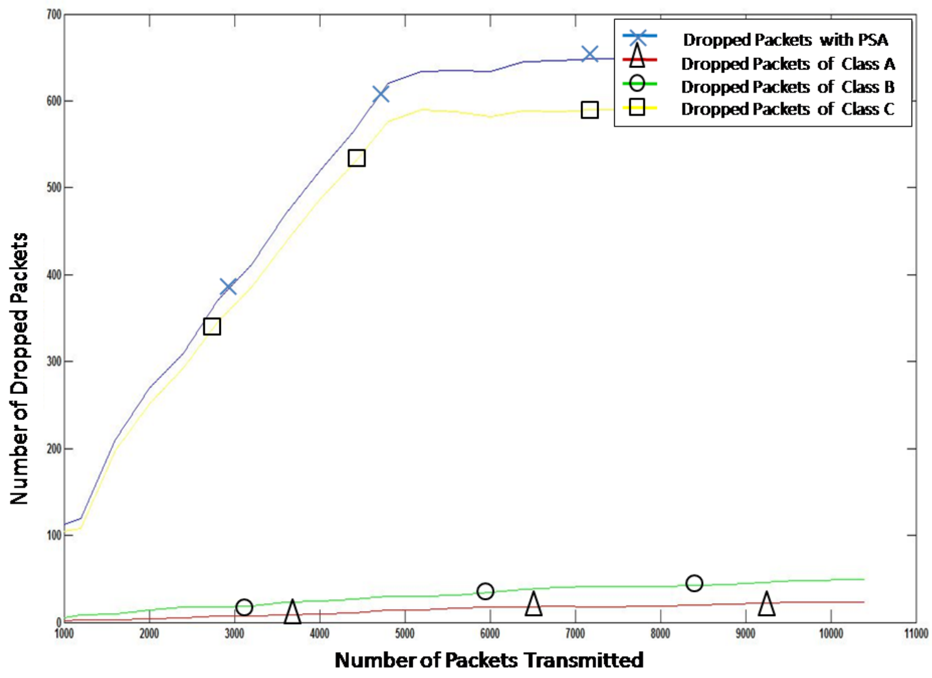

Figure 5.11: Class-wise Packet Loss Analysis of all Three Circles in LTE based WMN.

From Figure 5.11 we deduce that the packets of Class A has the highest priority, followed by packets of Class B, and the packets of Class C have the minimum priority for the entire LCN. Hence, Class A packets attain the highest throughput in the entire network in comparison to other classes of traffic. The above is in accordance with the prioritization of packets done by PSA in the LCN mesh of Figure 5.5.

5.4.5 Phase 5

In the Fifth and final phase of the simulation we compare the performance of PSA with another similar Smart Grid (SG) algorithm [131]. The simulation result of Packets Dropping Probability with increasing TI (increasing number of input packets) in the LCN mesh of Figure 5.5 for PSA and SG algorithm is displayed in Figure 5.12.

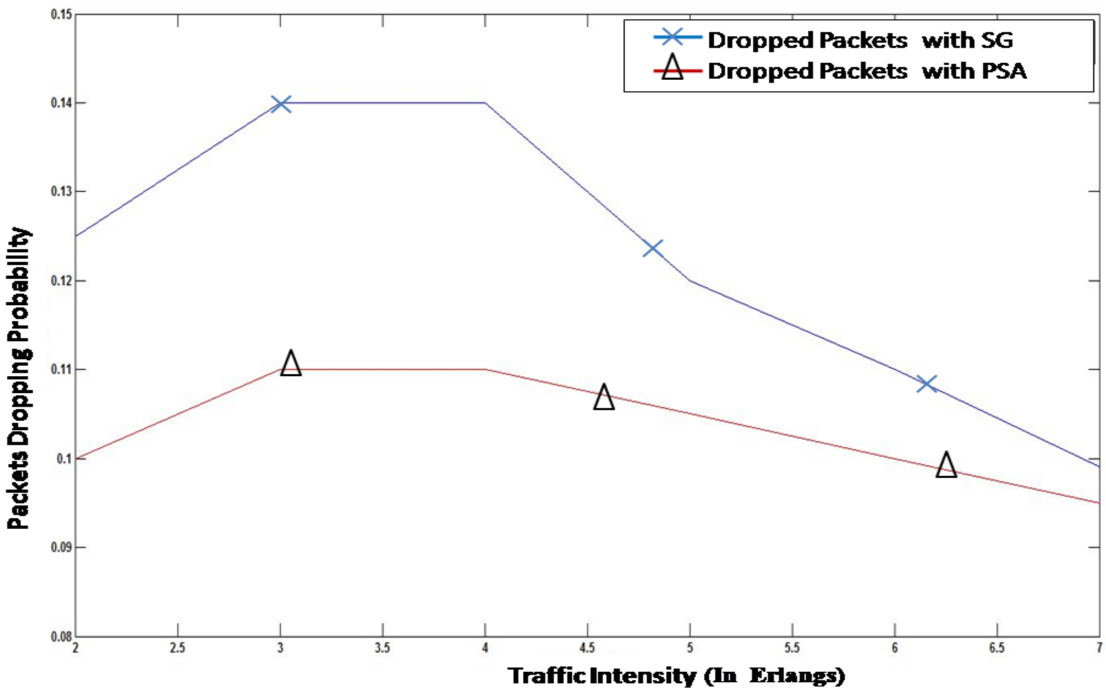

Figure 5.12: Comparison of performance for PSA and SG algorithm.

From the comparison of performance graph displayed in Figure 5.12, we observe that proposed PSA has substantially better performance in terms of lower packet blocking probability (packets lost / packets transmitted in the network) for same TI values. Further, PSA performs much better for lower TI values. Hence, the proposed PSA is a better priority scheduling algorithm for LCN.

The PSA primarily incorporates two levels of prioritization i.e. CoS prioritization and Circle-wise prioritization in the LCN mesh of Figure 5.5. We have seen in all the above simulation results that the number of dropped packets during the time of congestion in the LCN (at times of an emergency or natural calamity) has drastically reduced for packets of high priority class and packets originating from high priority Circle which is the “Affected Circle”. The reduction of packet loss (thereby reducing the need to retransmit) in critical time (during an emergency or natural calamity) is highly desirable in LCN.

5.4.6 Limitations of Research Work

The PSA algorithm can be easily ported to each node of LCN architecture provided the proprietary software allows porting of the algorithm and scheduling of traffic at each LCN node. Further, the parameters of Tolerable Delay and Circle Priority have to be available in real-time at each LCN node for effective employment of the PSA in a LCN architecture.

5.5 Summary

Present cellular networks have already incorporated high data rate wireless technologies like LTE/ LTE-Advance to ensure real time video and data centric traffic being effectively delivered to the cellular user. Due to high traffic inflow in the LCN at times of an emergency or natural calamity, the LCN experiences high congestion in the wireless/optical links resulting in high packet loss of critical information from the Affected Circle. The proposed PSA reduces the packet loss in the LCN, and incorporates QoS in the network which improves the overall throughput of the packets from high priority Affected Circle and for high priority CoS. The same has been validated by simulations. The incorporation of PSA in LCN to reduce the packet loss of priority traffic even at heavy traffic/congestion scenarios is highly desirable during an emergency or natural calamity situation.

Chapter 6

Conclusion and Future Work

In this chapter, main contributions and insights of the research work addressed in this thesis have been concluded. Further, scope for future work has been discussed.

6.1 Conclusion

The network operators in a developing nation like India do not generally under-load their telecommunication networks. The telecommunication network infrastructure is always planned so as to cater for 100 % utilization and at times to overload the network for greater revenues. Telecommunication networks have graduated from primarily being pure wireline networks to present day HTN. These HTN predominantly incorporate wireless access networks which are integrated to high data rate backbone wireline networks. Due to exponential growth in the telecom user base, the telecommunication network operators will face capacity problems in the near future. This will make QoS algorithms as discussed in earlier chapters termed suitably as Traffic Scheduling Algorithms (TSA) a good tool to implement at a minimal cost. On the other hand, upgrading the existing optical nodes to ultra DWDM systems is expensive in terms of procurement of new hardware. The wireless segment of HTN is already facing bandwidth scarcity to satisfy the QoS guaranteed for every user. The proposed TSA in this thesis can easily be incorporated as a software upgrade on existing DWDM systems, DMN and LCN nodes to substantially improve the number of users supported by these existing telecommunication networks.

Further, increasing capacity by laying new fibers in the backbone and adding additional cellular hardware in the access of HTN is an expensive option and requires huge investments in network planning, permissions for spectrum and licensing, and assuring multiple clearances from government agencies. Incorporation of TSA can improve the user capacity substantially in the existing laid fibers in the backbone and cellular architecture in the access of HTN for nearly loaded present day HTNs.

TSA is a software based algorithm with the computational complexity of the order O(nlog(n)). There are no costly upgrades in the hardware and only software code updates are needed for various TSA implementations in the present HTNs. The results obtained by implementing TSA in the pure optical backbone and wireless access network clearly indicate that the connection blocking probability and packet loss in HTN has been substantially reduced. Therefore, incorporating TSA effectively optimizes the use of existing optical and wireless network infrastructure, providing better QoS and enhanced connection establishment at a minimal cost in present and future HTNs. The incorporation of TSA for both the backbone and access segments of HTN is strongly recommended to intelligently optimize the HTN and substantially improve its performance for future deployments.

6.2 Future Work

The TSA has been shown to effectively improve connection blocking probability and packet loss in HTN which are based on LTE technology in the access segment. LTE in the near future would be replaced by 5G technology to improve data rates in the wireless links of HTN. Further, in future more of wired access nodes would be replaced by wireless nodes incorporating such 5G technologies as they will guarantee high data rate experience to the users on the move.

Therefore, implementing TSA in such future wireless nodes may also improve the connection handling capacity of future HTNs. The efficacy and performance of TSA in future wireless nodes incorporating 5G technologies can be duly validated as a future scope of this research work.

In addition, the channel measurement study conducted in his research work for pico-cells can be expanded to larger ranges to analyze channel parameter responses for effective design and development of transmitter and receivers for micro and macro cell deployments in Indain terrain conditions.

Finally, The TSA proposed in this research work can be deployed on actual telecommunication nodes in optical, military as well as wireless domains, in order to ascertain their performance in practical network conditions. The fallouts if any, can be researched to improve their performance on real networks.

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List of Publications

Published in Journals:

1. S. Shukla and V. Bhatia, "Traffic Grooming in PCE Based Architecture combined with RWA utilizing Dynamic Fiber State Information", *IETE Technical Review, pp. 1-14, Nov* 2016, DOI:*http://dx.doi.org/10.1080/02564602.2016.1242385* **(Impact Factor – 1.339)**.

2. S. Shukla and V. Bhatia, "Packet Scheduling Algorithm in LTE/ LTE-Advanced based Cellular Networks", *IETE Technical Review, pp. 1-11, Aug* 2017, DOI:h*ttp://doi.org/10.1080/02564602.2017.1342573* **(Impact Factor – 1.339)**.

3. S. Shukla and V. Bhatia, "Priority Scheduling Algorithm for Traffic in a LTE-based Defence Mesh Network Incorporating Centralized Scheduling Architecture", *Defence Science Journal, Oct 2017, Vol. 67, Issue 5, pp. 581-587, DOI: http://dx.doi.org/10.14429/dsj.67.10593* **(Impact Factor - 0.589)**.

Published in Conferences:

1. S. Shukla and V. Bhatia, "Traffic Grooming Algorithm in GMPLS Architecture combined with RWA utilizing Dynamic Fiber State Information", *IEEE INDICON*, India, pp. 1-6, Dec 2014, DOI:10.1109/INDICON.2014.7030587 (**Best Paper Award**).

2. S. Shukla and V. Bhatia, "Traffic Scheduling Algorithm for Wireless Mesh Networks based Defence Networks Incorporating Centralized Scheduling Architecture", *IEEE Sensor Signal Processing for Defence*, U.K. pp. 1-5, Sep 2015, DOI: 10.1109/SSPD.2015.7288525.