QoS based Route Management in Cognitive Radio Networks

By

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Abstract

QoS based Route Management in Cognitive Radio Networks

Anirudha Kulkarni

Cognitive radio has become a revolutionary technology that enables the functionalities of dynamic spectrum access. These are the radios that can be programmed and configured dynamically and aims at enhancing the efficiency of spectrum usage by allowing unlicensed users to access/share the licensed spectrum. Cognitive radio networks, a network of cognitive radios, are smart networks that automatically sense the channel and adjust the network parameters accordingly. Therefore, cognitive radio networks raise many challenges such as power management, spectrum management, route management, environment awareness, path robustness, and security issues.

As Cognitive Radio (CR) enables dynamic spectrum access which causes adverse effects on network performance because routing protocols that exists were designed considering fixed frequency band. Also, effective routing in CRNs needs local and continual knowledge of its environment. If licensed user (primary user) requests for its channel which is currently used by unlicensed user (secondary user) then unlicensed user has to return the channel to licensed user. However, unlicensed user has to search for another channel and accordingly it needs to seek for route discovery. So, all these important factors need to be accounted for while performing route management.

In this thesis, QoS based route management technique is proposed. Proposed model makes use of functionalities of profile exchange mechanism and location services. The proposed QoS routing algorithm contains following elements: (a) each licensed user prepares channel property table which lists all the properties of the channel, whereas all the unlicensed users in the network due to cognitive functionality sense the environment and prepare a table which contains identification information of neighbor node and channel present between them. All unlicensed users share their

table with central entity. (b) Central entity with the help of received information and location services prepares routing table for all the nodes in the network. (c) Various Quality of Service (QoS) metrics are considered to improve the performance of the network. The metrics include power transmission, probability of channel availability, probability of PU presence, and Expected Transmission Count. Central entity provides a route to destination based on the QoS level requested by unlicensed users.

Proposed model provides a route with minimum end-to-end transmission power, high probability of channel availability, low probability of PU presence and low value of expected transmission count, to increase life span of users in the network, to decrease the delay, to stabilize wireless connectivity and to increase the throughput of the communication, respectively, based on the QoS level requested by a secondary user.

Performance of the network is examined by simulating the network in NS2 under simulation environment with the help of end to end delay, throughput, packet delivery ratio, and % packet loss. Proposed model performs better than two other reference models mentioned in the thesis and is shown in the simulation results.

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All praises to Almighty GOD who enabled me to complete this task successfully. This thesis would have never been completed without the will and blessing of GOD, the most gracious, the most merciful.

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List of Acronyms

Acronyms	Meanings
ITU	International Telecommunication Union
CEPT	European conference of Postal and Telecommunication administrations
CITEL	Inter American Telecommunication Commission
ISM	Industrial, Scientific and Medical radio bands
FCC	Federal commission communication
DSA	Dynamic Spectrum Access
CR	Cognitive Radio
CRN	Cognitive Radio Network
PU	Primary User
SU	Secondary User
QoS	Quality of Service
NS2	Network Simulator 2
MAC	Media Access Control
CCC	Common Control Channels
PEM	Profile Exchange Mechanism
BS	Base Station
SU_{id}	Secondary User ID
PU_{id}	Primary User ID
$neighbor_{count}$	Total number of neighbors
srcNodeId	Source Node Id
destNodeId	Destination Node Id
nodeStatus	Status of a node
E2ETxP	End to End Transmission Power
$PROB_{K}$	Probability of Channel availability
$PROB_{PU}$	Probability of PU presence
$PROB_{link}$	Probability of link failure
ETX	Expected Transmission Count
CPT	Channel Property Table

CE	Central Entity
SSM	Spectrum Sensing Matrix
precedingNode	preceding node matrix
headValue	weight on each node
R_{RREQ}	Route Request
R_{RREP}	Route Reply
Path	List which contains a path from Source to destination
nextSrcNode	next hop in the path from Source to destination

Chapter 1

Introduction

Wireless communication has been a focus of many researchers all over the globe ever since Marconi built the first radio system in 1895 [1]. Just a concept of transferring data from one place to other over a spectrum/ frequency channel motivated researchers from various fields to explore the field of wireless data transfer. Radio spectrum is one of the tightly regulated resources. From cell phones to TV sets to garage-door opener, virtually every wireless device depends on access to radio spectrum [2]. Nowadays with the advent of technologies such as 3G, 4G and increase in wireless devices, consumer's desire for innovative devices, applications and content to be delivered wherever and whenever they want results in the increment of spectrum demand. It's becoming difficult to allocate frequency spectrum to each wireless device for their operation while resources are limited. Therefore this scenario of limited spectrum resources and high spectrum demand leads to spectrum scarcity problem.

Number of standard bodies such as ITU (International Telecommunication Union), CEPT (European Conference of Postal and Telecommunication Administrations), and CITEL (Inter American Telecommunication Commission) have assigned frequency bands in 3 types of allocation [3]:

- *No one may transmit:* Frequency reserved for radio astronomy to avoid interference at radio telescopes.
- *Anyone may transmit, as long as they respect certain limits such as transmission power:* Spectrum bands such as ISM and ultra wideband (unlicensed bands) used by unlicensed users.
- *Only licensed users may transmit:* Amateur radio frequency allocations are only used for licensed user application.

So, mostly unlicensed users are affected with spectrum scarcity issue. Spectrums are allocated to the licensed users exclusively. However, if licensed users do not use the allocated spectrums, they will be treated as a waste of resource, because neither licensed user used it nor unlicensed users are allowed to use licensed spectrum. Recent spectrum utilization measurements reveal that the usage of spectrum is concentrated on certain portions of spectrum while several licensed frequency bands are under-utilized [4]. Federal commission communication (FCC) chart shows underutilization bands as in Figure 1.1 [5].

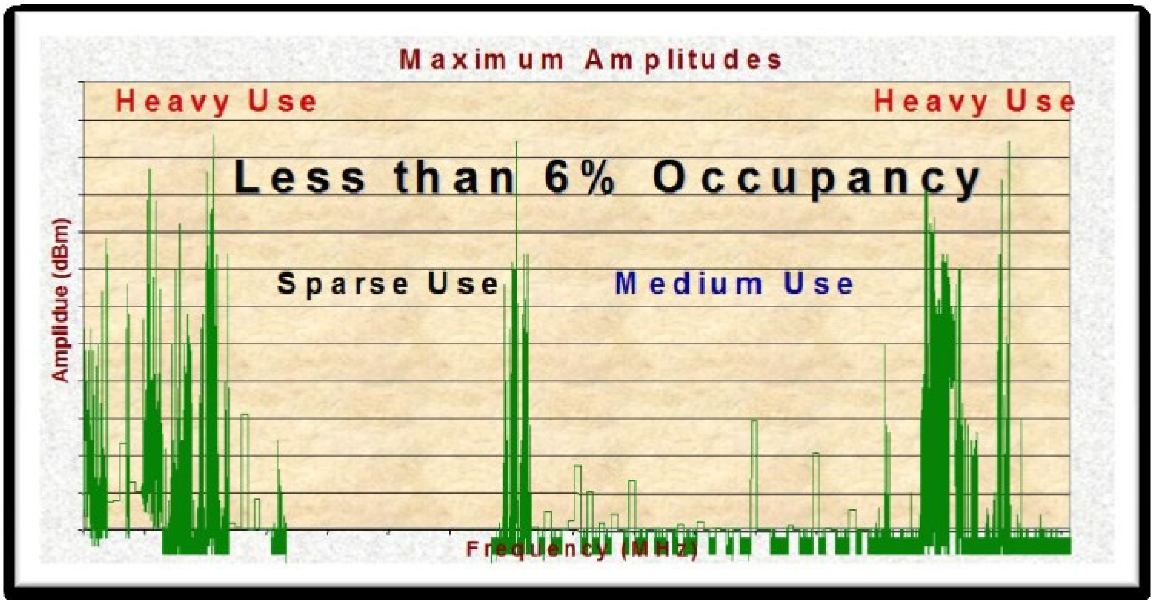


Figure 1.1: Spectrum utilization

Many solutions have been introduced to overcome the spectrum scarcity issue. One of them is DSA (Dynamic Spectrum Access) technique. DSA enables unlicensed users to access/share the spectrum of licensed users. Dynamic access is valid as long as both the users respect certain laws of communication and it includes factors such as interference, transmission power etc.

Cognitive radio (CR) inherits the functionality of dynamic spectrum access. Cognitive radios are the radios that can be programmed and configured dynamically and it aims at enhancing the efficiency of spectrum usage by allowing unlicensed users to access/share the licensed spectrum whenever spectrum owners do not use it. Hence, cognitive radio has become a revolutionary technology.

Two types of users are defined in a Cognitive Radio Network (CRN). Licensed and unlicensed users can be referred as primary users (PUs) and secondary users (SUs) respectively in a CRN. Primary users get the spectrum bands from their service providers and have the ability of using those spectrum bands whenever they want. While a secondary user detects the absence or presence of PU in spectrum bands in order to use them with minimal interference with PU [4-5].

Current routing protocols that exist for wireless networks were designed considering fixed frequency band. As Cognitive Radio (CR) enables dynamic spectrum access these routing protocols have adverse effects on network performance. Also, effective routing in CRNs needs local and continual knowledge of its environment. If PU requests for its channel which is currently used by SU then SU has to return the channel to PU. Hence, SU has to search for another channel and accordingly it needs to seek for route discovery. Therefore, these important factors need to be accounted for while performing route management.

In this thesis, routing management mechanism is explained which makes use of cognitive nature of radio to detect and use unused spectrums of PUs. A model is presented that makes use of profile exchange mechanism [6] to exchange the created profiles of SUs and PUs among each other and also, location services [7] in order to locate the position of each and every node in the network. Route management technique is illustrated with proper algorithm which considers different metrics for (QoS) quality of services. For each quality of service level, performance of routing algorithm is studied for various networks.

In this chapter, significance of cognitive radio and quality of service are reviewed. The motivation and objectives of proposed research work are listed. Eventually, organization of research work is outlined to illustrate the structure of this thesis.

1.1 Cognitive radio networks

The concept of cognitive radio networks is to intelligently organize a network of cognitive radios. Cognitive radios can be programmed and configured dynamically after learning the environment. This definition was generalized by FCC to be “a radio or system that senses its electromagnetic environment and can dynamically and automatically adjust its radio operating parameters to modify system operations, such as maximize throughput, mitigate interference, facilitate interoperability” [8]. So the two key features that distinguish cognitive radios from traditional radios are cognition capability and re-configurability.

1.1.1 Cognition capability

Cognition capability of cognitive radio is defined that has characteristics of spectrum sensing, spectrum analysis and spectrum decision. It allows cognitive radio to continuously observe dynamically changing radio environment. All these characteristics are collaboratively described as cognitive radio cycle which is illustrated in Figure 1.2.

1.1.1.1 Spectrum sensing

It refers to the ability of cognitive radio to monitor the available spectrum bands, capture its information and eventually detect the spectrum holes. Captured information could be power/energy levels, user activities etc. Spectrum sensing is one of the critical functions as it has to be fast in order to track variations in the radio environment. Various spectrum detecting techniques such as transmitter detection, co-operative detection and interference based detection are used to determine the status of the available spectrum.

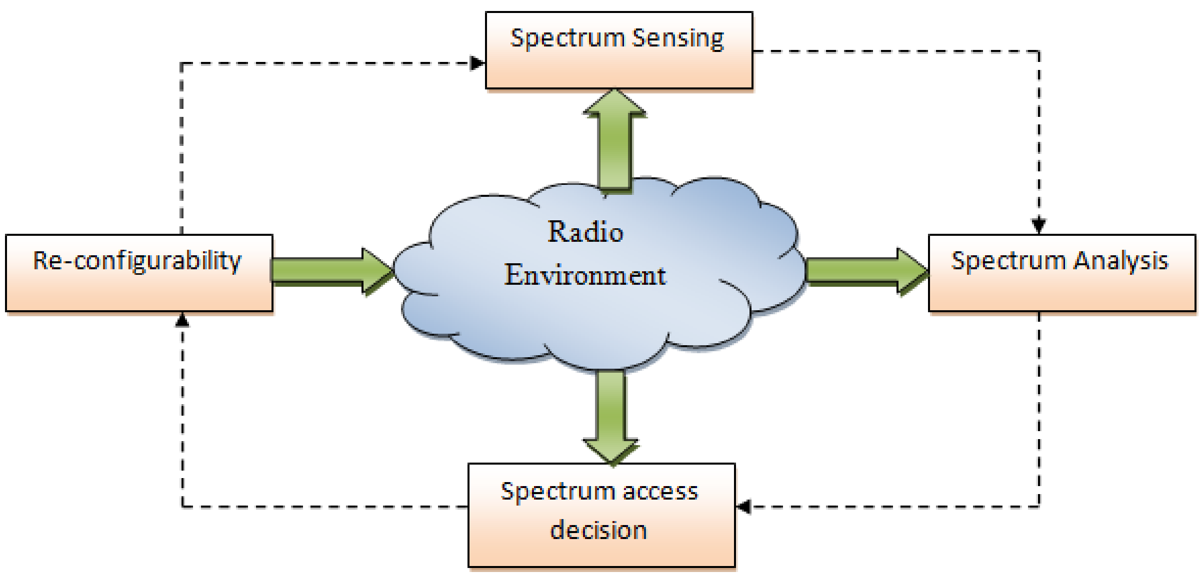


Figure 1.2: Cognitive radio cycle

1.1.1.2 Spectrum analysis

It is nothing but determining the characteristics and to identify the opportunities in the spectrum holes detected through spectrum sensing are estimated.

1.1.1.3 Spectrum access decision

The final stage in cognition capability is to decide set of transmission actions or parameters to be taken based on the results of spectrum sensing and analysis [8]. These parameters include data rate, transmission mode, power level and bandwidth of transmission. So, appropriate spectrum band is chosen based on spectrum characteristics and user requirements.

But if RF environment changes then the radio parameters are altered accordingly. This gives rise to cognitive radio re-configuration capability.

1.1.2 Re-configurability

As shown in Figure 1.2, this feature completes the cognition cycle. It has the ability of adapting to the changes in surrounding radio environment. Such adaptation includes the ability of re-tuning trans-receiver parameters, ability of reconfiguring transmission parameters such as transmission rate, power etc. Some of the reconfiguration parameters are listed as below.

1.1.2.1 Spectrum mobility

It refers to the process in which CR radios alter the frequency of operation. If primary user appears in the network then SU has to handover the channel that is being used for its communication. So, in order to have seamless wireless connectivity, cognitive radio terminal must be able to switch to a new frequency band/channel. But spectrum mobility has to be very fast so as to keep the performance of protocols under control.

1.1.2.2 Transmission power

Based on the status (idle/busy) of the channel, and PU's transmission power level, SUs decide spectrum access approach. There are two kinds of approaches by which a SU can access the frequency spectrum.

1.1.2.2.1 Overlay approach

If PU is not using its own spectrum then SU makes use of their spectrum/channel. Since, only one transmission is going on the channel, SU transmits on that channel with higher power level as far as it does not interfere with other ongoing communications. In short, in overlay access technique, only one type of user (either PU/SU) fully uses the spectrum channel at a time.

1.1.2.2.2 Underlay approach

In this approach SU co-exist with PU in the same channel. However, SU uses lower power levels than PU for communication so as to avoid interference with PUs. That is if SU wants to transmit the data on a channel which is currently being used by PU then it has to select low power levels for communication so that transmission from PU and SU does not interfere.

In brief, cognitive radio technology allows the unlicensed operations to be in licensed band [6]. CRN technology raises many technical challenges in spectrum sensing, spectrum management, route selection and robustness, trusted access and security, hidden node issues [6, 9].

1.2 Motivation

Cognitive radio has become an intelligent technology that enables wireless devices to utilize spectrum efficiently. It makes use of cognition capability and re-configurability features as discussed before. It allows licensed operations to be in licensed band. However, there are several research challenges that motivate us in our work and they are listed as below.

1.2.1 Quality of Service (QoS)

Quality of service is a measure of the ability of network and systems to provide different levels of services during communication set up. In CRN network, SU demands for specific QoS level from PU and PU searches for channels that meet the SU's requirement on QoS.

Research in CRN network has been enlarged in recent years but still a model/work with several QoS metrics is hardly possible to encounter, which motivates us to acknowledge QoS metrics to escalate the performance of communication. Hence four QoS metrics (QoS0, QoS1, QoS2 and QoS3) are proposed in our work. QoS0 is the basic level that any communication system has to follow. It considers 'power transmission' over spectrum/channel as a QoS metric. Selecting transmission power level is important during data transmission over channels. It is because if proper power level is not selected, it may cause interference issue to other users in wireless network. QoS1 considers 'delay', QoS2 considers 'PU presence', and QoS3 represents Expected Transmission Count (ETX) as QoS metrics. The significance and mathematical model of these QoS metrics will be discussed in Chapter 3.

1.2.2 Route Management

Basically route management stands for determining the best available path from source to destination while taking care of the requirements. In CRN networks, depending on the quality of service level demanded by SU, system provides path to destination. Crucial factors that can affect the network performance may include node mobility, channel availability, primary users presence etc.

Several routing algorithms that are featured for greedy forwarding of the packets and few algorithms that are mentioned in the Chapter 2 are less efficient when considered with different QoS levels. This motivates us to find solution to improve the network performance.

1.3 Problem statement

Cognitive radio allows the unlicensed users to access licensed spectrum. And this can be possible because of the cognitive cycle. Spectrum sensing allows SUs to sense the channels available with primary users. In order to ensure and to add sureness to the sensing information, already proposed profile exchange mechanism combined with location services functionality is studied. But this mechanism creates excessive control overheads on the network and affects network performance. Similarly, some of the routing algorithms mentioned in Chapter 2 come with certain impediments and that include long routes to destination which causes resource consumption, route to destination not reachable under various levels of QoS and delays in route discovery.

These problems are divided into two parts: First part is to look for a new working model that makes use of profile exchange mechanism and location services to reduce the overhead on the network and to enhance the network performance. Second part is to apply the same model into QoS based route management algorithm which looks after the issues discussed before. Our routing algorithm is implemented in NS2 so as to evaluate the performance of the network.

1.4 Objectives in research work

This section includes the objective of our work. Some research questions are presented to guide us to specify our objectives precisely. The key objective of our work is to propose a working model that can manage the spectrum efficiently and enhance the network performance through QoS based routing techniques.

In the first part, we will propose a working model that makes use of functionalities of profile exchange mechanisms and location services. In second part, objective of the first phase is to implement routing techniques while considering different QoS levels/metrics whereas second phase includes simulating the network in NS2 so as to analyze the performance of the implemented routing technique through factors such as delay, throughput, packet delivery ratio, and percentage packet loss. All efforts will be geared towards achieving following tasks.

I. To implement new working model that satisfies following objectives:
   - To enable sureness in the sensing information by profile exchange mechanism combined with location services.
   - To lower down the excess overhead on the network by reducing number of control and profile exchange messages to a greater extent.
   - To reduce the redundancy in profile exchange messages.

II. To implement a QoS based routing algorithm which has following features:
   - To decrease delay by selecting a path with high probability of channel availability.
   - To select a path with low end to end transmission power.
   - To stabilize wireless connectivity by selecting a route with low probability of PU presence.
   - To increase the throughput; reducing expected transmission count value by selecting a path with low probability of link failure.
   - To reduce the delay in route discovery and avoid packet loss due to route to destination not available.

III. To implement routing technique in simulation environment NS2 for various network scenarios.

1.5 Thesis organization

Chapter 2 reviews the literature of various routing issues in CRN technology. It also discusses QoS metrics that help to enhance the performance of network. Further this section focuses on various routing techniques that have been researched so far in CRN technology. In depth discussion is carried out on few routing techniques which worked as a reference for our thesis. The chapter ends with discussion about the impediments of these reference models that motivates us to improve the system performance.

Chapter 3 presents system QoS levels and their mathematical implementation in our model. Furthermore, all system components and workflow of our model is elucidated. Route management algorithm is illustrated with the help of pseudo code and flow charts. Finally, chapter is concluded and packet flow details are discussed with an example.

Chapter 4 presents performance measures of our model along with the reference models. At each level of QoS, all the models discussed so far are compared with each other for various network scenarios. Eventually, chapter is concluded with the discussion on NS2 simulation environment, AWK scripting, NS2 simulation results and analysis.

Chapter 5 presents the conclusion of the thesis work. It also recommends some future activities for CRN network topology to become more rigid.

1.6 Summary

In this chapter an overview on cognitive radio network has been provided. Furthermore motivation behind thesis problem statement has been defined so as to highlight our research objectives. Eventually, thesis organization has been outlined to address the significance of each chapter. In the next chapter, literature review on routing in cognitive radio and their issues are discussed. Few models used as reference in our thesis for comparison purposes are discussed in depth with their impediments.

Chapter 2

Literature Review

The concept of cognitive radio was first proposed by Joseph Mitola in 2000; after that majority of research has been carried out on physical and MAC layer i.e. lower layers of protocol stack. Recently, research community has started working on network and above layers. Routing in CRN is a challenging task as it affects the performance of CRN network [10].

Hence, in this chapter more insights into challenges and issues of routing in cognitive radio networks are provided. And routing metrics that can relate to these issues are highlighted along with its design challenges. Different routing techniques/protocols in CRN are listed along with their comparison chart.

Many researchers have developed different routing models which take into account different sets of routing metrics. In this chapter, we will review them one by one and use it as a foundation to our approaches. This chapter is organized as follows: first challenges and issues of routing in cognitive radio networks are presented and then various routing metrics along with their design challenges are listed. Next, different routing techniques which make use of mentioned routing metrics are described. And eventually, two models considered as reference models in our thesis are discussed in details along with their impediments which will enable us to design our model.

2.1 Routing challenges and issues in CRN

Routing in CRN is an important problem that affects the performance of the entire network. Different from traditional routing protocols, routing in CRN's has to deal with a number of challenges [12]. This section discusses the major challenges in routing carried by cognitive radios which are mentioned in [11-14].

2.1.1 Dynamic channel availability:

Channel availability for data transmission depends upon SU's physical location and channel utilization by PU's. Low channel utilization of PU resembles higher channel availability for SU's and vice-versa. Hence, this dynamic channel availability for SU's leads to link failure and due to this the need to perform routing operations may increase, resulting in higher amount of routing overhead on network.

As channel availability is dynamic there may come a scenario where SU switches to different operating frequency in order to complete the communication. But as center frequency of operation changes, data rate and transmission ranges changes as well which in turn affects route selection.

2.1.2 Dynamic common control channels (CCC):

In a network, two of types of channels are required namely CCC and data channel. SU exchange routing control packets such as RREQ, RREP through CCC and send data in data packets. Due to dynamic nature of channel availability, assumption of availability of a static CCC becomes impractical. Hence, it becomes necessary to design routing schemes in CRN without relying on static CCC.

2.1.3 Routing discovery considering channel availability:

In order to achieve end to end stable performance/ communication between SUs, stable links over intermediate SUs need to be selected. Hence, at every single moment, it is necessary to track channel information with dynamically changing channel availability.

2.1.4 Channel switching time:

As per the cognitive radio feature, PU has the highest priority in using the spectrum. Hence, if PU starts transmission over any of the channels and if SU is using the same then SU has to vacate the channel for PU and switch to other channel that can satisfy its communication requirements. But this switching requires certain amount of time called as ‘switching delay’. Design of routing protocol should minimize this switching delay.

2.1.5 Minimizing multiple transmissions for single broadcast:

Broadcasting is a common place in routing for control message exchange. Due to diversity in operating channels, each SU can use different available channel, single broadcast may not reach to all SUs. Hence, multiple transmissions of the messages are necessary. As a result bandwidth utilization increases but it does not contribute towards throughput performance.

Another way is to provide synchronization window where all SUs are tuned to a particular channel for broadcasting. However it needs synchronization or centralized clocking. As a result, a routing protocol should minimize this multiple transmissions.

2.1.6 Mobility of SUs:

Higher mobility of SU increases number of channel switches which in turn increases the overhead on the network. Movement of SU makes it more challenging for routing protocol to guarantee required QoS. Hence, routing schemes should be aware of the mobility of SUs.

2.1.7 Tradeoff between number of hops and network performance:

Route with lower number of hops has certain effects on the network performance. It may incur an increase in interference to PU's transmission, higher route maintenance cost, higher energy consumption due to long range. Hence, routing scheme should consider hop-count to meet desired requirements.

2.1.8 Best path selection and Route recovery:

Based on the QoS requirement of the application, a node looks for the best path. Out of the few paths, a path that satisfies the QoS requirement and optimizes the network performance is selected. Due to PU presence, SU mobility route recovery in CRN is essential.

	Challenges	Literature Reference
1.	Dynamic channel availability	[16][18][19]
2.	Dynamic common control channels	[20] [21] [22] [23] [24]
3.	Route discovery considering channel availability	[17] [20] [21] [25] [26]
4.	Channel switching time	[18] [31]
5.	Minimizing multiple transmissions	[25] [27] [28]
6.	Mobility of SUs	[29] [30]
7.	Number of hops and network performance	[31] [33] [34]
8.	Best path selection and route recovery	[15] [31] [32]

Table 2.1: List of routing challenges and corresponding literature summary

2.2 Routing techniques

In this section, we discuss various routing techniques that can be classified based on mode of communication, routing mechanism, spectrum knowledge, routing models and metric used for communication. There are certain other features that can be enabled into other routing schemes which are mentioned as well. Figure 2.1 shows the classification of routing schemes in CRNs [6] [10] [12] [13] [14].

2.2.1 *Mode of communication*:

There are two modes of communication: unicast and multicast which can be explained as below.

a. Unicast:

A message sent by a SU source node is only received by its intended SU destination node.

b. Multicast:

A message sent by a SU source node is received by all SU destination nodes that belong to same group. Multicasting in CRNs is more complex because of dynamic channel availability and diversity of operating frequency in CRN.

2.2.2 Routing mechanisms:

There are four different routing mechanisms mentioned in the literature as explained below.

a. Proactive:

It is also called as a 'table-driven' routing. Each SU node exchanges routing packets with neighbor nodes and keep track of each route in a route table. Optimized link state routing (OLSR) [35] is an example of proactive routing scheme. It provides up-to date information, which helps to reduce end to end delay. But on the other hand it increases BW consumption and network overhead. The performance depends on network scenario, such as network size, SU mobility. Network overhead increases with an increase in network size and SUs mobility.

b. Reactive:

It is called as 'on-demand routing'. Basically, SU floods the network with RREQ control packets. Upon receiving the RREQ packet, SU destination node responds with a RREP control packet.

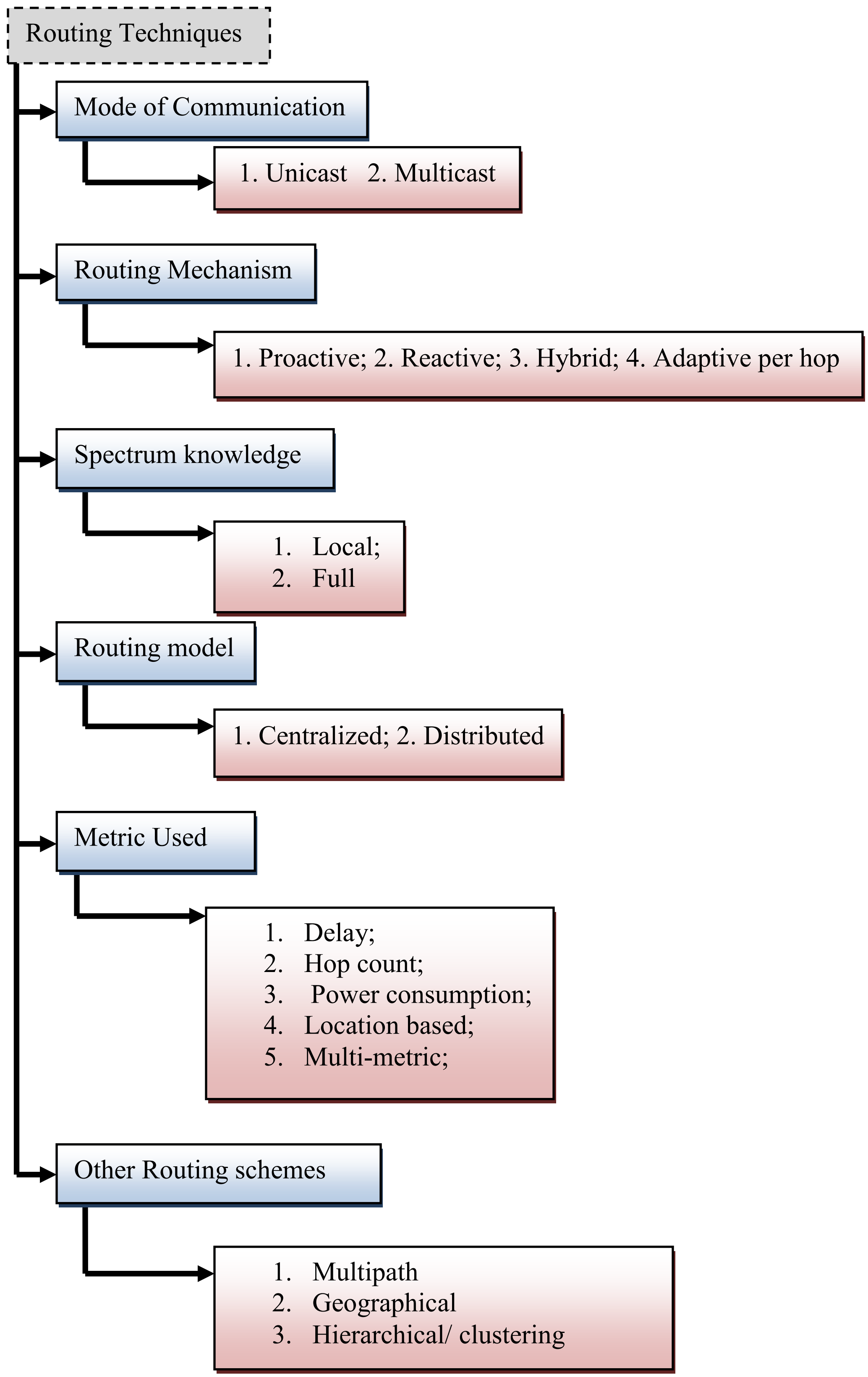


Figure 2.1: Classification of routing schemes

AODV (ad-hoc on demand distance vector routing) is a traditional reactive routing scheme [36]. Route discovery takes place only when source SU has packet to send. Hence it results in low BW consumption and overhead. But at the same time it incurs higher delay in route discovery.

c. Hybrid:

It combines the characteristics of both proactive and reactive routing techniques. It is used to balance the performance trade-off between mentioned schemes. As an example, there may be two clusters that use proactive routing for intra cluster communication and reactive routing for inter cluster communication, then it is an hybrid routing scheme enabled for balancing performance trade-offs. Zone routing protocol (ZRP) is an example of traditional hybrid routing scheme [37].

d. Adaptive per hop:

In adaptive routing, SU chooses its next hop based on the local information/ characteristics of the network and channels. Machine learning algorithms, such as 'reinforcement learning' RL [38] [39] enable routing schemes to select the next-hop based on local information. It reduces BW consumption and overhead on network.

2.2.3 Spectrum knowledge:

In spectrum aware routing, SU selects the route based on spectrum knowledge [11] [40].

a. Full spectrum knowledge:

Nodes in the network have full spectrum knowledge about the availability of spectrum. There are certain approaches such as graph abstraction or programming tools to model and design packet flows in the CRN network. Most of these approaches are based on centralized computation of routing paths.

b. Local spectrum knowledge:

In routing scheme based on this approach, information on spectrum availability is locally constructed at each SU through distributed protocol.

2.2.4 Routing models:

Routing models in CRNs can be either centralized or distributed. They are explained as below.

a. Centralized:

In this approach, when SU joins or leaves its neighbor SUs or any changes in the surrounding environment must be communicated to the central entity as it plays important role in taking decisions in CRN.

b. Distributed:

In distributed approach, when SU joins or leaves its neighbors, only one-hop or two-hop neighbors of the SU update their routing information and exchange control packets accordingly. It reduces the overhead on network.

2.2.5 Metric used:

There are a number of routing metrics used while performing routing in CRN. We will discuss few of the metrics mentioned in this section in detail with existing work on the same in next section.

a. Delay:

End to end delay along a route is a traditional metric for routing algorithms. It includes:

- Switching delay: It occurs when a node in a path changes its frequency of operation.
- Back-off delay: MAC results in back-off delay when trying to solve hidden terminal and exposed terminal problems. It is the difference between timings from the moment the packet is ready to be transmitted to the moment packet starts its successful transmission.
- Queuing delay: It depends on the transmission capacity of a node on a given frequency band.

b. Hop count:

Hop count can be used as a filtering metric. Lower the hop count, less number of resources (like communication channel) is being consumed for the communication.

c. Power consumption:

It is one of the major issues when dealing with mobile devices, as main aim is to conserve the limited battery resources. In CRNs, in addition to traditional tasks, SU has the extra overhead of continuously sensing the vacant spectrum and PU presence. Hence, it is more important to have power consumption as a metric for CRNs.

d. Location based routing:

Many of the today's wireless devices are location enabled. Location of the devices can be gathered through GPS system or via FCC geo-location databases [41] or can be estimated via measurements [42-49].

e. Multi-metric:

There are certain routing protocols that combine several metrics into one metric. It is done in order to provide better QoS to end user.

2.2.6 Other routing schemes:

It provides few features that can be inherited by routing schemes.

a. Multipath:

SU source node discovers more than one route to SU destination node so as to enhance the route reliability and achieve load balancing among pool of routes [50].

b. Geographical:

A route to destination is selected based on SU's physical location. Positioning data is obtained through GPS (global positioning system) installed at each SU.

c. Hierarchical/ clustering:

This feature allows organization of SU's into groups. Each group consists of cluster head. All SU's belonging to the same group send their control packets to cluster head, who forwards them to the gateway.

Out of these routing schemes and features, we will be mostly interested to review some research work done on metric enabled routing in next section.

2.3 Metric aware routing

In this section, we consider the metrics listed in the previous section and review the previous work done on these metrics.

2.3.1 Delay

In [51], distributed resource management approach is proposed that can improve the peak signal to noise ratio (PSNR) by effective transmission time (ETT) metric, which considers average length of packets, TX rate and packet error rate. It can be helpful for delay sensitive applications as it is used to minimize the end to end delay. But it takes decisions based on local information which leads to non-efficient solution, vulnerable to inaccurate information and malicious activities without achieving global fairness [52]. Moreover, nodes become complex in nature leading to most power consumption and hence a lower span of SU nodes. In [53], STOD-RP routing protocol is introduced which can simplify the collaboration between spectrum decision and route selection with the help of 'STOD' routing algorithm. It considers 'D_{switch}', which is switching delay caused by CR users due to multiple switches between two different frequency bands. It combines tree based 'proactive' routing and 'on-demand' route discovery. But as it involves exchange of control packets (broadcasting of routing requests) between roots of spectrum tree, overhead and network congestion increases as network grows. In [54] [6], DORP, a routing and spectrum assignment scheduling algorithm is proposed to achieve lower switching and back off delay. However, the algorithm is under the assumption that the node has two transceivers, one is traditional and the other is a cognitive radio, which means that each node has data to transmit and must know the frequency band choice of every node along the route to destination. This is costly in terms of energy consumption and it requires having global information. In [55] [10], cross layer approach is designed to decide a route with minimum delay (switching and queuing), maximum stability in dynamic CRNs. But this mechanism requires exchanging a lot of data amongst all nodes in the network in terms of global information about the network, control information about the status of spectrum and data related to routing. In [56] [10], cross layer approach is designed minimizing the delays. But it is based on the assumption that perfect spectrum sensing information is available with the cognitive nodes, which is difficult to achieve in CRN.

2.3.2 Hop-count

Resources consumed will be less if we select a path with minimum number of hops. In [57], SAMER follows the two tier routing approach that balances between long-term stability (based on the hop count) as path to the destination do not divert much from the shortest path and short-term opportunistic gain (based on higher spectrum availability). However, each node builds a set of candidate forwarding nodes to destination. So, as network grows, power/battery and memory consumption grows exponentially. In [58], CAODV based on modification of widely adopted AODV protocol is designed which avoids active primary users regions during route formation and packet forwarding. Hop count is used as a filtering metric to select between candidate routes. However, much more functionalities are put on SUs that makes it more complex. Also, broadcasting creates congestion problems in the network as it grows. In [59], SEARCH which is a spectrum aware routing for cognitive ad-hoc network protocol based on geographic location is designed. Hop count is used as a filtering metric. It compares hop count used in the original route formation to the number of hops used in the current path, which may differ from original route due to route maintenance based on PUs activity. If it is above threshold, it signals the need of new route information. However, as it is a modified AODV, greedy forwarding of packets takes place. It exchanges location information periodically between neighboring nodes through bacon updates, which results in extra overhead on the network.

2.3.3 Power consumption

In [60], MWRP (minimum weight routing protocol) link weights are defined as the TX power required to reach to the receiver; where TX power is directly proportional to the square of the distance. Each node selects a neighbor that minimizes this metric locally. However it leads to longer routes and sometimes route to destination cannot be set up. In [61], NDM_AODV protocol is proposed which selects route based on the remaining energy at each node along the route. Protocol measures the total remaining energy of all nodes in the path and then selects path with maximum total remaining energy. In [62], route decisions are made based on application and transmit power (ATP) metric. It improves the spectrum availability as it may use the channels even in the presence of primary users. However, delay increases with higher application load.

2.3.4 Location based routing

In [59], SEARCH uses a greedy location-based approach where it works on each available channel. SEARCH selects next hop neighbor as the neighbor closest to the destination from the current node within a focus region. But due to greedy forwarding sometimes more power is consumed. In [63] LAUNCH, which is again a location based PU aware routing protocol for CRNs, combines different metrics including PU activity, switching delay and location information. Neighboring node which is closest to destination node, with minimum PU activity and a channel with lower switching delay is selected as a next hop. But routing is based on greedy forwarding of packets.

2.3.5 Multi metric routing

In [64], the CR routing protocol (CRP) combines several key CR-specific performance metrics and it includes probability of bandwidth availability, variance in the number of bits sent over the link, PU receiver protection and finally spectrum sensing consideration. However, work is based on the assumption that the network architecture is composed of stationary PU transmitters with known locations and maximum coverage ranges. But practically, PU is a dynamic user as well. Hence, it may create PU interference issues. In [65], routing decisions are based on link modeling, interference avoidance and different transmission ranges with relaying methods. At the beginning of routing it chooses optimal route and by using route adaptation and route preservation it aims to retain optimal route. However, with the use of many metrics for route decision leads to improvement in performance but at the same time causes increase in computational complexity. The proposed algorithm in this thesis considers delay, power consumption, PU presence and ETX (expected transmission count) as a metric which can lead to long life time of users, link robustness and stability to the communication. Each metric works at a specified level of QoS, ***QoSLevelX***, where X=0, 1, 2, 3.

2.4 Reference Model 1

In this section, we discuss a reference model [6] which makes use of profile exchange mechanism (PEM) and a novel routing algorithm. Salient features, impediments/catches of using these are discussed in brief.

2.4.1 Profile Exchange Mechanism

In profile exchange mechanism, PUs and SUs exchange their profiles among each other. Profile exchange allows minimizing power utilization in sensing [4] and it increases the accuracy rate in spectrum sensing results. Figure 2.2 explains the detailed PEM, which considers communication between many SUs, PUs and between PUs from different clusters.

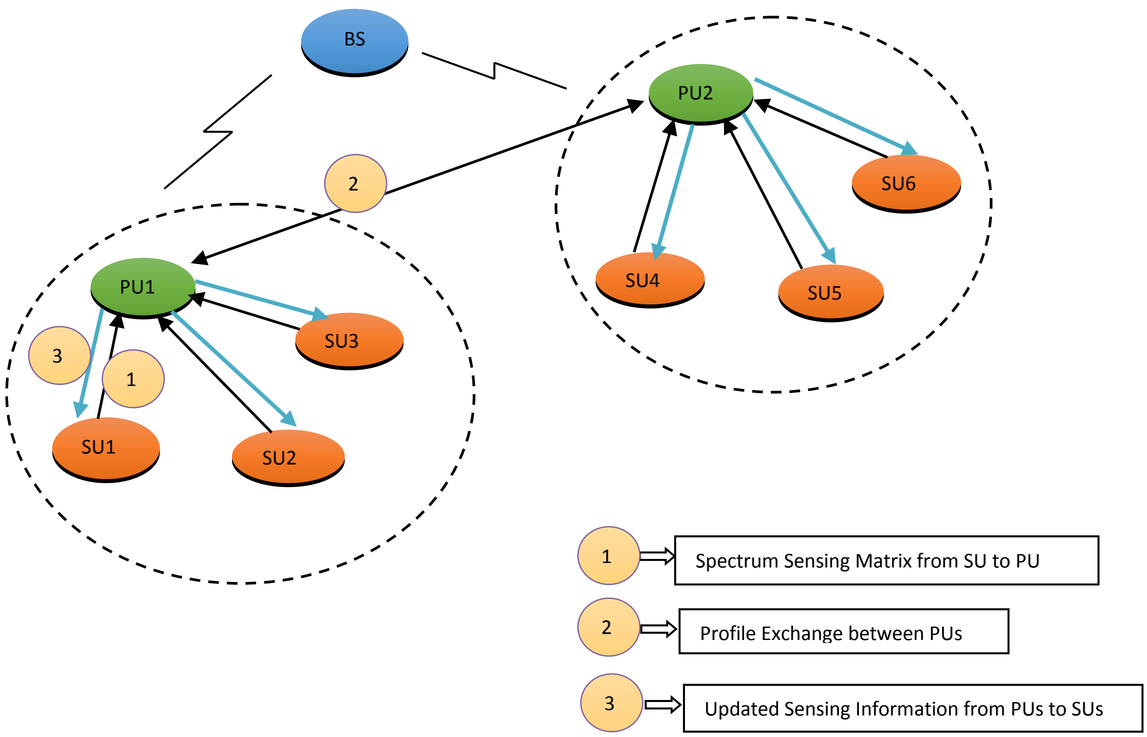


Figure 2.2: Profile exchange mechanism

Base station (BS) allocates the frequency channels to primary users (PUs). Secondary user (SUs) according to cognitive behavior performs sensing mechanism on available channels of sensed PUs and builds its own profile. Secondary User profile consists of records such as $Profile_{id}$, SU_{id}, K_{id}, PU_{id}, $neighbor_{count}$, [$neighbor_{id}$], $PROB_{K}$, $PROB_{PU}$ and $PROB_{link}$, where $Profile_{id}$ is the ID for SU's profile, SU_{id} is the secondary user ID, K_{id} is ID of the channel, PU_{id} is the ID of primary user, [$neighbor_{id}$] is the vector that contains the list of SU's neighbor ID, $neighbor_{count}$ is the total number of neighbors to SU_{id}, $PROB_K$ is the probability of channel availability, $PROB_{PU}$ is the probability of PU presence and $PROB_{link}$ is the probability of link failure. Similarly, PUs maintain their own record which consists of $Profile_{id}$, $Profile_{SUi}$, PU_{id}, $PROB_K$, $PROB_{PU}$ and $PROB_{link}$.

All SUs send their sensed information to PUs in the form of record. Once, this record is received at PUs they check the sureness in the sensed information after communicating with other PUs from different clusters. In the end PUs broadcast updated sensed information to all the SUs in the cluster. This technique helps to improve the sureness in the sensed information from SUs [4].

2.4.2 Routing algorithm

Once the exchange mechanism is carried out users start following the routing algorithm discussed in this section in order to communicate with other users. In this section, details of routing algorithm are discussed in brief. The core of algorithm looks for the minimum value of metric between source node and its neighbors. This metric can be either $PROB_K$ or $PROB_{PU}$ or $PROB_{link}$. And based on minimum value, corresponding neighbor node will be selected as a next source node. This process is continued till the actual destination is reached. The flow chart in the next section explains the mechanism.

2.4.2.1 Flow chart

Routing algorithm consists of two steps in which first step initializes the system variables (Figure 2.3) and second step (Figure 2.4) actually finds the path based on users requirements.

2.4.2.1.1 Step 1: Initialize the system variables:

In this step system variables, status of nodes (nodeStatus), deciding on source node (srcNode), destination node (destNode), user requirement (QoSLevelX), path list from source to destination (path) and an array to store metric values between links (storedArray), are initialized.

System sets the status of all nodes (‘numberOfNodes’: indicates total number of nodes) in the network to ‘0’, which indicates that initially, all the nodes in the network are available for communication. The values for srcNode, destNode and level of QoS are initially defined. ‘path’ is a list which contains a route from source to destination whereas ‘storedArray’ is an array which is used to store the link metrics between source node and destination node. Initially ‘path’ list and ‘storedArray’ is set to ‘Null’ (Figure 2.3).

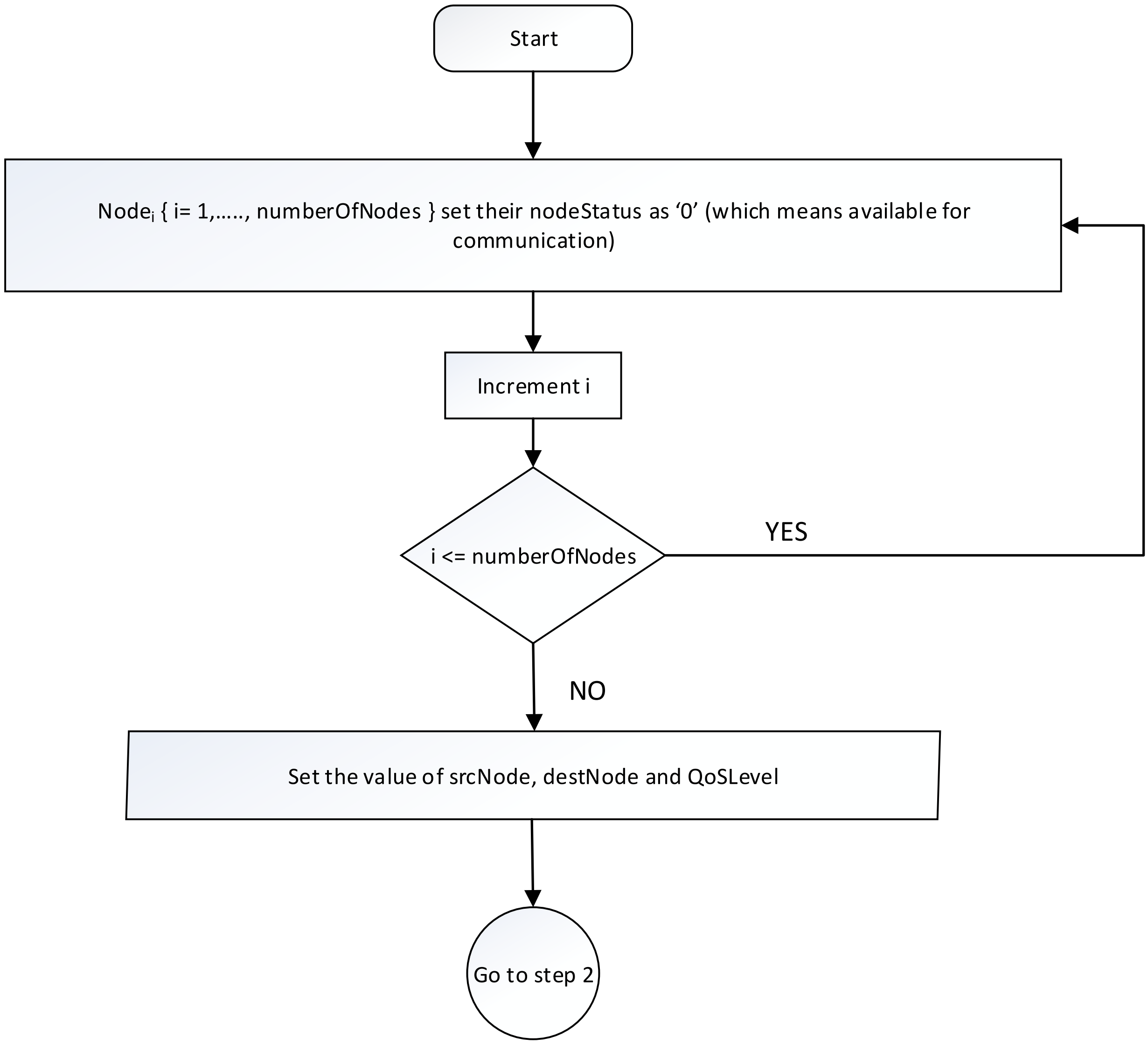


Figure 2.3: Step 1: Initializing the system variables

2.4.2.1.2 Step 2: Routing technique

In step 2, all the neighbor nodes are listed for source node and status of each neighbor node is checked. If status is ‘0’ then link metric value between source node and neighbor node is stored in ‘storedArray’ otherwise ‘Inf’ value is stored for corresponding neighbor node. Once all the metric values are stored in ‘storedArray’ then minimum value is selected along with corresponding neighbor node which becomes next srcNode. List ‘path’ is updated with recent srcNode. Node status of srcNode is set to ‘1’ and ‘storedArray’ is set to ‘Null’ again. Above procedure is repeated till (srcNode != destNode).

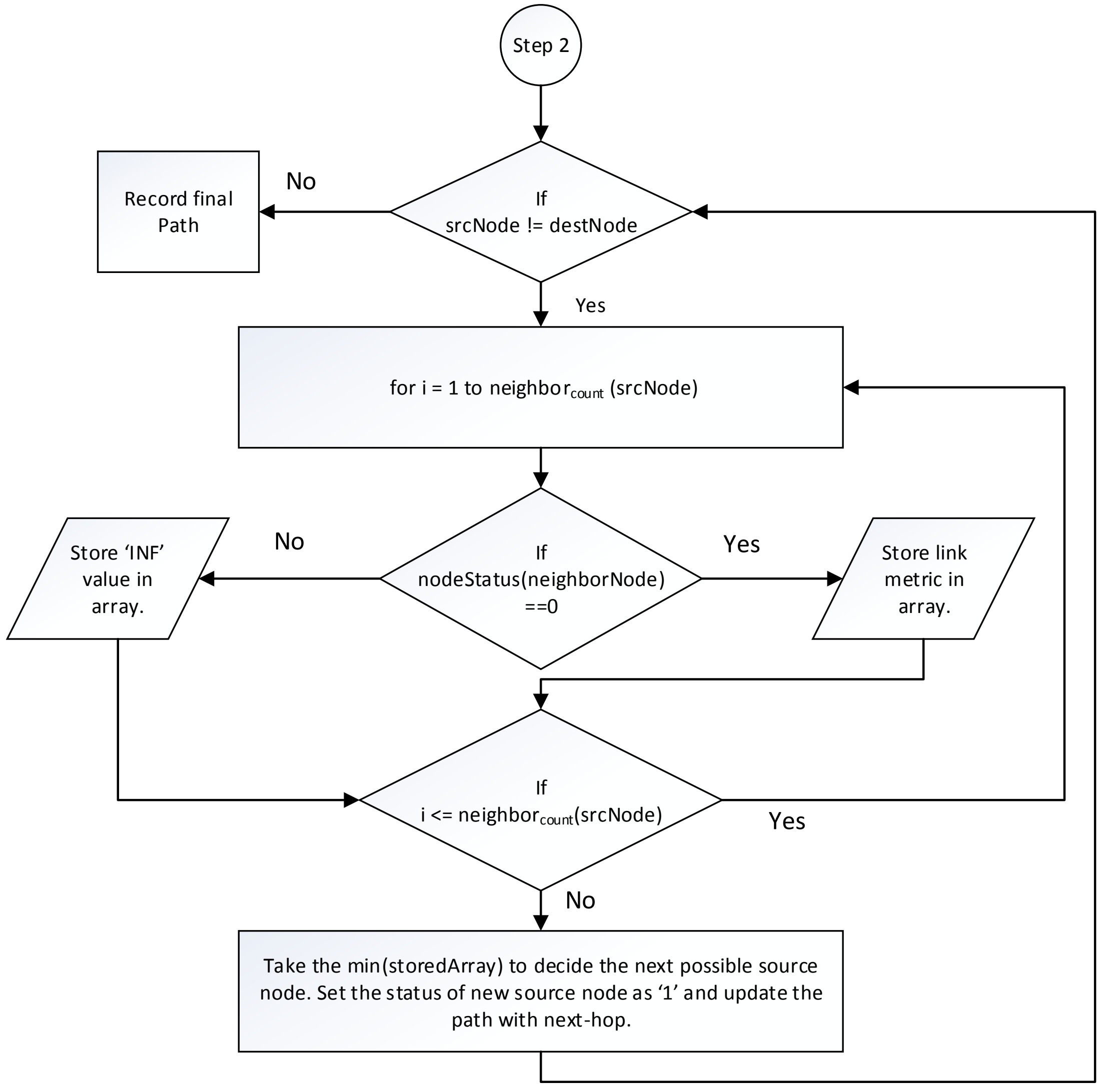


Figure 2.4: Step 2: Routing technique

2.4.2.2 Impediments/catches

After carefully going through the PEM and its routing technique, we came to understand few catches in the algorithm. In this section we provide a brief insight into these catches.

2.4.2.2.1 Profile exchange mechanism

Few things that need to be considered while setting up exchange mechanism. First is the amount of control overhead that is put onto the system. PEM discussed exchange heavy set of information/records and packets may carry redundant information between PUs and SUs. As it involves broadcasting of information between PUs and SUs, number of packets broadcasted or sent will be more if users are large in number. This may lead to congestion in network.

Moreover, if the network is dynamic then it leads to heavy control overhead during profile exchange.

2.4.2.2.2 Routing technique

Even though this routing algorithm looks after the loopback very carefully, it generates long routes to the destination, which causes resource consumption. Sometimes, route may not even be found between source and destination.

In order to explain it, we carried out an experiment where we considered 3 different scenarios. Scenario 1 has 10 networks with 10 nodes each. Scenario 2 has 10 networks with 13 nodes each. Scenario 3 has 10 networks with 20 nodes each. In each scenario, we look for percentage number of times destination is not reachable from different source nodes.

Figure 2.5 indicates that for Scenario 1, out of all combinations of source and destination pairs, 34% of time destination is not reachable for QoS Level 0; 37% of time for QoS Level 1 and approximately 40% of time for QoS Levels 2 and 38% of time for QoS Level 3. Similarly, Figure 2.5 also shows the result for Scenarios 2 and 3.

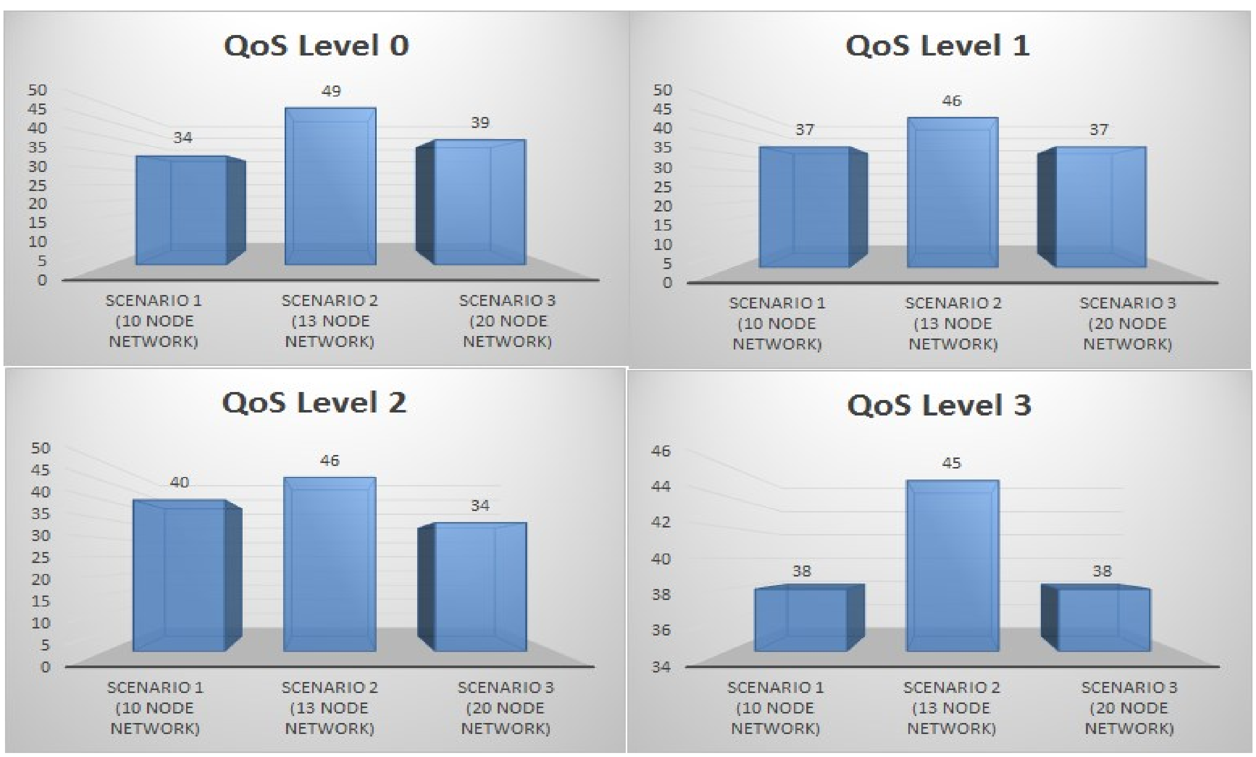


Figure 2.5: Percentage number of times destination is not reachable from source node

Hence, there is a need to look for new routing techniques which can satisfy different QoS levels and ensure communication establishment and subsequently reduce packet loss.

2.5 Reference Model 2

In this section, we discuss another reference model which makes use of location information to guide route discovery, maintenance and data forwarding [7] in a CRN network. Salient features, impediments/catches of using this technique are discussed in brief.

2.5.1 Location aided routing scheme

LAUNCH is one of the location aided routing scheme which is being explored for CRN networks [7]. According to this technique, apart from destination's position, each node needs to know only its own location and the location of neighbors in order to forward the packets. In order to learn current position of a specific node, help of location service is needed. When node does not know the position of a desired communication partner, it contacts the location service and requests for the communication. FCC–geo location databases are used to receive the location information of CRN nodes. This routing scheme incurs low control overhead.

2.5.2 Routing algorithm

Users start to follow the routing algorithm discussed in this section in order to communicate with other users. The core of algorithm looks for the minimum value of metric between neighboring nodes of source and destination. The metric used here is the distance. And based on this metric value, corresponding neighbor node will be selected as a next source node. This process is continued till the actual destination is reached.

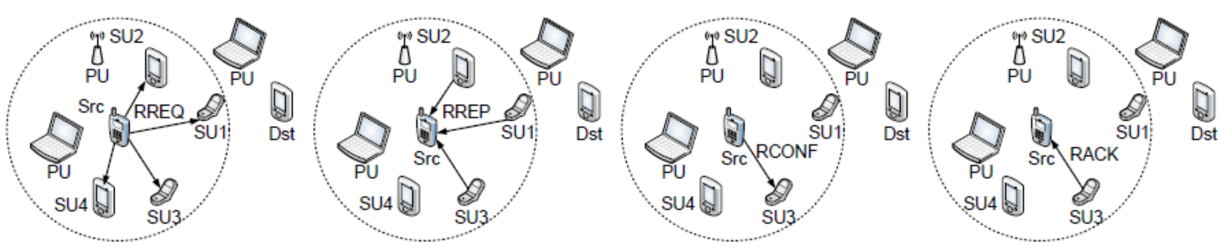


Figure 2.6: Operation of Reference model 2 [7]

When a node wants to select one of its neighbors for packet forwarding, it sends RREQ packets to all neighbor nodes as shown in Figure 2.6. Neighbor node sends route reply RREP with distance between destination node and itself. Upon reception of RREP requesting node selects next-hop based on minimum distance value. It then sends route confirmation RCONF message to next-hop neighbor node. Next-hop node sends route acknowledgement (RACK) packet for confirmation. The process continues till destination is reached. The algorithm is described by the flow chart mentioned below.

2.5.2.1 Flow chart

Routing algorithm consists of various steps which includes, sending routing requests to all the neighbors, getting routing replies from them, selecting valid node as a next source node, getting a confirmation from the next hop nodes and repeating this procedure till destination is reached.

2.5.2.1.1 Step 1: Initializing the system variables.

In this preliminary step, system variables such as path, srcNode and destNode are initialized. Status of all the nodes is set to 'available'.

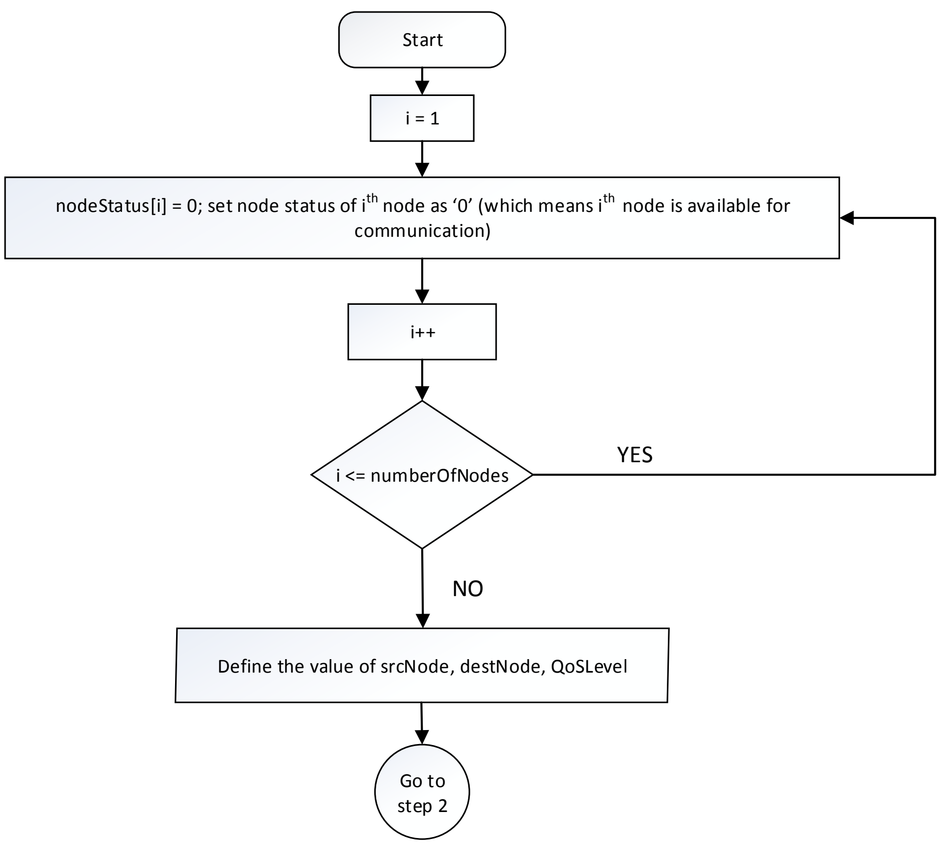


Figure 2.7: Step 1: Initialization of system variables

2.5.2.1.2 Step 2: discovering route to destination.

Source node broadcasts the routing request to all its neighbors. The request consists of 'destNodeId' of destination node, 'srcNodeId' of its own and 'timeStamp' information. Upon reception of routing request, each neighbor node sends route reply back to source node with distance between neighbor node and destination. When source node receives reply packet from neighbor nodes, it sends route confirmation request to a neighbor with minimum distance to destination. If next-hop agrees, it transmits route acknowledge packet to confirm on being as a next-hop, else it simply denies the request and source node selects sub-sequent next-hop with minimum metric value. Above process is repeated till destination is reached. Detailed flow graph is mentioned in Figure 2.8.

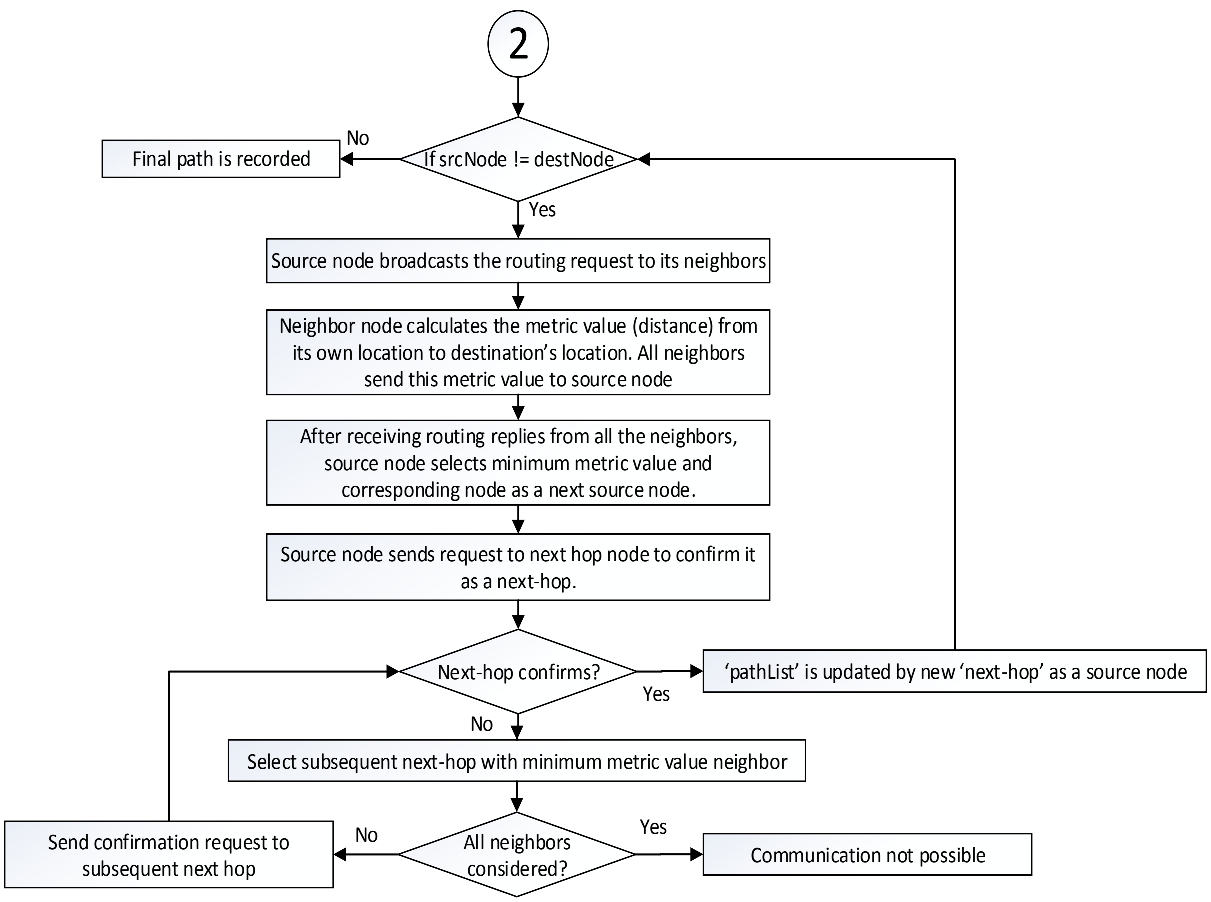


Figure 2.8: Step 2: discovering route to destination

2.5.3 Impediments/catches

Routing technique selects the neighbor as a next-hop which is closer to destination node; it stands as greedy forwarding of packets. Because of this it may consume more end to end transmission power than our model discussed in next chapter. Moreover it incurs initial delay in route set up. If neighbors to source nodes are more in number then amount of broadcasting messages exchanged are more. Even though it incurs less control overhead, sometimes route to destination is not reachable. This is as good as packet being lost before it reaches to destination. In addition this routing scheme requires routing algorithm to be implemented at each intermediate node.

In order to explain it, we carried out an experiment where we again considered 3 different scenarios with 10 different networks each. In each scenario, we look for percentage number of time destination is not reachable from different source nodes.

Figure 2.9 indicates for Scenario 1, out of all combinations of source and destination pairs, approximately 11% of time destination is not reachable for all QoS Levels. It is as good as a packet lost before reaching to the destination node. Similarly, Figure 2.9 also shows the result for Scenarios 2 and 3.

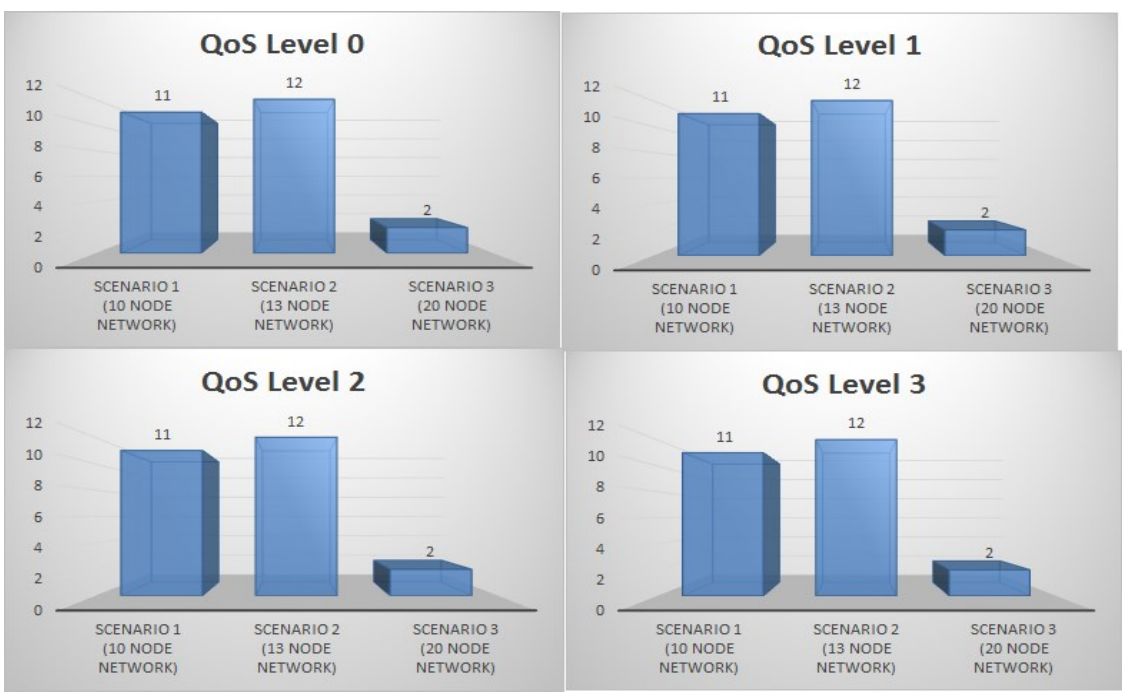


Figure 2.9: Percentage number of times destination is not reachable from source node

2.6 Summary

In this Chapter we described routing mechanisms proposed in literature with their metrics and catches. There is a need to overcome these impediments. We need to design a profile exchange mechanism that makes use of location information of nodes in the network to reduce the traffic (information exchange) overhead, number of control messages exchanged, delay in route discovery and can estimate the path before sending data packets to destination through intermediate nodes which may help to reduce the packet losses in the network. Such a model which makes use of salient features and functionalities of profile exchange and location aiding while keeping the functionality of SU simpler is explored in next Chapter.

Chapter 3
System Model

In this chapter, system QoS levels and their mathematical implementations in our model, system segments and roadmap, pseudo code and flow chart of our proposed route management algorithm are described. Eventually, packet flow details are discussed with an example.

3.1 System QoS

Quality of service is a measure of the ability of network and systems to provide different levels of services during communication set up. Clients that deploy such networks or systems have to invest in QoS capabilities so as to achieve better performance during communication. In CRN networks, a SU demands for a specific QoS level from PU. PU in turn searches from its channels and selects only those that can satisfy the SU's requirement of QoS. There are four different system QoS metrics considered which are named as QoSX; where X = 0, 1, 2 and 3. Table 3.1 indicates the significance of each QoSX.

System QoS	Significance
QoS0	Distance (D) between each and every other node in the network If distance between source and destination is more the power transmission level used for communication will be higher. It may lead to interference with other node's communication and decrease battery life of nodes.
QoS1	$PROB_K$ (probability of channel availability) If channel used for communication has maximum probability of channel availability then queuing delay incurred during communication will be less.
QoS2	$PROB_{PU}$ (probability of PU presence) If channel used for communication has minimum probability of PU presence then it maintains stability in communication because if PU makes its presence then SU has to release the allocated resources to PU and this hinders the communication in progress.
QoS3	$PROB_{link}$ (probability of link failure) If channel used for communication has minimum probability of link failure then number of retransmissions will be lower to convey the information

Table 3.1: System QoSX

3.2 List of QoS levels in the model

In our model, four different levels of QoS (QoSLevelX where X=0, 1, 2 and 3) are defined that include end to end transmission power, channel availability, PU presence and link robustness as metrics.

- QoSLevel0 contains:
  - End to end distance (QoS0 => D)
- QoSLevel1 contains:
  - End to end distance (QoS0 => D)
  - Channel availability (QoS1 => $PROB_K$)
- QoSLevel2 contains:
  - End to end distance (QoS0 => D)
  - Channel availability (QoS1 => $PROB_K$)
  - PU presence (QoS2 => $PROB_{PU}$)
- QoSLevel3 contains:
  - End to end distance (QoS0 => D)
  - Channel availability (QoS1 => $PROB_K$)
  - PU presence (QoS2 => $PROB_{PU}$)
  - Link robustness (QoS3 => $PROB_{link}$)

As seen from above, as we progress to higher levels of QoS, lower level of QoS makes its presence automatically with increase in cost of resources. Significance of each QoS level and mathematical implementation of these levels in our model is discussed in detail in next subsections. Here we assume that different QoS metrics have equal weights assigned within each QoS level (Equation 3.2, 3.3, 3.6). However, different weights may be assigned to each QoS metric based on network requirements.

3.2.1 QoSLevel0 – f (Distance)

QoSLevel0 stands for route with minimum end to end transmission power (E2ETxP) utilization. End to end transmission power is directly proportional to the square of the distance 'D' between source and destination node (Equation 4.1), which means, if distance between source and destination is more the power transmission level used to communicate with destination will be higher. It may lead to serious issues like interference of signals and may degrade the performance of network. In order to tackle this issue, if a SU requests for QoSLevel0 for communication then system looks for a route with minimum end to end distance.

$$\text{QoSLevel0} = \text{D} \tag{3.1}$$

Our objective is to minimize Equation 3.1. Hence, if a SU requests QoSLevel0, then PU searches through the system and allocates a path that has minimum end to end distance.

3.2.2 QoSLevel1 – f (Distance, $PROB_K$)

QoSLevel1 incorporates functionality of level 0 along with its own. Apart from distance, system looks for the channels that have maximum probability of channel availability ($PROB_K$). In CRN network, users are expected to experience wide variety of delays. Probability of channel availability is considered as one of the metrics in QoS to control delay. If channel used for communication has maximum probability of channel availability then delay incurred during communication will be less. So, if a SU requests for QoSLevel1 for communication then system looks for a route with minimum end to end distance and maximum end to end probability of channel availability.

$$\text{QoSLevel1} = \text{D} + \frac{1}{\text{PROB}_\text{K}} \tag{3.2}$$

Our objective is to minimize QoSLevel1. Hence, if a SU requests QoSLevel1, then PU searches through the system and allocates a path that has min(QoSLevel1).

3.2.3 QoSLevel2 – f (Distance, $PROB_K$, $PROB_{PU}$)

QoSLevel2 incorporates functionality of levels 0 and 1, along with its own. Apart from distance and channel availability, system looks for the channels that have minimum probability of PU presence ($PROB_{PU}$). According to cognitive radio functionality, if PU makes its presence then SU has to release the allocated resources to PU. This hinders the communication and leads to packet loss. In order to maintain the stability of service, system has to consider the PU presence. So, if a SU requests for QoSLevel2 for communication then system looks for a route with minimum end to end distance, maximum probability of channel availability and minimum probability of PU present.

$$\text{QoSLevel2} = D + \left(\frac{1}{\text{PROB}_K} * \text{PROB}_{PU}\right) \quad (3.3)$$

Our objective is to minimize QoSLevel2. Hence, if a SU requests QoSLevel2, then PU searches through the system and allocates a path that has min(QoSLevel2).

3.2.4 QoSLevel 3 – f (Distance, $PROB_K$, $PROB_{PU}$, $PROB_{link}$)

QoSLevel3 incorporates functionality of levels 0, 1 and 2, along with its own. Apart from distance, channel availability and PU presence, system looks for the channels that have minimum probability of link failure ($PROB_{link}$) or minimum value of Expected Transmission Count (ETX). ETX is a measure of quality of path between source and destination nodes and it indicates number of transmissions of packets and it includes retransmissions as well. So, if probability of link failure is lower, number of retransmissions will be lower. And hence, ETX will be lower (Equation 3.4) and throughput of the communication will be higher (Equation 3.5).

$$ETX \approx \frac{1}{(1-\text{PROB}_{\text{link}})} \quad (3.4)$$

$$Throughput \approx \frac{1}{\text{ETX}} \quad (3.5)$$

So, if a SU requests for QoSLevel3 for communication then system looks for a route with minimum end to end distance, maximum probability of channel availability, minimum probability of PU presence and minimum ETX as indicated in Equation 3.6.

$$\text{QoSLevel3} = D + \left(\frac{1}{\text{PROB}_K} * \text{PROB}_{PU} * \text{PROB}_{\text{link}}\right) \quad (3.6)$$

Our objective is to minimize QoSLevel3. Hence, if a SU requests QoSLevel3, then PU searches through the system and allocates a path that has min(QoSLevel3).

3.3 System components and their roles

In this section important system components are mentioned which eventually form the basic building block in information exchange, route management and communication link set up.

3.3.1 Primary user (PU)

Base station handovers channels to the primary user. Once channels are allocated to PU, it maintains Channel Property Table (CPT) where $channel_{ID}$ is the primary key to access CPT. CPT contains 'channelMetrics' which are various QoS values such as probability of channel availability '$PROB_K$', probability of PU presence '$PROB_{PU}$', and probability of link failure '$PROB_{link}$' for each '$channel_{ID}$' the unique ID assigned to the channel. For example, if base station assigns 'K' number of channels to PU, then CPT prepared by PU will look something like Table 3.2.

This CPT is sent to central entity 'CE' which is discussed in the coming subsection. According to CRN technique, if PU is not using the channels then it is allocated to secondary user for specific duration of time as on demand.

$Channel_{id}$	$PROB_K$	$PROB_{PU}$	$PROB_{link}$
1	$PROB_{K1}$	$PROB_{PU1}$	$PROB_{L1}$
…	…	…	…
K	$PROB_{KK}$	$PROB_{PUK}$	$PROB_{LK}$

Table 3.2: CPT prepared by PU

3.3.2 Secondary user (SU)

In CRN network, SU senses the channels allocated to PU and if any channel is detected as idle, SU lists such channels along with certain assets such as PU_{id}, and [$neighbor_{id}$, $channel_{id}$] pair. This list is termed as Spectrum Sensing Matrix (SSM). For example, consider a network scenario, where nodes 'A', 'B', 'C', 'D', 'E' and 'F' are secondary users connected as in Figure 3.1 and SSM prepared by each node is tabulated in Tables 3.3-3.8.

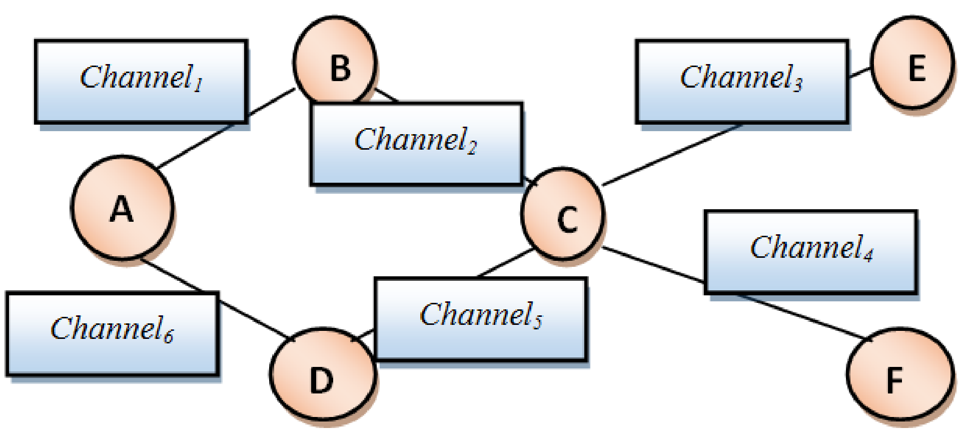


Figure 3.1: Sample network scenario to explain how SSM is prepared

$node_{id}$	PU_{id}	$[neighbor_{id}, channel_{id}]$ pair
A	PU_1	[B, $channel_1$]
	PU_1	[D, $channel_6$]

Table 3.3: SSM prepared by 'A' in the N/W

$node_{id}$	PU_{id}	$[neighbor_{id}, channel_{id}]$ pair
B	PU_1	[A, $channel_1$]
	PU_1	[C, $channel_2$]

Table 3.4: SSM prepared by 'B' in the N/W

$node_{id}$	PU_{id}	$[neighbor_{id}, channel_{id}]$ pair
C	PU_1	[B, $channel_2$]
	PU_1	[D, $channel_5$]
	PU_1	[E, $channel_3$]
	PU_1	[F, $channel_4$]

Table 3.5: SSM prepared by 'C' in the N/W

$node_{id}$	PU_{id}	$[neighbor_{id}, channel_{id}]$ pair
D	PU_1	[A, $channel_6$]
	PU_1	[C, $channel_5$]

Table 3.6: SSM prepared by 'D' in the N/W

$node_{id}$	PU_{id}	$[neighbor_{id}, channel_{id}]$ pair
E	PU_1	[C, $channel_3$]

Table 3.7: SSM prepared by 'E' in the N/W

$node_{id}$	PU_{id}	$[neighbor_{id}, channel_{id}]$ pair
F	PU_1	[C, $channel_4$]

Table 3.8: SSM prepared by 'F' in the N/W

Any node can act as a source node, destination node or an intermediate node in the network. Each node sends its own SSM to central entity (CE) which is discussed in the next subsection.

3.3.3 Central Entity (CE)

In our model, central entity (CE) operates as a server which accepts information packets from SUs and PUs in the network. Based on the received information and location aided service, it prepares 'neighborNode' table, 'QoSLevel0' table, 'QoSLevel1' table, 'QoSLevel2' table, 'QoSLevel3' table and finally the 'precedingNodeX' table for each QoS level as shown in Figure 3.2.

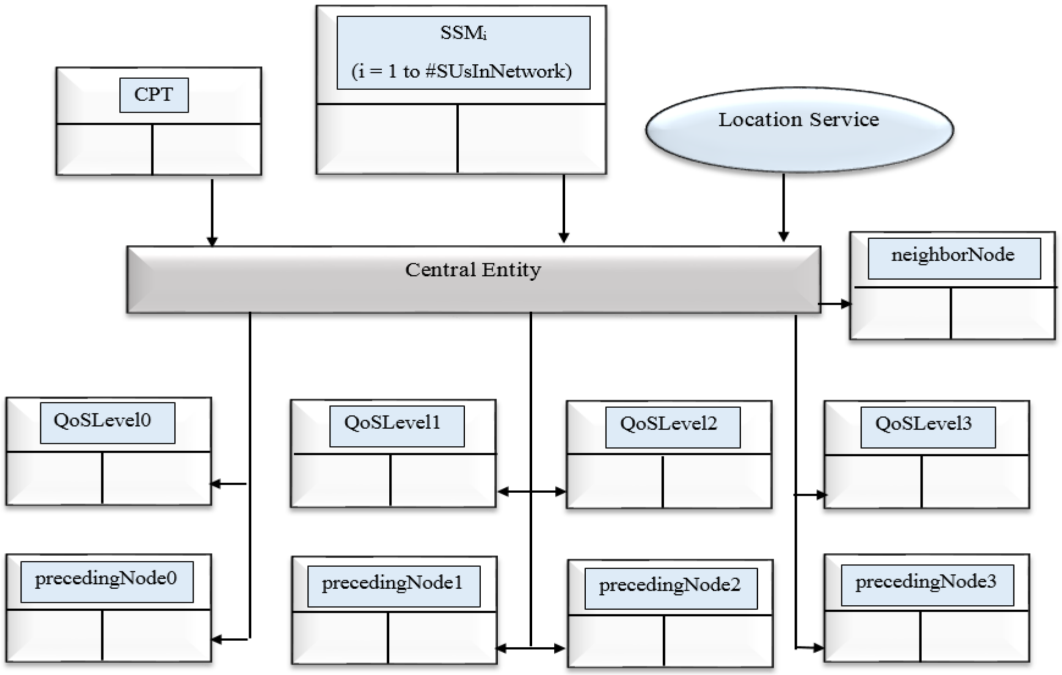
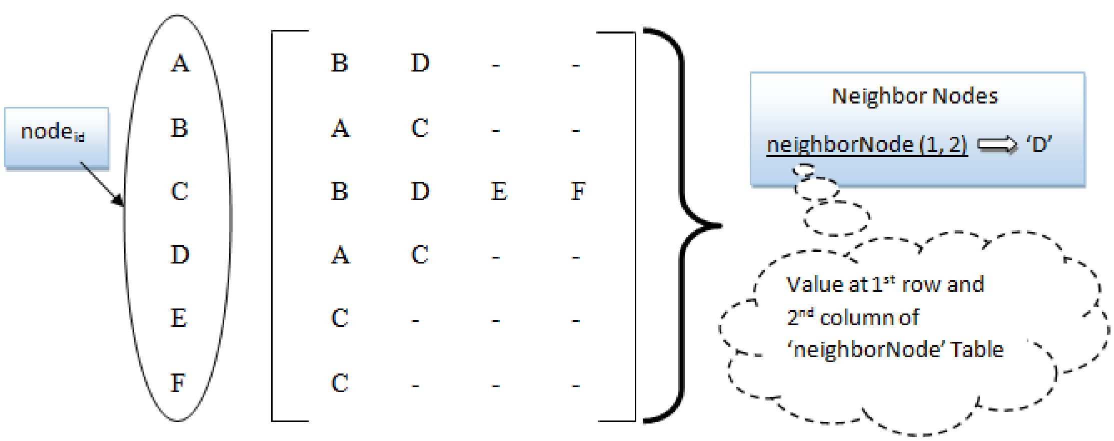


Figure 3.2: Central entity's operations

The 'neighborNode' table is constructed by 'CE' based on SSM received from SUs and it consists of node entries and their corresponding neighbor node$_{id}$. Table 3.9 illustrates 'neighborNode' table for sample example scenario in Figure 3.1.



node$_{id}$				
A	B	D	-	-
B	A	C	-	-
C	B	D	E	F
D	A	C	-	-
E	C	-	-	-
F	C	-	-	-

Table 3.9: 'neighborNode' table for sample network scenario

Based on received 'SSM' and 'CPT' at an instant, CE prepares table for all the QoS levels (QoSLevelX where X= 0 to 3). Tables 3.10 – 3.13 illustrate different QoS levels.

$node_{id}$	A	B	C	D	E	F
A	-	$QL0_{AB}=D_{AB}$	-	$QL0_{AD}=D_{AD}$	-	-
B	$QL0_{AB}=D_{AB}$	-	$QL0_{BC}=D_{BC}$	-	-	-
C	-	$QL0_{BC}=D_{BC}$	-	$QL0_{CD}=D_{CD}$	$QL0_{CE}=D_{CE}$	$QL0_{CF}=D_{CF}$
D	$QL0_{AD}=D_{AD}$	-	$QL0_{CD}=D_{CD}$	-	-	-
E	-	-	$QL0_{CE}=D_{CE}$	-	-	-
F	-	-	$QL0_{CF}=D_{CF}$	-	-	-

Table 3.10: QoSLevel0 table prepared by CE

As seen from Table 3.10, QoSLevel0 represents distance between neighboring nodes. E.g. as per the Equation 3.1, $QoSLevel0_{AB} = QL0_{AB} = QoS0_{AB} = D_{AB}$ (distance between node A and node B).

$node_{id}$	A	B	C	D	E	F
A	-	$QL1_{AB}=D_{AB}+[1/PROB_{K(AB)}]$	-	$QL1_{AD}$	-	-
B	$QL1_{AB}$	-	$QL1_{BC}$	-	-	-
C	-	$QL1_{BC}$	-	$QL1_{CD}$	$QL1_{CE}$	$QL1_{CF}$
D	$QL1_{AD}$	-	$QL1_{CD}$	-	-	-
E	-	-	$QL1_{CE}$	-	-	-
F	-	-	$QL1_{CF}$	-	-	-

Table 3.11: QoSLevel1 table prepared by CE

As seen from Table 3.11, QoSLevel1 is a function of distance (D) and probability of channel availability ($PROB_K$) between neighboring nodes. E.g. as per the Equation 3.2, $QoSLevel1_{AB}$ can be calculated by CE as below.

$$QoSLevel1_{AB} = QL1_{AB} = QoS0_{AB} + (1/QoS1_{AB}) = D_{AB} + [1/PROB_{K\,(AB)}]$$

As seen from Table 3.12, QoSLevel2 is a function of distance (D), probability of channel availability ($PROB_K$) and probability of PU presence ($PROB_{PU}$) between neighboring nodes. E.g. as per the Equation 3.3, $QoSLevel2_{AB}$ can be calculated by CE as below.

$$QoSLevel2_{AB} = QL2_{AB} = QoS0_{AB} + (QoS2_{AB}/QoS1_{AB}) = D_{AB} + [PROB_{PU\,(AB)}/PROB_{K\,(AB)}]$$

node$_{id}$	A	B	C	D	E	F
A	-	$QL2_{AB} = D_{AB} + [PROB_{PU\,(AB)}/PROB_{K\,(AB)}]$	-	$QL2_{AD}$	-	-
B	$QL2_{AB}$	-	$QL2_{BC}$	-	-	-
C	-	$QL2_{BC}$	-	$QL2_{CD}$	$QL2_{CE}$	$QL2_{CF}$
D	$QL2_{AD}$	-	$QL2_{CD}$	-	-	-
E	-	-	$QL2_{CE}$	-	-	-
F	-	-	$QL2_{CF}$	-	-	-

Table 3.12: QoSLevel2 table prepared by CE

As seen from Table 3.13, QoSLevel3 is a function of distance (D), probability of channel availability ($PROB_K$), probability of PU presence ($PROB_{PU}$) and probability of link failure ($PROB_{link}$) between neighboring nodes. E.g. as per the Equation 3.4, $QoSLevel3_{AB}$ can be calculated by CE as below.

$$QoSLevel3_{AB} = QL3_{AB} = QoS0_{AB} + (QoS2_{AB}/QoS1_{AB})*QoS3_{AB} = D_{AB} + [\{PROB_{PU\,(AB)} / PROB_{K\,(AB)}\} * PROB_{link}]$$

node$_{id}$	A	B	C	D	E	F
A	-	$QL3_{AB} = D_{AB} + [\{PROB_{PU\,(AB)} / PROB_{K\,(AB)}\} * PROB_{link}]$	-	$QL3_{AD}$	-	-
B	$QL3_{AB}$	-	$QL3_{BC}$	-	-	-
C	-	$QL3_{BC}$	-	$QL3_{CD}$	$QL3_{CE}$	$QL3_{CF}$
D	$QL3_{AD}$	-	$QL3_{CD}$	-	-	-
E	-	-	$QL3_{CE}$	-	-	-
F	-	-	$QL3_{CF}$	-	-	-

Table 3.13: QoSLevel3 table prepared by CE

Once CE is done with table preparation it actually starts executing the routing management algorithm (explained in next section) and finally, based on the results of management algorithm, it prepares 'precedingNodeX' tables which highlights the intermediate nodes to reach every possible destination. We will discuss in detail the route management algorithm and creation of 'precedingNodeX' tables in the next section.

3.4 System Roadmap

In the previous section, we discussed the functionalities and roles of system components such as PU, SU and CE. In this section, we will combine these components to examine how the entire system will work. Entire model with preliminary stage which includes, creating 'CPT', 'SSM' and sending them to CE, preparing 'neighborNode', 'QoSLevel' tables and then route management algorithm with pseudo code, flow chart with simple example is discussed. And eventually, data and control packet details are discussed in brief.

3.4.1 Atomic system workflow

As we have discussed before, PU, SU and CE form the basic building blocks of the system. The messages exchanged between these segments are shown in Figure 3.3. PU prepares CPT and sends it to central entity. Similarly, SUs prepares SSM and sends it to CE. Once, CE receives CPT and SSM, it prepares tables for 'neighborNode', 'QoSLevel0, 1, 2 & 3' and 'precedingNode0, 1, 2 & 3'.

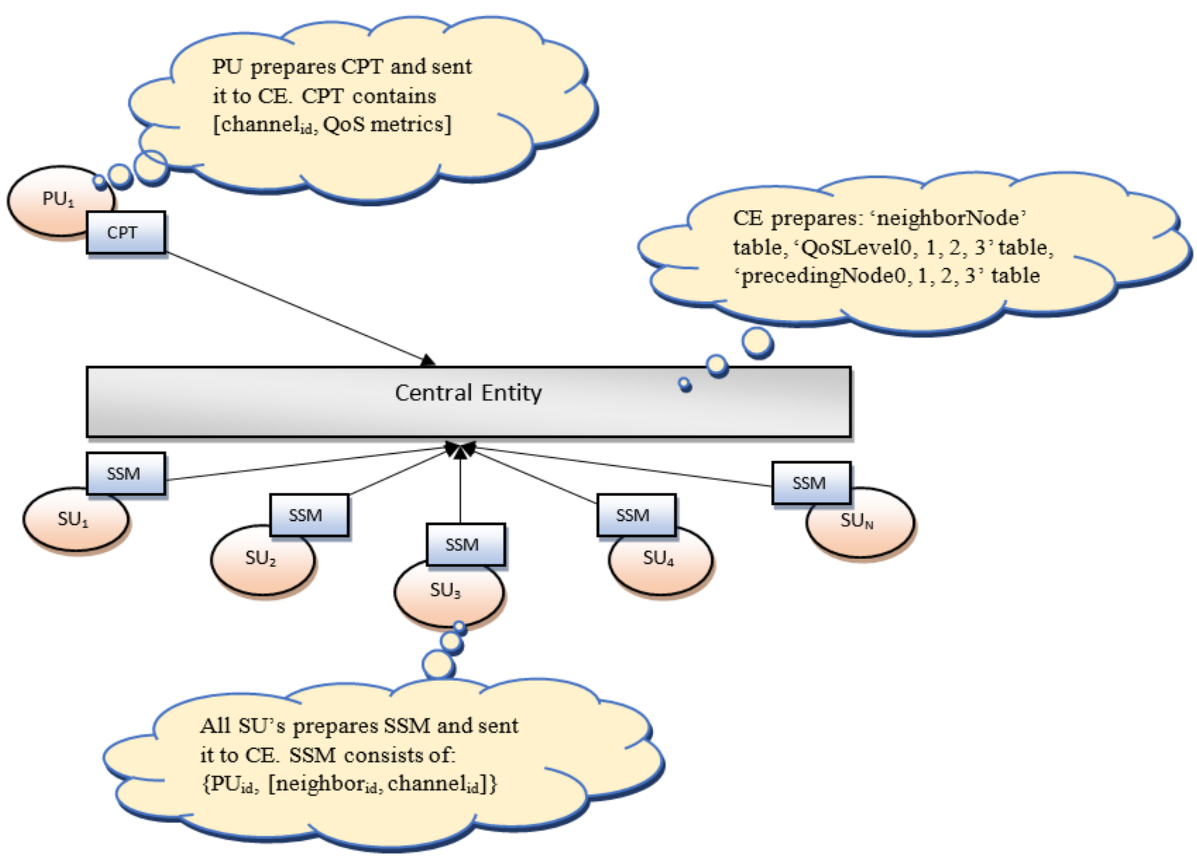


Figure 3.3: Atomic system model

3.4.2 System model stages

The system roadmap is divided into three stages. Preliminary stage includes creating CPT, SSM by PU and SUs respectively and where CE prepares its own tables. In the first stage, CE executes routing algorithm and prepares 'precedingNodeX' tables for every node in the network. In the second stage, actual packet level communication is established with exchange of control and data packets.

3.4.2.1 Preliminary stage: Profile Exchange and building tables

In this stage, PU prepares CPT. CPT consists of [$channel_{id}$, various QoS metric values] and various QoS metrics include $PROB_K$, $PROB_{PU}$ and $PROB_{link}$. CPT is sent to central entity (CE). On the other hand, each SU prepares SSM {PU_{id}, [$neighbor_{id}$, $channel_{id}$]} and sent it to CE. Upon reception of CPT and SSM, CE starts building its own tables which include 'neighborNode', 'QoSLevel0, 1, 2 & 3' and 'precedingNode0, 1, 2 & 3' tables that support in delivering route management. Pseudo code and flow chart (Figure 3.4) are presented in next sub-sections 3.4.2.1.1 and 3.4.2.1.2.

3.4.2.1.1 Pseudo code

Preliminary Stage

Parameters:

a. N: Total number of channels allocated to PU.
b. M: Total number of SUs.
c. CPT [$channel_{idj}$, $PROB_{Kj}$, $PROB_{PUj}$, $PROB_{linkj}$]: Channel property list of j^{th} channel which contains $channel_{id}$, probability of channel availability, PU presence and link failure.
d. SSM_i [PU_{id}, {$neighbor_{id}$, $channel_{id}$}]: Spectrum sensing matrix prepared by i^{th} SU in the network and it contains id of PU, neighbor and channel.
e. neighborNode: Table prepared by Central entity which contains list of neighbors for each node in the network.
f. QoSLevel0, QoSLevel1, QoSLevel2 and QoSLevel3: Tables that make use of QoS parameters such as distance, probability of channel availability, probability of PU presence and probability of link failure between neighboring nodes respectively.

```
1   Base station allocates the spectrum channels to PU with channel_id = [1, 2, ... , N]
2   /* PU activity (prepare CPT and send it to CE). CPT Table is prepared at the end of step 6 */
3   For j = 1 to N
4           prepare CPT [channel_idj, PROB_Kj, PROB_PUj, PROB_linkj] ;
5   End For
6   PU send CPT table to Central Entity. // End of PU activity
7   /* SU activity → prepare SSM and send it to CE */
8   SU [i = 1, 2, 3... M] senses the channels present between neighbors.
9   // SSM table is prepared by all SUs in the network and sent to CE.
10  For i = 1 to M
11          prepare SSM_i [PU_id, {neighbor_id, channel_id}] for SU_i
12          SU_i sends prepared SSM_i to CE
13  End For // End of SU activity
14  /* CE activity → Receive CPT, SSM and prepare 'neighborNode', 'QoSLevel0','QoSLevel1',
    'QoSLevel2' and 'QoSLevel3' tables. */
15  // prepare 'neighborNode' table.
16  For i = 1 to M
17          prepare neighborNode (i, :) table for each node in the network.
18  End For
19  // prepare 'QoSLevel0', 'QoSLevel1', 'QoSLevel2' and 'QoSLevel3' tables.
20  For i = 1 to M
21                  For j = 1 to M
22                          QoSLevel0[i,j] = D_(ij); //distance between node ‘i’ and ‘j’.
23                          QoSLevel1[i,j] = D_(ij)+ (1/PROB_K(ij));
24                          QoSLevel2[i,j] = D_(ij)+ [(PROB_PU(ij) /PROB_K(ij))];
25                          QoSLevel3[i,j] = D_(ij)+ [(PROB_PU(ij) /PROB_K(ij))*PROB_link (ij)];
26                  End For
27  End For// End of CE activity
```

3.4.2.1.2 Flow chart

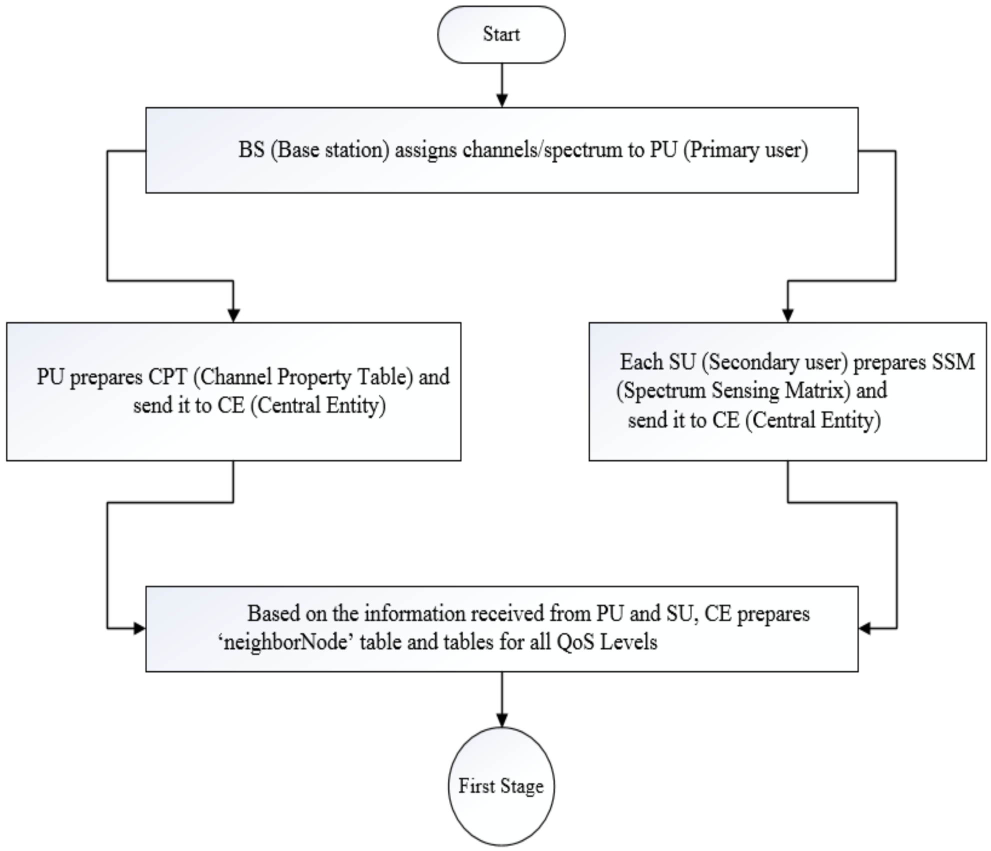


Figure 3.4: Preliminary stage

3.4.2.2 First stage: Route Management

Once, preliminary stage is over, system progresses towards first stage which consists of executing an actual route management algorithm. In this subsection we present our route management algorithm, pseudo code and flow chart for detailed explanation.

3.4.2.2.1 Route Management Algorithm

In this stage, based on the information from preliminary stage, CE commences route management algorithm.

Step 1: CE prepares 'edge' table which includes all possible edges in the network. In order to prepare 'edge' table, CE makes use of 'neighborNode' table. Consider Table 3.9 for example from which CE can build 'edge' table as in Table 3.14. From Table 3.14, CE decides that between nodes 'A' and 'B', link is present and it can easily identify the id of channel present in between this edge from 'SSM' received.

$node_{id}$	$neighborNode_{id}$
A	B
A	D
B	A
B	C
C	B
C	D
C	E
C	F
D	A
D	C
E	C
F	C

Table 3.14: 'edge' table for sample network scenario mentioned in Figure 3.1

<u>Step 2</u>: CE prepares initial 'headValue' and '$precedingNode_{srcNode}$' lists for a specific QoS level of length equal to the number of nodes in the network (numberOfNodes). At the index of source node (srcNode) which is called as 'srcNodeIndex', CE stores a value of '0'; otherwise it stores a value of 'Inf' in the 'headValue' list. '$precedingNode_{srcNode}$' is initialized to a value of '0'. Consider the sample example network scenario (Figure 3.1) and assume that 'srcNode' is 'A', then 'headValue', '$precedingNode_{srcNode}$' lists are as presented in Table 3.15.

$node_{id}$	A (srcNode)	B	C	D	E	F
headValue	0 (srcNodeIndex)	Inf	Inf	Inf	Inf	Inf
$precedingNode_{A}$	0	0	0	0	0	0

Table 3.15: Initial 'headValue' list for srcNode 'A'

In the next step, CE examines each row of 'edge' table one by one and simultaneously it investigates the following condition.

Condition:

$headValue(edge(\text{neighborNode}_{\text{id}})) > headValue(edge(\text{node}_{\text{id}}))$

$+ QoSLevelX_{edge(\text{nodeid})edge(\text{neighborNodeid})}$

Where, $QoSLevelX_{edge(\text{nodeid})edge(\text{neighborNodeid})}$= value of QoSLevelX present between $edge(\text{node}_{\text{id}})$ and $edge(\text{neighborNode}_{\text{id}})$ as obtained from Tables 3.10 – 3.13. E.g. if CE is at the first row of 'edge' table where $edge(\text{node}_{\text{id}})$ = 'A' and $edge(\text{neighborNode}_{\text{id}})$ = 'B'. And if user is in need of QoSLevel1 then the above condition can be re-written as below:

- ➔ headValue(B) > headValue(A) + $QoSLevel1_{AB}$
- ➔ Inf > 0 + $QL1_{AB}$; from Table 3.11 and Table 3.15.

If the condition is 'true' then 'headValue' and '$precedingNode_{srcNode}$' table is updated with new value otherwise it is kept as it was before. Value assigned to update the 'headValue' and '$precedingNode_{srcNode}$' table is as presented below.

Updating value:

$headValue(edge(\text{neighborNode}_{\text{id}}))= headValue(edge(\text{node}_{\text{id}}))$

$+ QoSLevelX_{edge(\text{nodeid})edge(\text{neighborNodeid})};$

$precedingNodeX(edge(\text{neighborNode}_{\text{id}})) = edge(\text{node}_{\text{id}});$

As in above example, condition is 'true', hence the updated value is: $QL1_{AB}$ and updated 'headValue' and '$precedingNode_{srcNode}$' list is as in Table 3.16.

$node_{id}$	A (srcNode)	B	C	D	E	F
headValue	0 (srcNodeIndex)	$QL1_{AB}$	Inf	Inf	Inf	Inf
$precedingNode_A$	0	A	0	0	0	0

Table 3.16: updated 'headValue' and 'precedingNode1' table for QoSLevel1

Finally, all the edges in Table 3.14 are considered and path based on the required QoS Level is obtained from source node to every other node in the network. For sample network scenario

(Figure 3.1), if source node is ‘A’ and required QoS level is ‘QoSLevel1’ then source node A entry in ‘precedingNode1’ table is denoted by ‘$precedingNode_A$’ and is listed as in Table 3.17.

$node_{id}$	A (srcNode)	B	C	D	E	F
headValue	0	$QL1_{AB}$	$(QL1_{AB} + QL1_{BC})$ **OR** $(QL1_{AD} + QL1_{DC})$	$QL1_{AD}$	$(QL1_{AB} + QL1_{BC} + QL1_{CE})$ **OR** $(QL1_{AD} + QL1_{DC} + QL1_{CE})$	$(QL1_{AB} + QL1_{BC} + QL1_{CF})$ **OR** $(QL1_{AD} + QL1_{DC} + QL1_{CF})$
$precedingNode_A$	0	A	B **OR** D	A	C	C

Table 3.17: $precedingNode_A$ entry in precedingNode1 table for QoSLevel1

From ‘$precedingNode_A$’ entry it can be clear that we can reach to destination node ‘C’, either through intermediate node ‘B’ or ‘D’ based on min value between ($QL1_{AB} + QL1_{BC}$, $QL1_{AD} + QL1_{DC}$).

Step 3: Steps 1 and 2 are repeated for all the nodes in the network considering them as ‘srcNode’. Finally, CE combines all the ‘$precedingNode_{srcNode}$’ entries in a single table and name it as a ‘precedingNodeX’ table.

If we consider the sample network scenario, the prepared ‘precedingNode’ table will be as presented in Table 3.18.

srcNode	precedingNodeX
A	$precedingNode_A$
B	$precedingNode_B$
C	$precedingNode_C$
D	$precedingNode_D$
E	$precedingNode_E$
F	$precedingNode_F$

Table 3.18: ‘precedingNodeX’ table for sample network scenario for QoSLevelX

3.4.2.2.2 Pseudo code

Route Management

---

1. Parameters:
    a. ‘numberOfNodes’: total number of nodes (SUs) in the network.
    b. P: Indicates number of neighbors for specific node in network.
    c. ‘actualLengthOfNeighbor []’: An array that contains count on number of neighbors for each node (SUs) in the network.
    d. ‘edge’: Table that contains all the edges in the network.
    e. ‘srcNode’: source node.
    f. ‘headValue []’: An array that contains weights on each node for the current srcNode.
    g. ‘precedingNodeX[i, :]’: A matrix that contains preceding node values for all the nodes in the network for QoSLevelX. And hence, i vary from 1 to numberOfNodes.
    h. QoSLevelX; where X = 0, 1, 2 and 3. QoSLevelX tables as generated in preliminary stage.
    i. neighborNode: Table as generated in preliminary stage.

```
2.  //Preparation of 'edge' table.
3.  count = 0;
4.  For i = 1 to numberOfNodes
5.  P = actualLengthOfNeighbor(i);
6.          For j = 1 to P
7.                  count++;
8.                  edge(count,1) = i;
9.                  edge(count,2) = neighborNode(i, j);
10.         End For
11. End For
12. // Preparation of ‘headValue’ array and ‘precedingNode’ Table
```

```
13. i = 1; //Set the value of i. It indicates node_id is '1'
14. While ( i < = numberOfNodes)        // run → step 14 to 36 otherwise step 37;
15.     srcNode = i;
16. // Initialize 'headValue' and 'precedingNode' for the srcNode
17.     precedingNodeX[i, :] = zeros(1, numberOfNodes);
18.         For j = 1 to numberOfNodes
19.                 if (j = = srcNode)
20.                         headValue(j) = '0';
21.                 Else
22.                         headValue(j) = 'Inf';
23.                 End If
24.         End For
25. //Update 'headValue' and 'precedingNode'
26.     For m = 1 to  numberOfNodes
27.         For j = 1 to length(edge) // number of rows in 'edge' table (total edges in the network)
28.                 If ( headValue(edge(j, 2) ) > headValue( edge(j, 1) ) +
                                                 QoSLevelX edge (j, 1) edge (j, 2))
29.                     // Update headValue if condition is TRUE
30.                     headValue(edge(j, 2)) = headValue(edge(j, 1) ) +
                                                 QoSLevelX edge (j, 1) edge (j, 2)
31.                    // Update precedingNode table if condition is TRUE
32.                     precedingNodeX[i, edge(j, 2)] = edge(j, 1);
33.                 End If
34.         End For
35.     End For
36. End While
37. // CE prepares final 'precedingNode' table for all the nodes in the network.
```

3.4.2.2.3 Flow chart

Flow chart in Figure (3.5-a) indicates the step 1 in First stage. It includes initialization of 'headValue' and 'precedingNode' table.

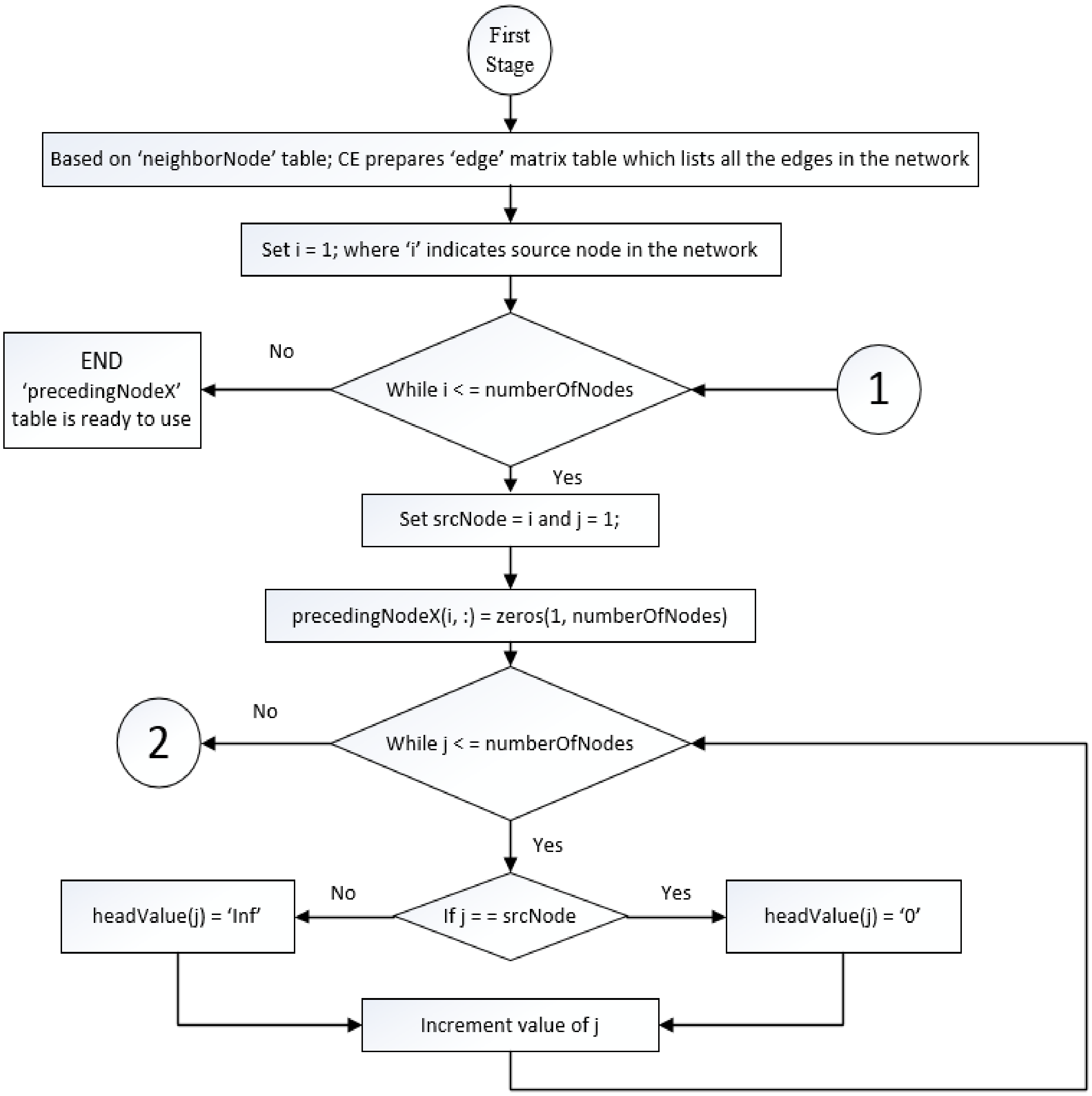


Figure 3.5-a: First Stage: Initialization of 'headValue' and 'precedingNode' table

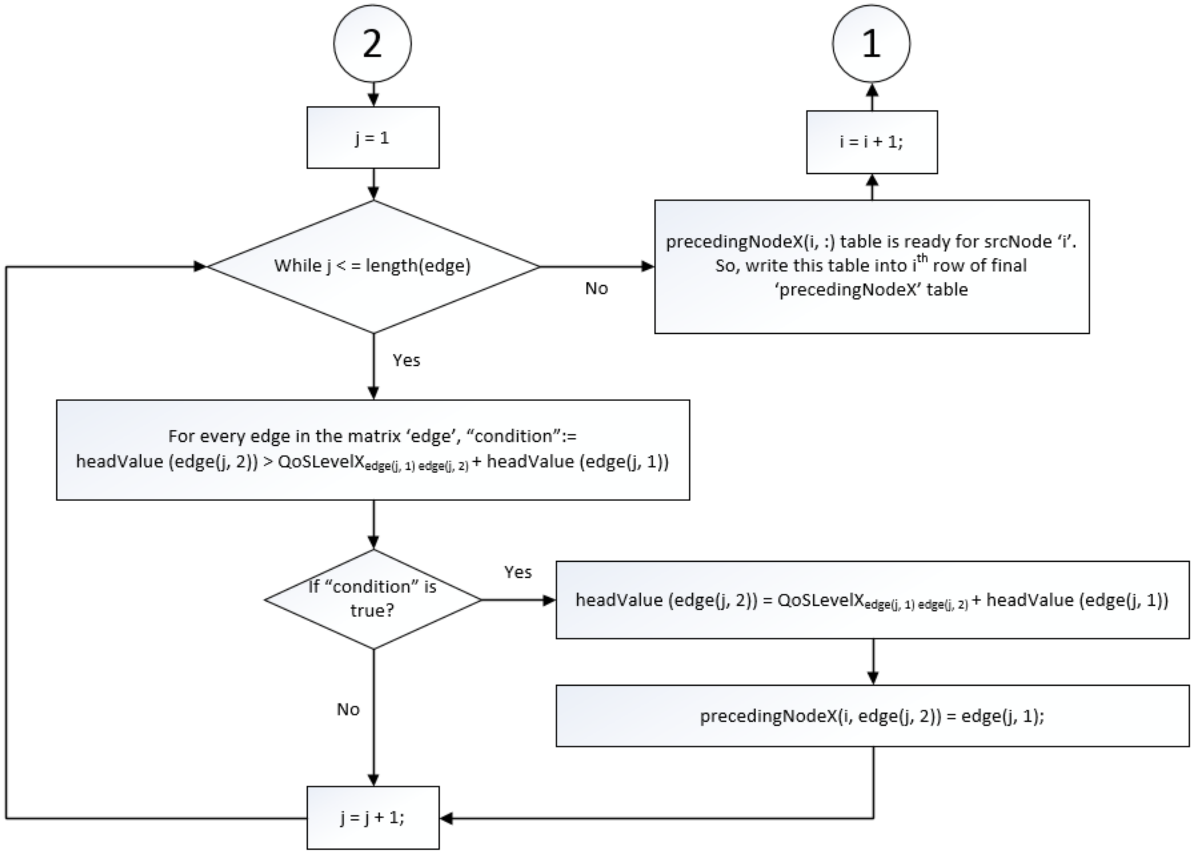


Figure 3.5-b: First stage: building 'headValue' and 'precedingNode' table for srcNode

Figure 3.5-b indicates the step 2 for each source node in First stage which is repeated for the number of nodes in the network to build the 'precedingNodeX' table for the source node. We repeat steps 1 and 2 for all other source nodes in the network. It includes building 'headValue' and 'precedingNodeX' table for all the nodes in the network.

3.4.2.3 Second stage: Packet level communication

In this stage, actual packet level communication is established with exchange of control and data packets among users. This section is subdivided into two subsections mainly for sending control packets (R_{REQ}, R_{REPLY}) and forwarding & receiving the data packets. Eventually, flow chart illustrates when the node has to send, receive and forward data packets.

3.4.2.3.1 Sending R_{REQ} (control) packets

As shown in Figure 3.6, if srcNode A wants to communicate with destNode E, node A prepares a R_{REQ} packet and sends it to Central Entity (CE).

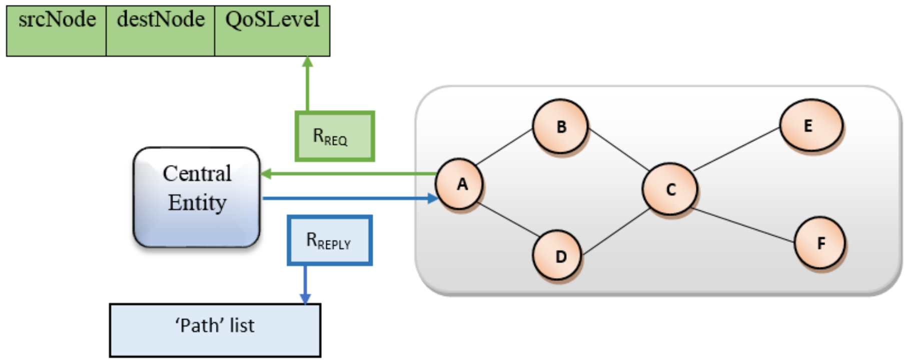


Figure 3.6: Exchange of Control Packets between srcNode and Central Entity

R_{REQ} packet consists of 3 fields:

I. *srcNode:* It indicates the $node_{id}$ which is willing to establish a connection with destination node.

II. *destNode:* It indicates the $node_{id}$ to which srcNode wants to communicate.

III. *QoSLevel:* This field indicates one of the four levels of QoS with which 'srcNode' wants to communicate to 'destNode'.

3.4.2.3.2 Sending R_{REPLY} (control) packet

Once, CE receives the R_{REQ} packet, it extracts 'srcNode' field and compares with the first column 'srcNode' of 'precedingNodeX' table for QoSLevelX requested (Table 3.18). And once, it locates the 'srcNode' in the table, CE selects that row to analyze the route to 'destNode'. It is explained in Figure 3.7 in brief for source node 'A' and destination node 'E' with QoSLevel1. Assume, list stored inside the '$precedingNode_A$' consists of ['0', 'A', 'B', 'A', 'C', 'C'] (Table 3.17). As explained in Figure 3.8, CE tracks the path based on '$precedingNode_A$', and returns the 'Path' list to source node.

We define 'ReversePath' list to store path from destination to source. Initially it is set to an empty list. It gets updated when CE traces the precedingNode table from destination towards source.

- Destination E finds C as a preceding node and ReversePath list updated as {E, C}
- Node C finds B as a preceding node and ReversePath list updated as {E, C, B}
- Node B finds A as a preceding node and ReversePath list updated as {E, C, B, A}

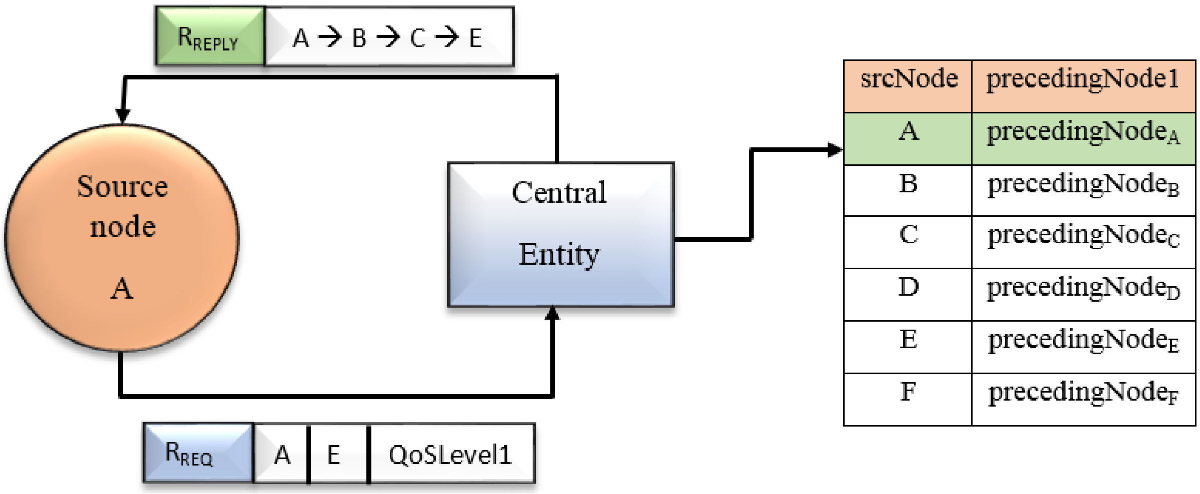


Figure 3.7: How CE reacts after receiving R_{REQ} packets

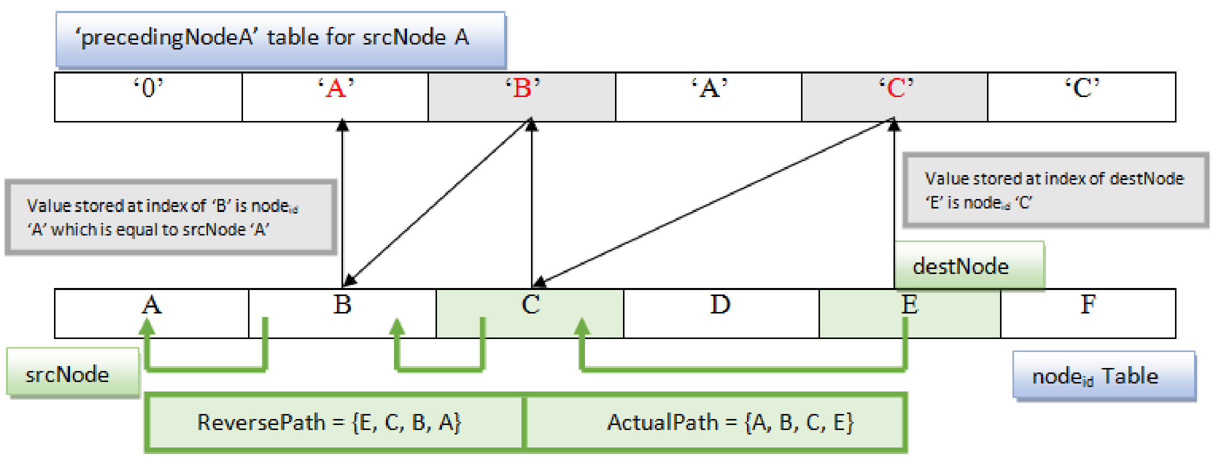


Figure 3.8: How CE finds the ActualPath after receiving R_{REQ} packets

Once the source node is reached, the tracing process terminates. 'Path' list is the nodes in the reverse order of 'ReversePath' list as shown in Table 3.19. If path to destination is not possible then CE puts 'Null' for 'Path' list.

srcNode	destNode	'Path' list
A	E	{A, B, C, E}

Table 3.19: R_{REPLY} from CE to srcNode

3.4.2.3.3 Transmitting data packets

When srcNode receives packet to transmit, it checks the length of ‘Path’ list. If it is zero the process of sending the data packets is not initiated. Therefore, no resources are consumed at all. But if length of ‘Path’ list is not zero then the source node initiates sending of the packets whereas the intermediate nodes forward and destination node receives data packets.

3.5 Complexity analysis

In this section, we discuss complexity of the routing algorithm studied for the two reference models and for our model as well. In reference model 1 (Figure 2.2), each SU sends its profile to all sensed PUs. PU exchanges received profiles with other PUs in the network. Updated information is conveyed back to every SU. If any SU requests for any connection to a specific destination, the search will be processed by PU. Suppose we consider a network of ‘N’ SUs and a single PU then number of messages exchanged between PU and SUs will be O(N).

In reference model 2 (Figure 2.6), source node sends routing requests to all the neighbors, which send route reply RREP messages with distance between destination node and itself. Upon reception of RREP, requesting node selects next-hop based on minimum distance value. It then sends route confirmation RCONF message to next-hop neighbor node. Next-hop node sends route acknowledgement (RACK) packet for confirmation. The process continues till destination is reached. Suppose we have a network of ‘N’ SUs and each SU has certain neighbor nodes denoted by ‘neighborNode’ and ‘hopCount’ indicates number of hops in the route, then number of messages exchanged during route selection can be given approximately as ‘hopCount * neighborNode ’ which is complexity of second order.

In our model, SU sends spectrum sensing table and PU sends channel property table to central entity and central entity prepares routing table based on the information received. Suppose we have ‘N’ number of SUs and single PU in the network then number of messages exchanged for creating route table will be O(N). This is done just once before any communication between nodes. Whenever any source node wants to communicate with other nodes in the network, it sends one route request to central entity and central entity replies back with the route. During this route request, number of messages exchanged is O(1).

With respect to memory usage, our model requires N*N entries in the Central Entity, where N is number of SUs in the network. For each node in the network Central Entity prepares 1*N entries which help to determine route from source to destination. Hence, for N SUs, Central Entity prepares N*N entries for each QoS level. Increase in the number of SUs in the network will increase memory utilization as well as processing at the Central Entity level.

3.6 Summary

In this chapter, system QoS levels along with their mathematical implementations are listed. The system model stages and purpose of each stage is illustrated. The routing algorithm was presented with the help of pseudo code and flow chart. In the next chapter, the performance measures are presented through simulation for each level of QoS.

Chapter 4
Performance Measures

In this chapter, performance of all models at each level of QoS has been studied with an example. At each level of QoS, our model 3 is compared with other reference models. Eventually, chapter is concluded with the discussion on NS2 simulation environment, AWK scripting, simulation results and analysis.

4.1 Network Example Overview

In this section, overall network scenario is explained along with few important network parameters. Consider a network of 13 nodes as shown in Figure 4.1, which we will be using in subsequent sections to highlight the performance of all models under each level of QoS.

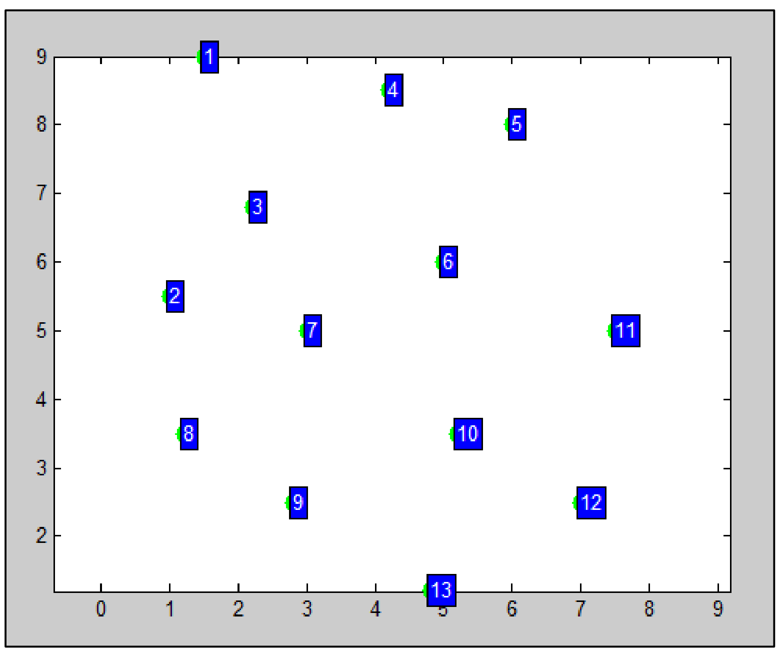


Figure 4.1: Network Scenario.

4.1.1 Network Parameters

Table 4.1 provides cognitive radio network parameters used. Radio range for each node is assumed to be 4 m; area of receiver antenna is 1 m^2, transmitter antenna gain (G_t) is 1 which is a constant and minimum received power (P_r) to be 100 mW. Minimum received power indicates the amount of power that must be received at the receiver node in order to communicate successfully whereas radio range indicates that any node can become a neighbor of other node if they are in the radio range of each other.

Parameters	Parameter Value
Radio Range of each node	4 m
Area of Receiver Antenna (A_r)	1 m^2
Transmitter Antenna Gain (G_t)	1
Min. received power (P_r)	100 mW

Table 4.1: Network parameters

4.1.2 Network node positions

Each node knows the position of every other node through location services; so that each node decides its own neighbor based on radio range. For simulation purposes, consider Table 4.2 which indicates the X and Y co-ordinates of nodes. These co-ordinates are generated randomly.

Node ID	X co-ordinate	Y co-ordinate
1	1.5	9.0
2	1.0	5.5
3	2.2	6.8
4	4.2	8.5
5	6.0	8.0
6	5.0	6.0
7	3.0	5.0
8	1.2	3.5
9	2.8	2.5
10	5.2	3.5
11	7.5	5.0
12	7.0	2.5
13	4.8	1.2

Table 4.2: Node positions X & Y co-ordinates

4.1.3 Neighbor node table

Based on node positions in the network and mentioned radio range, we can easily calculate the distance between available nodes and eventually, can prepare neighbor node entries for each node in the network as shown in Table 4.3.

Node ID	Neighbor Node IDs
1	2 3 4
2	1 3 7 8 9
3	1 2 4 5 6 7 8
4	1 3 5 6 7
5	3 4 6 11
6	3 4 5 7 10 11
7	2 3 4 6 8 9 10
8	2 3 7 9 10
9	2 7 8 10 13
10	6 7 8 9 11 12 13
11	5 6 10 12
12	10 11 13
13	9 10 12

Table 4.3: Neighbor nodes

4.1.4 Transmitted Power

We can calculate the transmitted power between two nodes with the help of known parameters as below.

$$\text{Transmitted Power } (P_t) = \frac{(4\pi) * {D_{ij}}^2 * P_r}{A_r * G_t} \quad (4.1)$$

Where,

D_{ij}: distance between node i and node j.

P_r: Minimum power needed to be received at the receiver node.

A_r: Area of receiver antenna.

G_t: Transmitter antenna gain.

According to Equation 4.1, transmitted power is directly proportional to square of the distance between the two nodes. As the distance between two nodes increases, transmitter node has to send the signal at a higher power level. We consider end to end power transmission as one of the QoS metric in routing.

4.1.5 QoS Metrics

In this section, we list the QoS values for all the levels. The significance of each QoS metric is mentioned in chapter 3 in detail.

4.1.5.1 *QoS0 (Distance)*

As we have discussed in previous chapters, QoS0 is used for distance metric. The values associated in QoS0 are calculated during run time depending upon the position of nodes in the network. So, based on node position and neighbor node table, we generated Table 4.4 as below that gives us the values for distance between neighbors.

Nodes	1	2	3	4	5	6	7	8	9	10	11	12	13
1	0	3.5355	2.3087	2.7459	4.6098	4.6098	4.2720	5.5082	6.6287	6.6287	7.2111	8.5147	8.4694
2	3.5355	0	1.7692	4.3863	5.5902	4.0311	2.0616	2.0100	3.4986	4.6519	6.5192	6.7082	5.7385
3	2.3087	1.7692	0	2.6249	3.9850	2.9120	1.9698	3.4482	4.3417	4.4598	5.5973	6.4444	6.1741
4	2.7459	4.3863	2.6249	0	1.8682	2.6249	3.7000	5.8310	6.1612	5.0990	4.8104	6.6212	7.3246
5	4.6098	5.5902	3.9850	1.8682	0	2.2361	4.2426	6.5795	6.3632	4.5706	3.3541	5.5902	6.9051
6	4.6098	4.0311	2.9120	2.6249	2.2361	0	2.2361	4.5486	4.1340	2.5080	2.6926	4.0311	4.8042
7	4.2720	2.0616	1.9698	3.700	4.2426	2.2361	0	2.3431	2.5080	2.6627	4.5000	4.7170	4.2048
8	505082	2.0100	3.4482	5.8310	6.5795	4.5486	2.3431	0	1.8868	4.0000	6.4761	5.8856	4.2720
9	6.6287	3.4986	4.3417	6.1612	6.3632	4.1340	2.5080	1.8868	0	2.6000	5.3235	4.2000	2.3854
10	6.6287	4.6519	4.4598	5.0990	4.5706	2.5080	2.6627	4.0000	2.6000	0	2.7459	2.0591	2.3345
11	7.2111	6.5192	5.5973	4.8104	3.3541	2.6926	4.5000	6.4761	5.3235	2.7459	0	2.5495	4.6615
12	8.5147	6.7082	6.4444	6.6212	5.5902	4.0311	4.7170	5.8856	4.2000	2.0591	2.5495	0	2.5554
13	8.4694	5.7385	6.1741	7.3246	6.9051	4.8042	4.2048	4.2720	2.3854	2.3345	4.6615	2.5554	0

Table 4.4: QoS0: Distance between nodes in the network

As the table indicates, for example distance between node 1 and 2 (D_{12}) is 3.5355 m.

4.1.5.2 *QoS1 (Probability of channel availability)*

QoS1 considers for probability of channel availability which is a property of the channel. The values of $PROB_K$ are tabulated in the Table 4.5 and are generated randomly. As the table indicates, probability of channel availability between node 1 and 2 ($PROB_{K12}$) is 0.2597.

Nodes	1	2	3	4	5	6	7	8	9	10	11	12	13
1	0	0.2597	0.2231	0.4378	0	0	0	0	0	0	0	0	0
2	0.2597	0	0.5445	0	0	0	0.8771	0.5550	0.2258	0	0	0	0
3	0.2231	0.5445	0	0.0251	0.5375	0.3613	0.6572	0.2584	0	0	0	0	0
4	0.4378	0	0.0251	0	0.1477	0.3300	0.8823	0	0	0	0	0	0
5	0	0	0.5375	0.1477	0	0.9477	0	0	0	0	0.2400	0	0
6	0	0	0.3613	0.3300	0.9477	0	0.8038	0	0	0.2309	0.3794	0	0
7	0	0.8771	0.6572	0.8823	0	0.8038	0	0.0963	0.5697	0.2094	0	0	0
8	0	0.5550	0.2584	0	0	0	0.0963	0	0.1107	0.2778	0	0	0
9	0	0.2258	0	0	0	0	0.5697	0.1107	0	0.6675	0	0	0.5024
10	0	0	0	0	0	0.2309	0.2094	0.2778	0.6675	0	0.5904	0.2575	0.3519
11	0	0	0	0	0.2400	0.3794	0	0	0	0.5904	0	0.7568	0
12	0	0	0	0	0	0	0	0	0	0.2575	0.7568	0	0.0986
13	0	0	0	0	0	0	0	0	0.5024	0.3519	0	0.0986	0

Table 4.5: QoS1: Probability of channel availability

4.1.5.3 *QoS2 (Probability of PU presence)*

QoS2 considers for probability of PU presence which is also a property of the channel. The values of $PROB_{PU}$ are tabulated in the Table 4.6 and are generated randomly. Lower the PU presence is, better the channel will be.

Nodes	1	2	3	4	5	6	7	8	9	10	11	12	13
1	0	0.9426	0.1364	0.8352	0	0	0	0	0	0	0	0	0
2	0.9426	0	0.0822	0	0	0	0.6602	0.6190	0.3670	0	0	0	0
3	0.1364	0.0822	0	0.1068	0.9264	0.4700	0.6454	0.4167	0	0	0	0	0
4	0.8352	0	0.1068	0	0.1029	0.2645	0.3352	0	0	0	0	0	0
5	0	0	0.9264	0.1029	0	0.0324	0	0	0	0	0.9276	0	0
6	0	0	0.4700	0.2645	0.0324	0	0.9231	0	0	0.0120	0.6860	0	0
7	0	0.6602	0.6454	0.3352	0	0.9231	0	0.1313	0.7788	0.2142	0	0	0
8	0	0.6190	0.4167	0	0	0	0.1313	0	0.6407	0.0971	0	0	0
9	0	0.3670	0	0	0	0	0.7788	0.6407	0	0.6127	0	0	0.3356
10	0	0	0	0	0	0.0120	0.2142	0.0971	0.6127	0	0.9621	0.4635	0.2067
11	0	0	0	0	0.9276	0.6860	0	0	0	0.9621	0	0.8028	0
12	0	0	0	0	0	0	0	0	0	0.4635	0.8028	0	0.1501
13	0	0	0	0	0	0	0	0	0.3356	0.2067	0	0.1501	0

Table 4.6: QoS2: Probability of PU presence.

4.1.5.4 *QoS3 (Probability of link failure)*

QoS3 considers for probability of link failure which is also a property of the channel itself. The values of $PROB_{link}$ are tabulated in Table 4.7 and are generated randomly. Lower the $PROB_{link}$ is, better the channel will be.

Nodes	1	2	3	4	5	6	7	8	9	10	11	12	13
1	0	0.6416	0.2602	0.5392	0	0	0	0	0	0	0	0	0
2	0.6416	0	0.5981	0	0	0	0.2780	0.4098	0.5678	0	0	0	0
3	0.2602	0.5981	0	0.7861	0.7491	0.0588	0.8972	0.3821	0	0	0	0	0
4	0.5392	0	0.7861	0	0.1270	0.2459	0.4270	0	0	0	0	0	0
5	0	0	0.7491	0.1270	0	0.9062	0	0	0	0	0.7630	0	0
6	0	0	0.0588	0.2459	0.9062	0	0.8667	0	0	0.1325	0.6989	0	0
7	0	0.2780	0.8972	0.4270	0	0.8667	0	0.6099	0.5902	0.9058	0	0	0
8	0	0.4098	0.3821	0	0	0	0.6099	0	0.0720	0.7828	0	0	0
9	0	0.5678	0	0	0	0	0.5902	0.0720	0	0.3438	0	0	0.5886
10	0	0	0	0	0	0.1325	0.9058	0.7828	0.3438	0	0.7813	0.3308	0.2622
11	0	0	0	0	0.7630	0.6989	0	0	0	0.7813	0	0.8031	0
12	0	0	0	0	0	0	0	0	0	0.3308	0.8031	0	0.3210
13	0	0	0	0	0	0	0	0	0.5886	0.2622	0	0.3210	0

Table 4.7: QoS3: Probability of link failure

In upcoming sections, we will look into performance of all models at each level of QoS with an example.

4.2 Performance Evaluation for QoS Level 0

As we have discussed earlier in Chapter 3, in QoS level 0, we consider power transmission between nodes as a metric for routing the packets. Only aim in this level is to route the packets in such a way that end to end distance and indirectly power transmission between source & destination nodes is minimal. In this section, we study the performance of all models against QoS level 0 for specific source and destination pair of the specimen network; and eventually, we compare our model with other models for all source and destination pairs in various networks.

4.2.1 Reference Model 1

As mentioned in chapter 3, reference model 1 will always search for next hop based on min {QoSLevelX}value between source node and its neighbor. As far as QoS level 0 is concerned; model 1 looks for next-hop based on min {Distance value} node. So, Node ‘A’ chooses a node ‘B’ as a next-hop if it is closer to node ‘A’ than any other node. This is explained in Table 4.8

with an example in which source node is node '1' and destination node is node '12'. Route from source node to destination node is obtained as shown in Figure 4.2.

Iteration No.	Source Node	Neighbors	Active Neighbors	Distance between source node and its neighbors	Next Source Node
1	1	[2,3,4]	[2,3,4]	[3.5355, 2.3087, 2.7459]	3
2	3	[1, 2, 4, 5, 6, 7, 8]	[2, 4, 5, 6, 7, 8]	[1.7692, 2.6249, 3.9850, 3.4482, 1.9698, 3.4482]	2
3	2	[1, 3, 7, 8, 9]	[7, 8, 9]	[2.0616,2.0100,3.4986]	8
4	8	[2, 3, 7, 9, 10]	[7, 9, 10]	[2.3431, 1.8868, 4.0000]	9
5	9	[2, 7,8, 10, 13]	[7, 10, 13]	[2.5080, 2.6000, 2.3854]	13
6	13	[9, 10, 12]	[10, 12]	[2.3345, 2.5554]	10
7	10	[6, 7, 8, 9, 11, 12, 13]	[6, 7, 11, 12]	[2.5080, 2.6627, 2.7459, 2.0591]	12

Table 4.8: Steps followed in reference model 1 under QoS Level 0

- Path selected = [1 → 3 → 2 → 8 → 9 → 13 → 10 → 12]
- No. of channels used: 7 : Represents min {distance} values.
- End to end power transmitted= 39.4886 Watt. : Represents nodes are inactive.

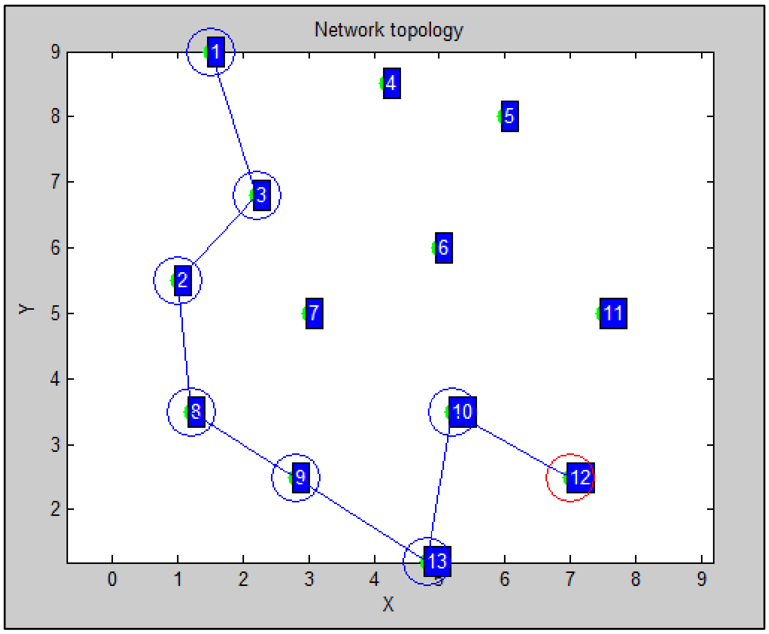


Figure 4.2: Route of Reference Model 1 under QoS Level 0

Advantage of this model is as packets are routed to next node which is at a minimum distance node transmits the packets at minimum power which increases the life time of the node's battery.

But it may lead to more channel or resource consumptions and sometimes route to destination is not reachable.

4.2.2 Reference Model 2

As mentioned in chapter 3, reference model 2 will search for next-hop based on the distance between neighbor node and destination node. This is explained in Table 4.9 with an example in which source node is node ‘1’ and destination node is node ‘12’ and route to destination is obtained as shown in Figure 4.3.

Iteration No.	Source Node	Neighbors	Active Neighbors	Distance between neighbor node and destination node	Next Source Node
1	1	[2,3,4]	[2,3,4]	[6.7082, 6.4444, 6.6212]	3
2	3	[1, 2, 4, 5, 6, 7, 8]	[2, 4, 5, 6, 7, 8]	[6.7082, 6.6212, 5.5902, 4.0311,4.7170, 5.8856]	6
3	6	[3, 4, 5, 7, 10, 11]	[4, 5, 7, 10, 11]	[6.6212, 5.5902, 4.7170, 2.0591, 2.5495]	10
4	10	[6, 7, 8, 9, 11, 12, 13]	[7, 8, 9, 11, 12, 13]	[4.7170, 5.8856, 4.2000, 2.5495, 0, 2.5554]	12

Table 4.9: Steps followed in reference model 2 under QoS Level 0

- Path selected = [1 → 3 →6→ 10 → 12]
- No. of channels used: 4
- End to end power transmitted= 30.5710 Watt.

■: Represents nodes are inactive.
■: Represents min {distance} values.

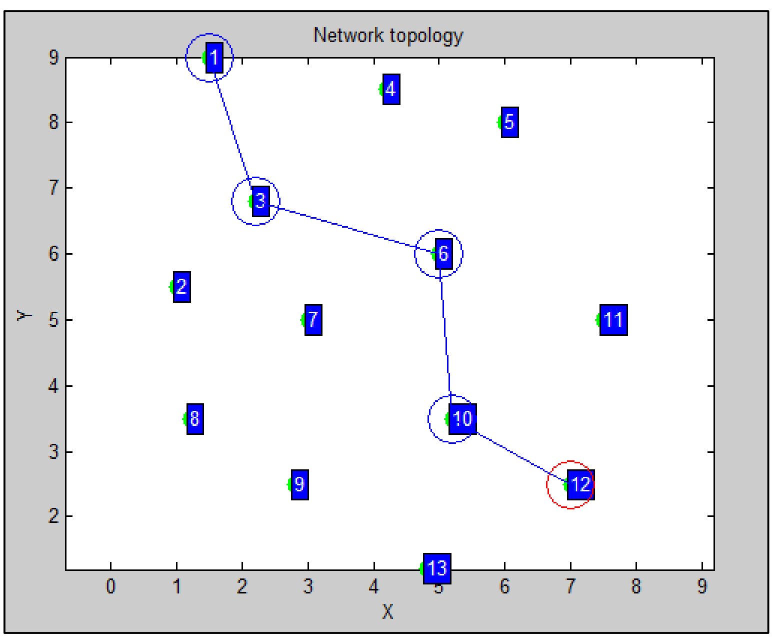


Figure 4.3: Route of Reference Model 2 under QoS Level 0

The advantage of this model over reference model 1 is, it uses less number of iterations, less resource consumptions and mainly, the end to end power transmission is less as compared to reference model 1. But this model has few drawbacks such as it may cause inter-channel interference because of greedy packet forwarding mechanism and most of the power is consumed in sending routing requests and reply between nodes. Hence, here comes a need to think of another model which considers the exact distance between source and destination.

4.2.3 Our Model 3

As mentioned in chapter 3, our model 3 will search for routing path based on the exact distance between source node and destination node. It follows all the stages mentioned in chapter 3 which includes; initially setting 'Head Value' to 'INF' on every node except for source node, checking the condition, updating the 'Head Value' on respective node and finally, maintaining and updating preceding node table. It is well explained with an example in which source node is node '1' and destination node is node '12'.

4.2.3.1 Initially setting the 'Head Values':

In the first stage, we set the head value on each node to 'INF' except for source node '1' as it is a source node. It is tabulated as in Table 4.10.

Node	1	2	3	4	5	6	7	8	9	10	11	12	13
headValue	0	INF	INF	INF	INF	INF	INF	INF	INF	INF	INF	INF	INF

Table 4.10: Head Value Table for each node

Initial 'PrecedingNode' Table 4.11 consists of all zeros for each node entry.

Node	1	2	3	4	5	6	7	8	9	10	11	12	13
PrecedingNode1	0	0	0	0	0	0	0	0	0	0	0	0	0

Table 4.11: Initial PrecedingNode values for each node in the network

4.2.3.2 Checking the condition, updating the 'Head values' and 'PrecedingNode' on respective nodes:

In this subsection, we are going to form a table at each iteration. And each iteration consists of certain tasks such as checking the QoS condition, updating the 'head value' on respective node and updating the preceding node table. Condition that we need to check at each iteration is stated as below.

Condition:

HeadValue (NeighborNodeID) > QoSLevelX(NeighborNodeID, NodeID) +

HeadValue(NodeID)

If this condition is 'TRUE' then we will update the 'HeadValue' by 'QoSLevelX(NeighborNodeID, NodeID) + HeadValue (NodeID)' on respective nodes. The 'PrecedingNode1' table is updated accordingly.

Iteration 1: For node ID '1':

NodeID	NeighborNodeID	HeadValue	Condition (TRUE/FALSE)	Update Needed? (YES/NO)	Updated HeadValue
1	2	INF	TRUE	YES	3.5355
1	3	INF	TRUE	YES	2.3087
1	4	INF	TRUE	YES	2.7459

Table 4.12: Table for NodeID '1'

As the table indicates, NodeID '1' has three neighbors (2, 3 and 4). HeadValue on each neighbor node is (INF, INF and INF) respectively. As the condition is true for each neighbor node, the 'HeadValue' is updated on respective nodes. The preceding node Table 4.11 is updated.

Node	1	2	3	4	5	6	7	8	9	10	11	12	13
PrecedingNode1	0	1	1	1	0	0	0	0	0	0	0	0	0

Table 4.13: Preceding node entry after Iteration #1

This preceding node entry in Table 4.13 indicates that after iteration #1, in order to reach from source node 1 to node 2, packet must reach to node 1 first. In this iteration, source node and preceding node value is same. We will go for next iterations in detail.

Iteration 2: For node ID '2':

NodeID	NeighborNodeID	HeadValue	Condition (TRUE/FALSE)	Update Needed? (YES/NO)	Updated HeadValue
2	1	0	FALSE	NO	0
2	3	2.3087	FALSE	NO	2.3087
2	7	INF	TRUE	YES	5.5971
2	8	INF	TRUE	YES	5.5455
2	9	INF	TRUE	YES	7.0341

Table 4.14: Table for NodeID '2'

Node	1	2	3	4	5	6	7	8	9	10	11	12	13
PrecedingNode1	0	1	1	1	0	0	2	2	2	0	0	0	0

Table 4.15: Preceding node entry after Iteration #2

Table 4.14 and Table 4.15 indicate that after iteration #2, in order to reach at node 7 from node 1, packet has to traverse total distance of 5.5971 m. And as preceding node to node 7 is node 2 and at node 2, preceding node is node 1; hence path traversed is 1 → 2 →7 after iteration 2. We will go to next iteration level to see the 'HeadValue' and 'PrecedingNode' value on each node.

Iteration 3: For node ID '3':

NodeID	NeighborNodeID	HeadValue	Condition (TRUE/FALSE)	Update Needed? (YES/NO)	Updated HeadValue
3	1	0	FALSE	NO	0
3	2	3.5355	FALSE	NO	3.5355
3	4	2.7459	FALSE	NO	2.7459
3	5	INF	TRUE	YES	6.2937
3	6	INF	TRUE	YES	5.2207
3	7	5.5971	TRUE	YES	4.2785
3	8	5.5455	FALSE	NO	5.5455

Table 4.16: Table for NodeID '3'

Node	1	2	3	4	5	6	7	8	9	10	11	12	13
PrecedingNode1	0	1	1	1	3	3	3	2	2	0	0	0	0

Table 4.17: Preceding node entry after Iteration #3

Table 4.16 and Table 4.17 indicate that after iteration #3, in order to reach at node 7 from node 1, packet has to traverse total distance of 4.2785 m. And as preceding node to node 7 is node 3 and at node 3, preceding node is node 1; hence path traversed is 1 →3 →7 after iteration 3. Note that path from node 1 to node 7 is updated from iteration #2 (1 →2 →7) to iteration #3 (1 →3 →7), we will go to next iteration level to see the 'HeadValue' and 'PrecedingNode' value on each node.

Iteration 4: For node ID '4':

NodeID	NeighborNodeID	HeadValue	Condition (TRUE/FALSE)	Update Needed? (YES/NO)	Updated HeadValue
4	1	0	FALSE	NO	0
4	3	2.3087	FALSE	NO	2.3087
4	5	6.2937	TRUE	YES	4.6141
4	6	5.2207	FALSE	NO	5.2207
4	7	4.2785	FALSE	NO	4.2785

Table 4.18: Table for NodeID '4'

Node	1	2	3	4	5	6	7	8	9	10	11	12	13
PrecedingNode1	0	1	1	1	4	3	3	2	2	0	0	0	0

Table 4.19: Preceding node entry after Iteration #4

Iteration 5: For node ID '5':

NodeID	NeighborNodeID	HeadValue	Condition (TRUE/FALSE)	Update Needed? (YES/NO)	Updated HeadValue
5	3	2.3087	FALSE	NO	2.3087
5	4	2.7459	FALSE	NO	2.7459
5	6	5.2207	FALSE	NO	5.2207
5	11	INF	TRUE	YES	7.9682

Table 4.20: Table for NodeID '5'

Node	1	2	3	4	5	6	7	8	9	10	11	12	13
PrecedingNode1	0	1	1	1	4	3	3	2	2	0	5	0	0

Table 4.21: Preceding node entry after Iteration #5

Iteration 6: For node ID '6':

NodeID	NeighborNodeID	HeadValue	Condition (TRUE/FALSE)	Update Needed? (YES/NO)	Updated HeadValue
6	3	2.3087	FALSE	NO	2.3087
6	4	2.7459	FALSE	NO	2.7459
6	5	4.6141	FALSE	NO	4.6141
6	7	4.2785	FALSE	NO	4.2785
6	10	INF	TRUE	YES	7.7287
6	11	7.9682	FALSE	NO	7.9682

Table 4.22: Table for NodeID '6'

Node	1	2	3	4	5	6	7	8	9	10	11	12	13
PrecedingNode1	0	1	1	1	4	3	3	2	2	6	5	0	0

Table 4.23: Preceding node entry after Iteration #6

Iteration 7: For node ID '7':

NodeID	NeighborNodeID	HeadValue	Condition (TRUE/FALSE)	Update Needed? (YES/NO)	Updated HeadValue
7	2	3.5355	FALSE	NO	3.5355
7	3	2.3087	FALSE	NO	2.3087
7	4	2.7459	FALSE	NO	2.7459
7	6	5.2207	FALSE	NO	5.2207
7	8	5.5455	FALSE	NO	5.5455
7	9	7.0341	TRUE	YES	6.7865
7	10	7.7287	TRUE	YES	6.9412

Table 4.24: Table for NodeID '7'

Node	1	2	3	4	5	6	7	8	9	10	11	12	13
PrecedingNode1	0	1	1	1	4	3	3	2	7	7	5	0	0

Table 4.25: Preceding node entry after Iteration #7

Iteration 8: For node ID ‘8’:

NodeID	NeighborNodeID	HeadValue	Condition (TRUE/FALSE)	Update Needed? (YES/NO)	Updated HeadValue
8	2	3.5355	FALSE	NO	3.5355
8	3	2.3087	FALSE	NO	2.3087
8	7	4.2785	FALSE	NO	4.2785
8	9	6.7865	FALSE	NO	6.7865
8	10	6.9412	FALSE	NO	6.9412

Table 4.26: Table for NodeID ‘8’

Node	1	2	3	4	5	6	7	8	9	10	11	12	13
PrecedingNode1	0	1	1	1	4	3	3	2	7	7	5	0	0

Table 4.27: Preceding node entry after Iteration #8

Iteration 9: For node ID ‘9’:

NodeID	NeighborNodeID	HeadValue	Condition (TRUE/FALSE)	Update Needed? (YES/NO)	Updated HeadValue
9	2	3.5355	FALSE	NO	3.5355
9	7	4.2785	FALSE	NO	4.2748
9	8	5.5455	FALSE	NO	5.5455
9	10	6.9412	FALSE	NO	6.9412
9	13	INF	TRUE	YES	9.1719

Table 4.28: Table for NodeID ‘9’

Node	1	2	3	4	5	6	7	8	9	10	11	12	13
PrecedingNode1	0	1	1	1	4	3	3	2	7	7	5	0	9

Table 4.29: Preceding node entry after Iteration #9

Iteration 10: For node ID '10':

NodeID	NeighborNodeID	HeadValue	Condition (TRUE/FALSE)	Update Needed? (YES/NO)	Updated HeadValue
10	6	5.2207	FALSE	NO	5.2207
10	7	4.2785	FALSE	NO	4.2785
10	8	5.5455	FALSE	NO	5.5455
10	9	6.7865	FALSE	NO	6.7865
10	11	7.9682	FALSE	NO	7.9682
10	12	INF	TRUE	YES	9.003
10	13	9.1719	FALSE	NO	9.1719

Table 4.30: Table for NodeID '10'

Node	1	2	3	4	5	6	7	8	9	10	11	12	13
PrecedingNode1	0	1	1	1	4	3	3	2	7	7	5	10	9

Table 4.31: Preceding node entry after Iteration #10

Iteration 11: For node ID '11':

NodeID	NeighborNodeID	HeadValue	Condition (TRUE/FALSE)	Update Needed? (YES/NO)	Updated HeadValue
11	5	4.6141	FALSE	NO	4.6141
11	6	5.2207	FALSE	NO	5.2207
11	10	6.9412	FALSE	NO	6.9412
11	12	9.003	FALSE	NO	9.003

Table 4.32: Table for NodeID '11'

Node	1	2	3	4	5	6	7	8	9	10	11	12	13
PrecedingNode1	0	1	1	1	4	3	3	2	7	7	5	10	9

Table 4.33: Preceding node entry after Iteration #11

Iteration 12: For node ID '12':

NodeID	NeighborNodeID	HeadValue	Condition (TRUE/FALSE)	Update Needed? (YES/NO)	Updated HeadValue
12	10	6.9412	FALSE	NO	6.9412
12	11	7.9682	FALSE	NO	7.9682
12	13	9.1719	FALSE	NO	9.1719

Table 4.34: Table for NodeID '12'

Node	1	2	3	4	5	6	7	8	9	10	11	12	13
PrecedingNode1	0	1	1	1	4	3	3	2	7	7	5	10	9

Table 4.35: Preceding node entry after Iteration #12

Iteration 13: For node ID '13':

NodeID	NeighborNodeID	HeadValue	Condition (TRUE/FALSE)	Update Needed? (YES/NO)	Updated HeadValue
13	9	6.7865	FALSE	NO	6.7865
13	10	6.9412	FALSE	NO	6.9412
13	12	9.003	FALSE	NO	9.003

Table 4.36: Table for NodeID '13'

Node	1	2	3	4	5	6	7	8	9	10	11	12	13
PrecedingNode1	0	1	1	1	4	3	3	2	7	7	5	10	9

Table 4.37: Preceding node entry after Iteration #13

Finally, each node, their 'HeadValue' and 'PrecedingNode' value is summarized in a single Table 4.38 as below.

Node	1	2	3	4	5	6	7	8	9	10	11	12	13
PrecedingNode1	0	1	1	1	4	3	3	2	7	7	5	10	9
HeadValue	0	3.5355	2.3087	2.7459	4.6141	5.2207	4.2785	5.5455	6.7865	6.9412	7.9682	9.003	9.1719

Table 4.38: HeadValue and PrecedingNode value for each node for QoS level 0

As Table 4.38 indicates, in order to reach destination node 12, we will check PrecedingNode value for node 12. As it is node 10, that means, we can reach to node 12 through node 10. Similarly, if we traverse back from destination node to source node, it is clear that path will be 1 →3 →7 →10 →12. And total distance traversed by packet will be the HeadValue on destination node 12 which is 9.003 m. The route to destination is obtained as shown is Figure 4.4

Hence, to conclude on Our Model 3:

- Path: 1 →3 →7→10 →12
- No. of channels used: 4.
- End to end transmission power: 25.7982 Watts

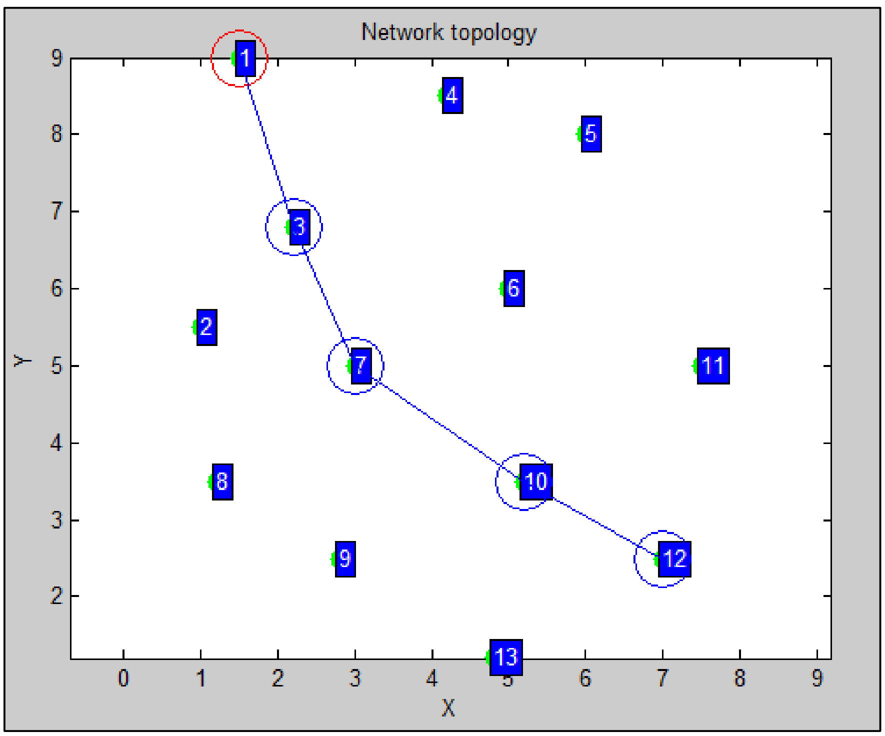


Figure 4.4: Route of our Model 3 under QoS Level 0

We see from the results of these 3 models, end to end power transmission is less in our model 3. Until now, we have seen only one sample example which elaborates how these different models work and effectiveness of model 3 over other models. In the next subsection, we consider the effectiveness of our model 3 for different source and destination combinations.

4.2.4 Comparison of Models 1, 2 and 3 for QoS Level 0

We have seen till now the methodology and how all the models work for only one source node and destination node in the network of 13 nodes. In our example, we have seen that how our model 3 works better (end to end transmission power) as compared to other models. But we need to check the effectiveness of our model 3 for each and every combination of source and destination node. For this reason, we have carried out few steps which are as below:

1. We consider 10 different networks where each network consists of 10 nodes. We repeat the same for 13 nodes and 20 nodes networks.
2. We calculate the end to end transmission power for all possible combinations of source node and destination node. E.g. for a network with 10 nodes, possible combinations of source and destination node is 90 and that for network with 20 nodes, possible combinations will be 380.
3. For all those different combinations of source and destination nodes, we compare the end to end transmission power for models 1, 2 and 3.
4. After this we calculate average percentage number of times our model 3 is better than models 1 and 2.

Figure 4.5 shows the comparison result of our model 3 as better than other two reference models.

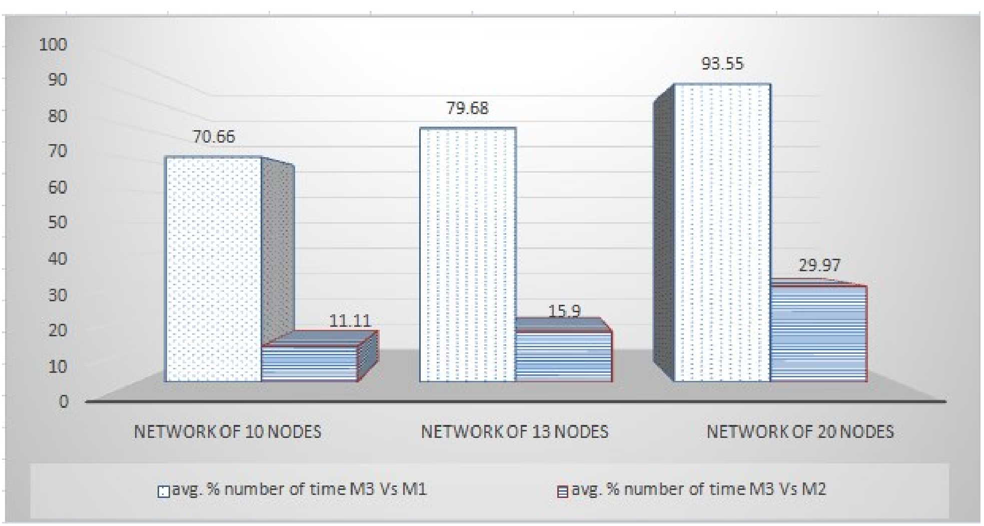


Figure 4.5: Average % number of times Our Model 3 is better than other reference models to achieve QoS Level 0

From Figure 4.5, we can say that, if we have 100 combinations of source and destination nodes then on an average 70 number of times we get better results in our model 3 than in reference model 1 and about on an average 11 number of times we received better results in model 3 than in reference model 2 for the network of 10 nodes. In the network of 13 nodes, model 3 is better than model 1 approximately 80% of the times and better than model 2 in approximately 16% of the times. In the network of 20 nodes, model 3 is better than model 1 in almost 94% cases and better than model 2 in approximately 30% cases.

Figure 4.5 only indicates the number of times our model 3 is better than 1 and 2 in the network of 10, 13 and 20 nodes. But it does not indicate the value by which it is better than another model. So for that we carried out another task. The steps included in this task are as below. For this task we again considered 10 different networks for a network of 10 nodes, 13 nodes and 20 nodes. Steps below are mentioned for network of 20 nodes and same steps will be followed for other networks too.

1. We consider a network of 20 nodes. For every single possible combination of source and destination node, we check whether model 3 provides better result than model 1 and 2. If the results are better, we move to second step otherwise next possible combination of source and destination pair is considered.
2. *Case a:* model 3 result is better than model 1: Average of percentage difference between end-to-end transmission power of model 3 and model 1 is calculated for all possible combinations of source and destination pairs where model 3 is better than model 1.

   % difference between end-to-end transmission power = $\frac{(Model\ 1\ Transmission\ power) - (Model\ 3\ Transmission\ power)}{(Model\ 1\ Transmission\ power)} * 100$

   Case b: model 3 result is better than model 2: we repeat the same procedure as mentioned for case 'a', and calculate the average percentage difference for end to end TX power for models 2 and 3.
3. Figure 4.6 shows average percentage difference of end-to-end transmission power in models 3 & 1, and similarly in models 3 & 2 for a network of 20 nodes.

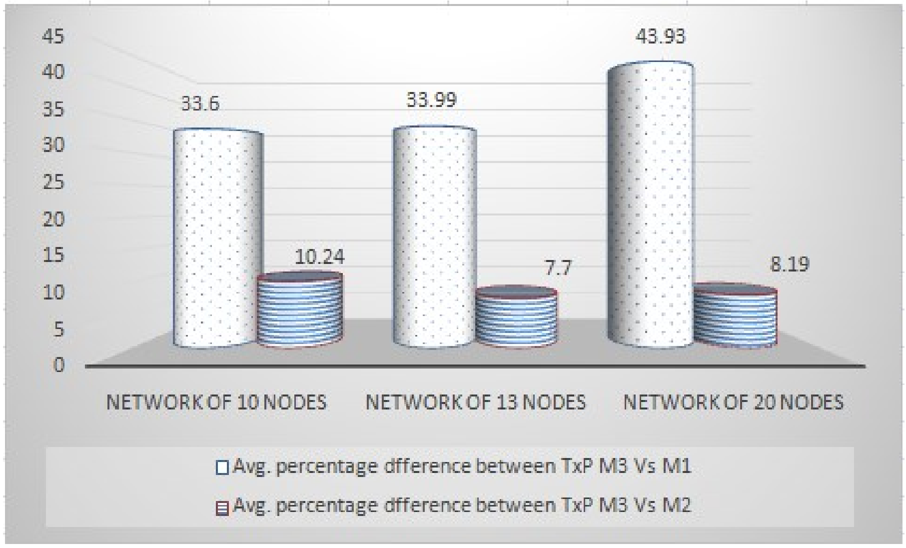


Figure 4.6: Average % difference between transmission power of Our Model 3 and other reference models for QoS Level 0

If the required end-to-end transmission power in model 1 and model 2 is 100 mW then in the network of 20 nodes, end-to-end transmission power in model 3 will be approximately 44 % less than model 1 (approximately 56 mW) and 8 % less than that of model 2 (approximately 92 mW). Same analogy can be used in case of the other two networks.

Next we compare reference models 1 and 2 with our model 3 in terms of reachability (route to destination exists) for different networks.

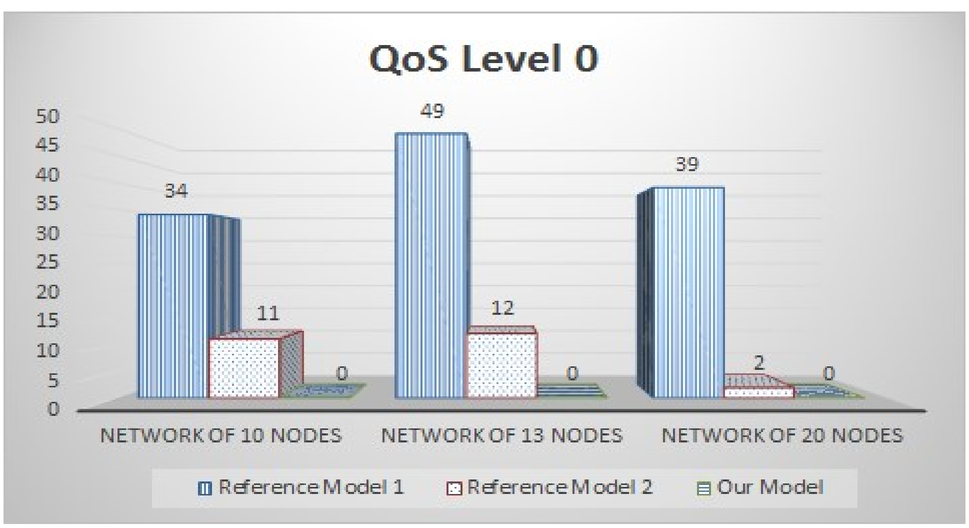


Figure 4.7: Percentage number of times destination is not reachable from source node for QoS Level 0

For each network as mentioned above, we look for percentage number of times destination is not reachable from different source nodes. Figure 4.7 indicates that, route to destination is always reachable in our model for QoSLevel0 assuming each node has at least one neighbor node in all the networks.

4.2.5 Summary

In this section, each model was discussed with an example under QoS level 0. Finally, all the models are compared to each other on the basis of end to end transmitted power. Comparison shows that our model performs better than other reference models.

4.3 Performance Evaluation for QoS Level 1

As mentioned earlier, in QoS level 1, we consider 'power transmission' and 'probability of channel availability' between nodes as a metric to route the packets such that 'end to end power transmission' between nodes is minimal and '$PROB_K$' is maximum. As path evaluation depends on 'Power Transmission' and '$PROB_K$', our algorithm will always look for min {QoSLevelX} and QoSLevelX for quality of service level 1 is calculated by formula mentioned in chapter 3. In this section, we study the performance of all models against QoS level 1 for specific source and destination pair of the network mentioned in Section 4.1; and eventually, we compare our model with other models for all source and destination pairs in various networks.

4.3.1 Reference Model 1

As mentioned in Chapter 3, reference model 1 will always search for next hop based on min {QoSLevelX} value between source node and its neighbor. As far as QoS level 1 is concerned; model 1 looks for next-hop based on min {QoSLevelX} value. This 'value' is summation of normalized distance and ($1/PROB_K$) where $PROB_K$ is probability of channel availability. This is explained with an example in which source node is node '4' and destination node is node '13'.The detailed explanation is presented in the form of Table 4.39.

Iteration No.	Source Node	Neighbors	Active Neighbors	Term 1	Term 2	Term 1 + Term 2	Next Source Node
				Normalized Distance between source node and its neighbors	1/(PROB$_K$ between source node and its neighbors)		
1	4	[1,3,5,6,7]	[1,3,5,6,7]	[0.3225, 0.3083, 0.2194, 0.3083, 0.4345]	[2.2841, 39.8406, 6.7705, 3.0303, 1.1334]	[2.6066, 40.1489, 6.9899, 3.3386, 1.5679]	7
2	7	[2,3,4,6,8,9,10]	[2,3,6,8,9,10]	[0.2421, 0.2313, 0.2626, 0.2752, 0.2945, 0.3127]	[1.1401, 1.5216, 1.2441, 10.3842, 1.7553, 4.7755]	[1.3822, 1.7529, 1.5067, 10.6594, 2.0498, 5.0882]	2
3	2	[1,3,7,8,9]	[1,3,8,9]	[0.4152, 0.2078, 0.2361, 0.4109]	[3.8506, 1.8365, 1.8018, 4.4287]	[4.2658, 2.0434, 2.0379, 4.8396]	8
4	8	[2,3,7,9,10]	[3,9,10]	[0.4050, 0.2216, 0.4698]	[3.8700, 9.0334, 3.5997]	[4.2750, 9.2550, 4.0695]	10
5	10	[6,7,8,9,11,12,13]	[6,9,11,12,13]	[0.2945, 0.3054, 0.3225, 0.2418, 0.2742]	[4.3309, 1.4981, 1.6938, 3.8835, 2.8417]	[4.6254, 1.8035, 2.0163, 4.1253, 3.1159]	9
6	9	[2,7,8,10,13]	[13]	[0.2801]	[1.9904]	[2.2705]	13

Table 4.39: Steps followed in reference model 1 under QoS Level 1

- Path: [4 → 7 → 2 → 8 → 10 → 9 → 13]
- No. of channel used: 6
- End-to-end transmission power: 63.3401 Watts.
- End to end probability of channel availability: 0.0400 = $PROB_{K(4,\ 7)}$ * $PROB_{K(7,\ 2)}$ * $PROB_{K(2,\ 8)}$ * $PROB_{K(8,\ 10)}$ * $PROB_{K(10,\ 9)}$ * $PROB_{K(9,\ 13)}$ (Calculated from Table 4.5)

■ : Represents nodes are not active.

■ : Minimum (Term 1 + Term 2).

4.3.2 Reference Model 2

Table 4.40 is described for reference model 2 with QoS level 1 based on the algorithm mentioned previously. This model searches for minimum 'distance' between neighbor node and destination node specified by the user. Once the path is found, end to end probability of channel availability is calculated. The detailed explanation is presented in the form of Table 4.40.

Iteration No.	Source Node	Neighbors	Active Neighbors	Term 1: Normalized Distance between neighbor and destination node	Next Source Node
1	4	[1,3,5,6,7]	[1,3,5,6,7]	[0.9947, 0.7251, 0.8110, 0.5642, 0.4938]	7
2	7	[2,3,4,6,8,9,10]	[2,3,6,8,9,10]	[0.6739, 0.7251, 0.5642, 0.5017 0.2801, 0.2742]	10
3	10	[6,7,8,9,11,12,13]	[6,8,9,11,12,13]	[0.5642, 0.5017, 0.2801, 0.5475 0.3001, 0]	13

Table 4.40: Steps followed in reference model 2 under QoS Level 1

- Path: [4 → 7 → 10 → 13]
- No. of channels used: 3
- End to end transmission power: 32.9449 Watts.
- End to end probability of channel availability: 0.065 (Calculated from Table 4.5)

(Green): Represents nodes are not active.
(Cyan): Represents minimum (Term 1).

4.3.3 Our Model 3

Table 4.41 is described for our model based on the algorithm mentioned in Chapter 3. Our model searches for minimum 'value' from source to destination node. This 'value' is summation of normalized distance and ($1/PROB_K$). Table 4.41 provides the end result of the program/algorithm.

Node	1	2	3	4	5	6	7	8	9	10	11	12	13
PrecedingNode	4	7	7	0	6	7	4	2	7	9	6	11	9
HeadValue	2.606	2.9502	3.3209	0	4.3924	3.0746	1.5679	4.9880	3.6178	5.4213	6.0266	7.6474	5.8884

Table 4.41: HeadValue and PrecedingNode value for each node for QoS Level 1

It indicates that if source node is 4 and destination node is 13 then according to last column and 13^{th} index of the pool, preceding node to node 13 is 9. It indicates that in order to reach node 13, packets should reach to node 9 before. As we progress to 9^{th} index of the pool from last column, stored node value is node 7. This indicates that, in order to reach node 9, packets should reach to node 7 before. Now, as we look at 7th index of the pool, stored value is node 4, which clearly indicates that packet must originate from node 4 and then traversed to destination node 13 with node values 7 and 9 in between.

- Path: [4 → 7 → 9 → 13]
- No. of channels used: 3.
- End-to-end transmission power: 32.2415 Watts.
- End to end probability of channel availability: 0.2525 (Calculated from Table 4.5)

4.3.4 Comparison of Models 1, 2 and 3 for QoS Level 1

In our example, we have seen that how our model 3 works better (end to end transmission power and $PROB_K$) as compared to other reference models. But we need to check the effectiveness of model 3 for each and every combination of source and destination node. For this reason, we considered 3 different scenarios and they are network of 10 nodes, network of 13 nodes and network of 20 nodes. Each of these scenarios contains 10 different networks.

We carried out same steps as mentioned in the previous Section 4.2.4. For QoS level 1, we look for the percentage number of cases where our model 3 is better than reference models 1 and 2 in end to end transmission power and probability of channel availability.

From Figure 4.8, we can say that, if we have 100 combinations of source and destination nodes then average 65 numbers of times we get better results in our model 3 than in reference model 1 and about average 20 numbers of times we obtained better results in our model than in reference model 2 for the network of 10 nodes. In the network of 13 nodes, model 3 is better than model 1 approximately 56 numbers of times and better than model 2 in approximately 18 number of times. In the network of 20 nodes, model 3 is better than model 1 in almost 43 numbers of times and better than model 2 in approximately 7 numbers of times.

Figure 4.8 only indicates the number of times our model 3 is better than reference models 1 and 2 in the network of 10, 13 and 20 nodes. But it does not indicate the value by which it is better than another model. So for that reason, we carried out another task. The steps included in this are very much similar to what we explained in previous section. But in addition to end to end transmission power, we look for $PROB_K$ as well.

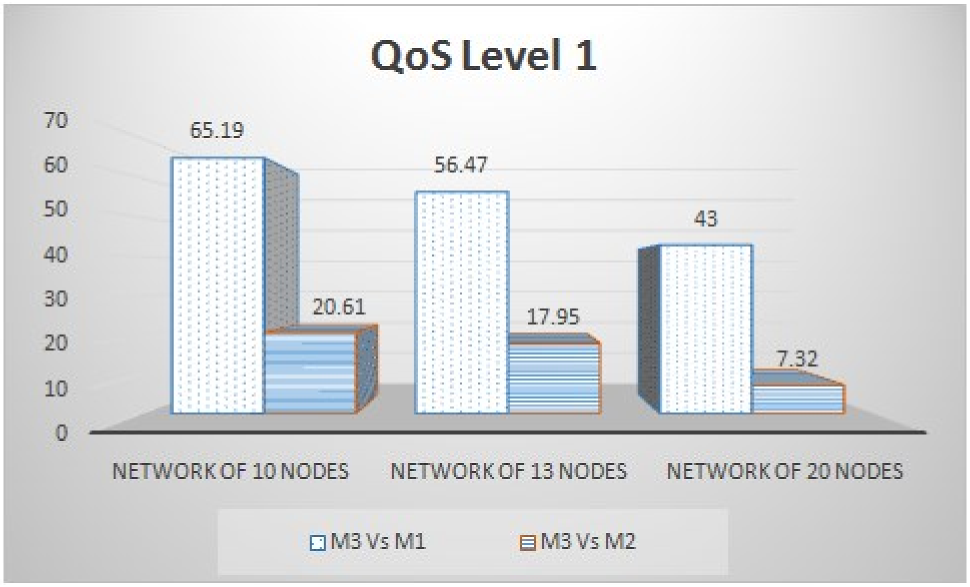


Figure 4.8: Average % number of times Our Model 3 is better than other reference models 1 and 2 to achieve QoS Level 1

In this task, we look for the source-destination pairs where our model 3 is better in end to end transmission power and probability of channel availability than reference models 1 and 2. Once we find those pairs, we take the difference of end-to-end transmission power and $PROB_K$ for all these combinations of source and destination pairs and calculate the average percentage difference between transmission power and $PROB_K$. Result is as shown in Figure 4.9.

Figure 4.9 indicates that, if end to end transmission power in models 1 and model 2 is 100 mW then in the network of 10 nodes, end to end TX power in model 3 will be approximately 52 % less than model 1 (approximately 48 mW) and 22 % less than that of model 2 (approximately 78 mW). Moreover, according to Figure 4.9 in the network of 10 nodes, model 3 has probability of channel availability approximately 53% more and 54% more than reference models 1 and 2 respectively.

We compare reference models 1 and 2 with our model 3 in terms of reachability (route to destination exists) for different networks. For each network as mentioned above, we look for percentage number of times destination is not reachable from different source nodes. Figure 4.10 indicates that, route to destination is always reachable in our model for QoSLevel1 assuming each node has at least one neighbor node in all the networks.

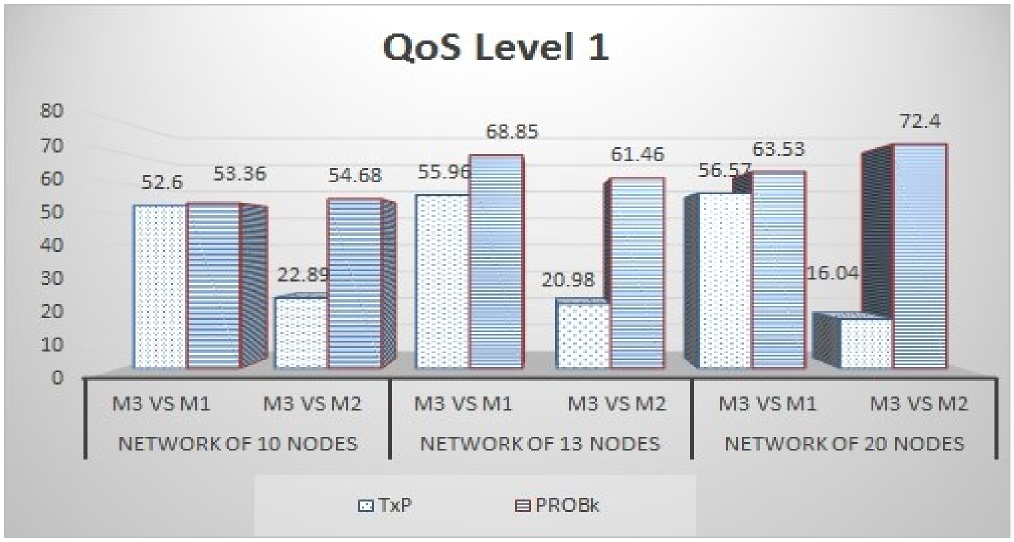


Figure 4.9: Average % difference between transmission power and $PROB_K$ of Our Model 3 and other reference models 1 and 2 for QoS Level 1

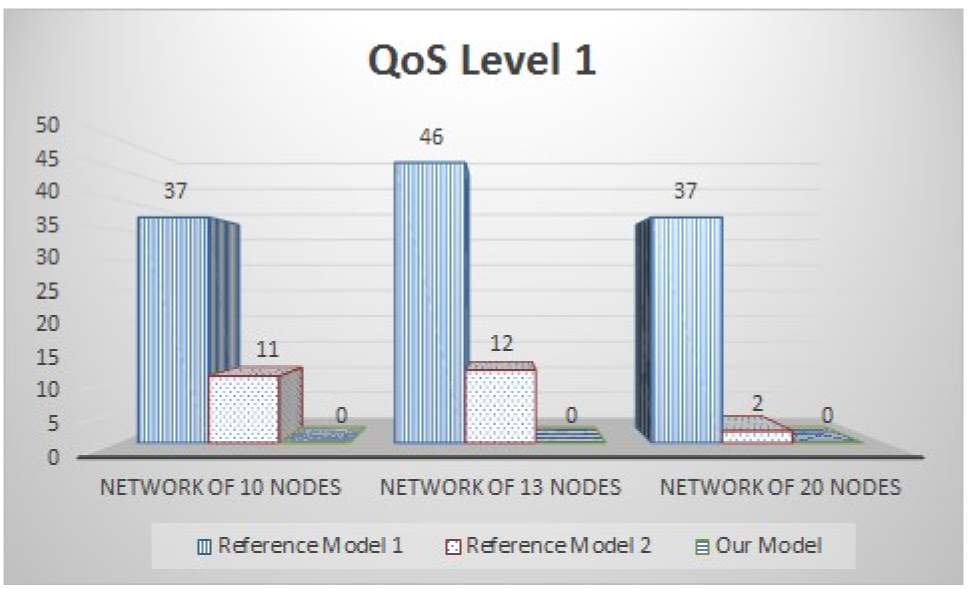


Figure 4.10: Percentage number of times destination is not reachable from source node for QoS Level 1

4.3.5 Summary

In this section, each model is discussed with an example under QoS level 1. Finally, all the models are compared to each other on the basis of end to end transmitted power and ‘probability of channel availability’ between nodes. Comparison shows that our model 3 performs better than other reference models.

4.4 Performance Evaluation for QoS Level 2

As mentioned earlier, in QoS level 2, we consider 'power transmission', 'probability of channel availability' and 'probability of PU presence' between nodes as metrics for routing the packets. Aim in this level of QoS is to route the packets in such a way that 'end to end power transmission' and '$PROB_{PU}$' between nodes is minimal, and '$PROB_K$' is maximum. As path evaluation depends on 'Power Transmission', '$PROB_K$' and '$PROB_{PU}$', our algorithm will always look for min {QoSLevelX} and QoSLevelX for quality of service level 2 is calculated by formula mentioned in Chapter 3. In this section, we study the performance of all models against QoS level 2 for specific source and destination pairs of the network mentioned in Section 4.1; and eventually, we compare our model with other reference models for all source and destination pairs in various networks.

4.4.1 Reference Model 1

Table 4.42 is described for reference model 1 with QoS level 2 based on the algorithm mentioned previously. This model searches for minimum 'value' between source node and its neighbors. This 'value' is a function of 3 parameters (distance, $PROB_K$, $PROB_{PU}$) and this function can be formulated as summation of normalized distance and multiplication of ($1/PROB_K$) with $PROB_{PU}$. The detailed explanation is presented in the form of Table 4.42.

- Path: As we can see from above table entries, once packet reach node 1 from node 4 along the path [4→7→ 2 → 3→1], packets cannot be routed ahead as there is no next node available to forward the packets.
- Hence, communication is not possible with this QoS Level in model 1.
- End to end transmission power will be INF and it's impossible to calculate the end to end channel availability and end to end PU presence.
- Figure 2.5 shows percentage number of times destination may not even be reachable for reference model 1.

Iteration No.	Source Node	Neighbors	Active Neighbors	Term 1	Term 2	Term 3	Min { Term1 + (Term 2 * Term 3) }	Next Source Node
				Normalized Distance between source node and its neighbors	1/($PROB_K$) (between source node and its neighbors)	$PROB_{PU}$ (between source node and its neighbors)		
1	4	[1,3,5,6,7]	[1,3,5,6,7]	[0.3225, 0.3083, 0.2194, 0.3083, 0.4345]	[2.2841, 39.8406, 6.7705, 3.0303, 1.1334]	[0.8352, 0.1068, 0.1029, 0.2645, 0.3352]	[2.2302, 4.5633, 0.9161, 1.1098, 0.8144]	7
2	7	[2,3,4,6,8,9,10]	[2,3,6,8,9,10]	[0.2421, 0.2313, 0.2626, 0.2752, 0.2945, 0.3127]	[1.1401, 1.5216, 1.2441, 10.3842, 1.7553, 4.7755]	[0.6602, 0.6454, 0.9231, 0.1313, 0.7788, 0.2142]	[0.9948, 1.2123, 1.4110, 1.6386, 1.6615, 5.3024]	2
3	2	[1,3,7,8,9]	[1,3,8,9]	[0.4152, 0.2078, 0.2361, 0.4109]	[3.8506, 1.8365, 1.8018, 4.4287]	[0.9426, 0.0822, 0.6190, 0.3670]	[4.0448, 0.3588, 1.3514, 2.0362]	3
4	3	[1, 2, 4, 5, 6, 7, 8]	[1, 5, 6, 8]	[0.2711, 0.4680, 0.3420, 0.4050]	[4.4823, 1.8605, 2.7678, 3.8700]	[0.1364, 0.9264, 0.4700, 0.4167]	[0.8825, 2.1916, 1.6429, 2.1076]	1
5	1	[2, 3, 4]	[NULL]	[NULL]	[NULL]	[NULL]	[NULL]	-

Table 4.42: Steps followed in reference model 1 under QoS Level 2

4.4.2 Reference Model 2

Table 4.43 is described for model 2 with QoS level 2 based on the algorithm mentioned previously. This model searches for minimum ‘distance’ between neighbor node and destination node specified by the user. Once the path is found, model 2 considers $PROB_K$ and $PROB_{PU}$ and calculates end to end probability of channel availability and PU presence. The detailed explanation is presented in the form of Table 4.43.

Iteration No.	Source Node	Neighbors	Active Neighbors	Term 1	Next Source Node
				Normalized Distance between neighbor and destination node	
1	4	[1,3,5,6,7]	[1,3,5,6,7]	[0.9947, 0.7251, 0.8110, 0.5642, 0.4938]	7
2	7	[2,3,4,6,8,9,10]	[2,3,6,8,9,10]	[0.6739, 0.7251, 0.5642, 0.5017 0.2801, 0.2742]	10
3	10	[6,7,8,9,11,12,13]	[6,8,9,11,12,13]	[0.5642, 0.5017, 0.2801, 0.5475 0.3001, 0]	13

Table 4.43: Steps followed in reference model 2 under QoS Level 2

- Path: [4 → 7 → 10 → 13]
- No. of channels used: 3
- End to end transmission power: 32.9449 Watts.
- End to end probability of channel availability: 0.0650 (Calculated from Table 4.5)
- End to end probability of PU presence: 0.0148 (Calculated from Table 4.6)

: Represents nodes are not active.

: Represents minimum (Term 1).

4.4.3 Our Model 3

Table 4.44 is described for our model 3 based on the algorithm mentioned previously. This model searches for minimum 'value' from source to destination node. This 'value' is summation of normalized distance and multiplication of ($1/PROB_K$) with $PROB_{PU}$. Once we step into the end of the program/algorithm, the end result is presented in the form of Table 4.44.

Node	1	2	3	4	5	6	7	8	9	10	11	12	13
PrecedingNode	4	7	7	0	4	4	4	10	7	6	6	10	10
HeadValue	2.230	1.8093	2.0278	0	0.9161	1.1098	0.8145	2.2756	2.4760	1.4563	3.2341	3.4981	2.3179

Table 4.44: HeadValue and PrecedingNode value for each node for QoS Level 2

According to the above chart, if source node is 4 and destination node is 13 then according to last column and 13^{th} index of the pool, preceding node to node 13 is 10. It indicates that in order to reach node 13, packets should reach to node 10 before. As we progress to 10^{th} index of the pool from last column, stored node value is node 6. This indicates that, in order to reach node 10, packets should reach to node 6 before. Now, as we look at 6^{th} index of the pool, stored value is node 4, which clearly indicates that packet must originate from node 4 and then traverse to destination node 13 with in between node values 6 and 10.

- Path: [4 → 6 → 10 → 13]
- No. of channels used: 3.
- End to end transmission power: 23.3993 Watts.
- End to end probability of channel availability: 0.0268 (Calculated from Table 4.5)
- End to end probability of PU presence: 0.0007 (Calculated from Table 4.6)

4.4.4 Comparison of Models 1, 2 and 3 for QoS Level 2

We need to check the effectiveness of our model 3 for each and every combination of source and destination node. For this reason, we considered 3 different scenarios again and they are network of 10 nodes, network of 13 nodes and network of 20 nodes. Each of these scenarios contains 10 different networks.

We carried out same steps as mentioned in the previous section. For QoS level 2, we look for the percentage number of cases where our model 3 is better than reference models 1 and 2 in end to end transmission power, Probability of channel availability and in probability of PU presence.

From Figure 4.11, we can say that, if we have 100 combinations of source and destination nodes then average 45 numbers of times we get better results in our model 3 than in reference model 1 and about average 23 numbers of times we obtained better results than reference model 2 for the network of 10 nodes. In the network of 13 nodes, model 3 is be better than model 1 approximately 47 number of times again and better than model 2 in approximately 21 number of times. In the network of 20 nodes, model 3 is better than model 1 in almost 45 cases and better than model 2 in approximately 17 cases.

Figure 4.11 only indicates the number of times our model 3 is better than reference models 1 and 2 in the network of 10, 13 and 20 nodes. But it does not indicate the value by which it is better than another model. So for that reason, we carried out another task. The steps included in this are very much similar to what we explained in previous section. But in addition to end to end transmission power, we look for $PROB_K$ and $PROB_{PU}$ as well. In this task we look for the source-destination pairs where our model 3 is better in end to end transmission power, probability of channel availability and probability of PU presence than reference models 1 and 2. Once we find those pairs, we take the difference of end to end transmission power, probability of channel availability and probability of PU presence for all these combination of source and destination pairs and calculate the average percentage difference between transmission power, $PROB_K$ and $PROB_{PU}$.

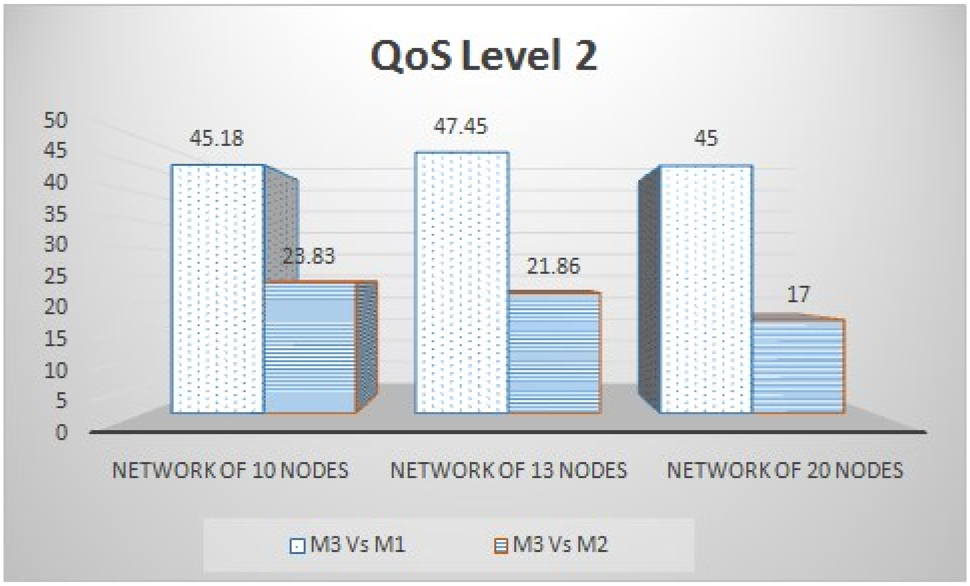


Figure 4.11: Average % number of times Our Model 3 is better than other models to achieve QoS Level 2

Figure 4.12 indicates that, if end to end transmission power in model 1 and model 2 is 100 mW then in the network of 10 nodes, end to end Transmission power in model 3 will be approximately 50 % less than model 1 (approximately 50 mW) and 28 % less than that of model 2 (approximately 72 mW). Moreover, in the network of 10 nodes, model 3 has probability of channel availability approximately 60% more and 55% more than models 1 and 2 respectively. Similarly, in the network of 10 nodes, model 3 has probability of PU presence approximately 20% less and approximately 70% less than model 1 and 2 respectively. Since our model 3 selects a route with lower transmission power which increases life span of nodes in the network as well as it may avoid interference with other users, higher $PROB_K$ which offers lower delay during communication, and increase in the stability of communication by lowering the PU presence than reference models 1 and 2.

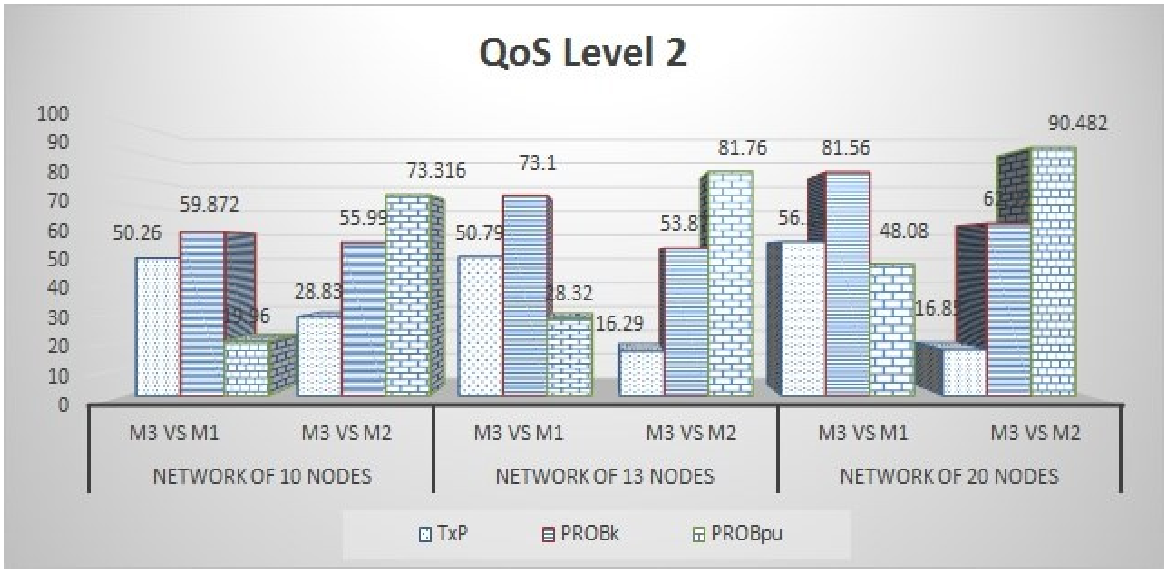


Figure 4.12: Average % difference between Transmission Power, $PROB_K$ & $PROB_{PU}$ of Our Model 3 and other models for QoS Level 2

We compare reference models 1 and 2 with our model 3 in terms of reachability (route to destination exists) for different networks for QoSLevel2. For each network as mentioned above, we look for percentage number of times destination is not reachable from different source nodes. Figure 4.13 indicates that, route to destination is always reachable in our model for QoSLevel2 assuming each node has at least one neighbor node in all the networks.

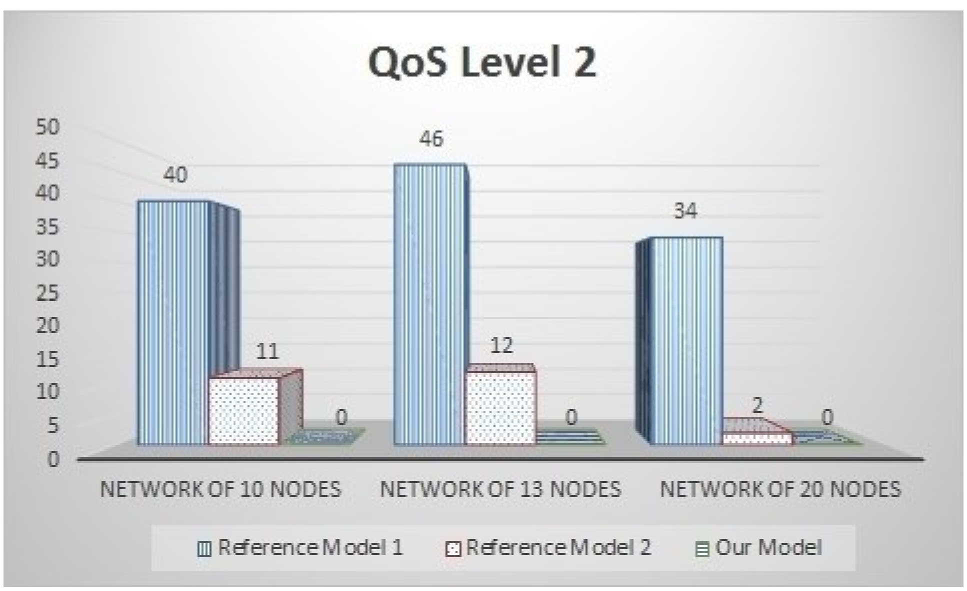


Figure 4.13: Percentage number of times destination is not reachable from source node for QoS Level 2

4.4.5 Summary

In this section, each model is discussed with an example under QoS level 2. Finally, all the models are compared to each other on the basis of end to end transmitted power, probability of channel availability and probability of PU presence. Comparison shows that our model 3 performs better than other reference models.

4.5 Performance Evaluation for QoS Level 3

As mentioned earlier, in QoS level 3, we consider 'power transmission', 'probability of channel availability', 'probability of PU presence' and 'probability of link failure' between nodes as metrics for routing the packets. Aim in this level of QoS is to route the packets in such a way that 'end to end power transmission', '$PROB_{PU}$' and '$PROB_{link}$' between nodes is minimal, and '$PROB_K$' is maximum. As path evaluation depends on 'Power Transmission', '$PROB_K$', '$PROB_{PU}$' and '$PROB_{link}$', our algorithm will always look for min {QoSLevelX} and QoSLevelX for quality of service level 3 is calculated by formula mentioned in Chapter 3. In this section, we study the performance of all models against QoS level 3 for specific source and destination pairs of the network mentioned in Section 4.1; and eventually, we compare our model with other models for all source and destination pairs in various networks.

4.5.1 Reference Model 1

Table 4.45 is described for reference model 1 with QoS level 3 based on the algorithm mentioned previously. This model searches for minimum 'value' between source node and its neighbors. This 'value' is a function of 4 parameters f(distance, $PROB_K$, $PROB_{PU}$, $PROB_{link}$) and this function can be formulated as summation of normalized distance and multiplication of ($1/PROB_K$), $PROB_{PU}$ and $PROB_{link}$.

- Path: [4 → 5 → 6 → 10 →13] : Represents min (Term 1+ (Term2* Term3* Term4)).
- No. of channels used: 4.
- End to end transmission power: 25.4089 Watts.
- End to end probability of channel availability: 0.0114 (Calculated from Table 4.5)
- End to end probability of PU presence: 0.000008 (Calculated from Table 4.6)
- End to end ETX value: 14.31 (Calculated from Table 4.7)

Iteration No.	Source Node	Active Neighbors	Term 1 Normalized Distance between source node and its neighbors	Term 2 1/(PROB$_K$ between source node and its neighbors)	Term 3 PROB$_{PU}$ Between source node and its neighbors	Term 4 PROB$_{link}$ Between source node and its neighbors	Min { Term 1 + (Term 2 * Term 3 * Term 4) }	Next Source Node
1	4	[1,3,5,6,7]	[0.3225, 0.3083, 0.2194, 0.3083, 0.4345]	[2.2841, 39.8406, 6.7705, 3.0303, 1.1334]	[0.8352, 0.1068, 0.1029, 0.2645, 0.3352]	[0.5392, 0.7861, 0.1270, 0.2459, 0.4270]	[1.3511, 2.3766, 0.3079, 0.5054, 0.5967]	5
2	5	[3, 6, 11]	[0.4680, 0.2626, 0.3939]	[1.8605, 1.0552, 4.1667]	[0.9264, 0.0324, 0.9276]	[0.7491, 0.9062, 0.7630]	[1.7591, 0.2936, 3.3429]	6
3	6	[3, 7, 10, 11]	[0.3420, 0.2626, 0.2945, 0.3162]	[2.7678, 1.2441, 4.3309, 2.6357]	[0.4700, 0.9231, 0.0120, 0.6860]	[0.0588, 0.8667, 0.1325, 0.6989]	[0.4185, 1.2579, 0.3014, 1.5799]	10
4	10	[7, 8, 9, 11, 12, 13]	[0.3127, 0.4698, 0.3054, 0.3225, 0.2418, 0.2742]	[4.7755 3.5997 1.4981 1.6938 3.8835 2.8417]	[0.2142 0.2142 0.6127 0.9621 0.4635 0.2067]	[0.9058 0.7828 0.3438 0.7813 0.3308 0.2622]	[1.2393, 0.9163, 0.6210, 1.5957, 0.8372, 0.4282]	13

Table 4.45: Steps followed in reference model 1 under QoS Level 3

4.5.2 Reference Model 2

Table 4.46 is described for reference model 2 with QoS level 3 based on the algorithm mentioned previously. This model searches for minimum 'distance' between neighbor node and destination node specified by the user. Once the path is found, we look into the PROB$_K$, PROB$_{PU}$ and PROB$_{link}$; and we will calculate end to end probability of channel availability, PU presence and probability of link failure. The detailed explanation is presented in the form of Table 4.46.

Iteration No.	Source Node	Neighbors	Active Neighbors	Term 1	Next Source Node
				Distance between neighbor and destination node	
1	4	[1,3,5,6,7]	[1,3,5,6,7]	[0.9947, 0.7251, 0.8110, 0.5642, 0.4938]	7
2	7	[2,3,4,6,8,9,10]	[2,3,6,8,9,10]	[0.6739, 0.7251, 0.5642, 0.5017 0.2801, 0.2742]	10
3	10	[6,7,8,9,11,12,13]	[6,8,9,11,12,13]	[0.5642, 0.5017, 0.2801, 0.5475 0.3001, 0]	13

Table 4.46: Steps followed in reference model 2 under QoS Level 3

- Path: [4 → 7 → 10 → 13]
- No. of channels used: 3
- End to end transmission power: 32.9449 Watts.
- End to end probability of channel availability: 0.0650 (Calculated from Table 4.5)
- End to end probability of PU presence: 0.0148 (Calculated from Table 4.6)
- End to end ETX: 13.72 (Calculated from Table 4.7)

■ : Represents nodes are not active

■: Represents minimum (Term 1)

4.5.3 Our Model 3

Table 4.47 is described for our model 3 based on the algorithm mentioned previously. This model searches for minimum 'value' from source to destination node. This 'value' is summation of normalized distance and multiplication of ($1/PROB_K$), $PROB_{PU}$ and $PROB_{link}$. Once we step into the end of the program/algorithm, the end result is presented in Table 4.47.

Node	1	2	3	4	5	6	7	8	9	10	11	12	13
PrecedingNode	4	7	6	0	4	4	4	10	10	6	6	10	10
HeadValue	1.351	1.0481	0.9239	0	0.3079	0.5054	0.5968	1.5502	1.4277	0.8068	2.0853	1.6441	1.2350

Table 4.47: HeadValue and PrecedingNode value for each node for QoS Level 3

According to the above chart, if source node is 4 and destination node is 13 then according to last column and 13th index of the pool, preceding node to node 13 is 10. It indicates that in order to reach node 13, packets should reach to node 10 before. As we progress to 10th index of the pool from last column, stored node value is node 6. This indicates that, in order to reach node 10, packets should reach to node 6 before. Now, as we look at 6th index of the pool, stored value is node 4, which clearly indicates that packet must originate from node 4 and then traverse to destination node 13 with in between node values 6 and 10.

- Path: [4 → 6 → 10 → 13]
- No. of channels used: 3.
- End to end transmission power: 23.3993 Watts.
- End to end probability of channel availability: 0.0268 (Calculated from Table 4.5)
- End to end probability of PU presence: 0.0007 (Calculated from Table 4.6)
- End to end ETX: 3.83 (Calculated from Table 4.7)

4.5.4 Comparison of Models 1, 2 and 3 for QoS Level 3

In our example, we have seen how our model 3 works better (end to end transmission power, $PROB_K$, $PROB_{PU}$ and ETX) as compared to other reference models. But we need to check the effectiveness of model 3 for each and every combination of source and destination node. For this reason, we considered 3 different scenarios again and they are network of 10 nodes, network of 13 nodes and network of 20 nodes. Each of these scenarios contains 10 different networks.

We carried out same steps as mentioned in the previous section. For QoS level 3, we look for the percentage number of cases where model 3 is better than model 1 and 2 in end to end transmission power, Probability of channel availability, probability of PU presence and ETX.

From Figure 4.14, we can say that, if we have 100 combinations of source and destination nodes then average 42 numbers of times we get better results in our model 3 than in reference model 1 and about average 21 numbers of times we obtained better results in our model 3 than in reference model 2 for the network of 10 nodes. In the network of 13 nodes, model 3 is be better than model 1 approximately 76 number of times and better than model 2 in approximately 29 number of times. In the network of 20 nodes, model 3 is better than model 1 in almost 41 cases and better than model 2 in approximately 12 cases.

Figure 4.14 indicates only the number of times model 3 is better than 1 and 2 in the network of 10, 13 and 20 nodes. But it does not indicate the value by which it is better than another model. So for that reason, we carried out another task. The steps included in this are very much similar to what we explained in previous section. But in addition to end to end transmission power, we look for $PROB_K$, $PROB_{PU}$ and ETX as well.

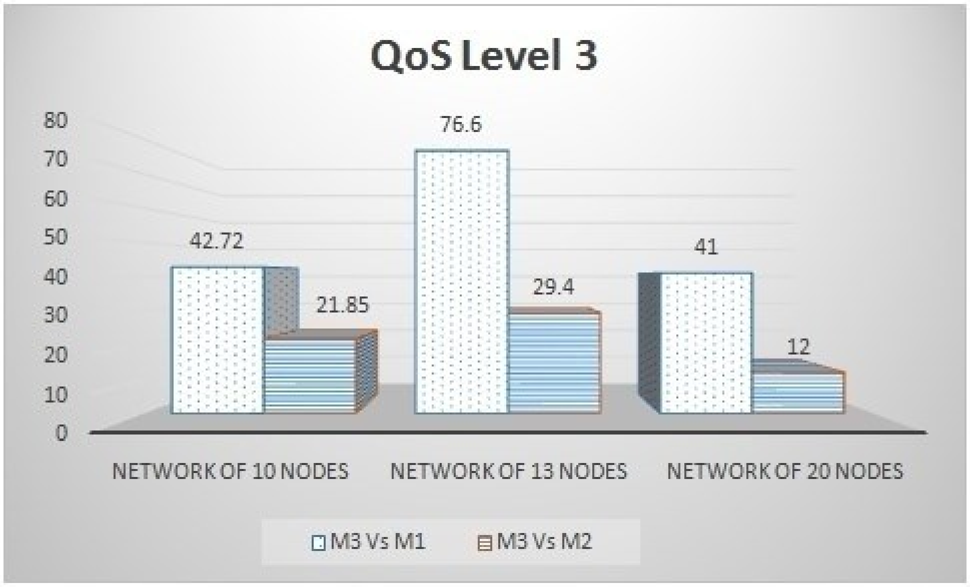


Figure 4.14: Average % number of times Our Model 3 is better than other reference models to achieve QoS Level 3

In this task, we look for the source-destination pairs where our model 3 is better in end to end transmission power, probability of channel availability, probability of PU presence and ETX than reference models 1 and 2. Once we find those pairs, we took the difference of end-to-end transmission power, probability of channel availability, probability of PU presence and ETX for all these combination of source and destination pairs and calculate the average percentage difference between Transmission Power, $PROB_K$, $PROB_{PU}$ and ETX. Result is as shown in Figure 4.15.

This Figure 4.15 indicates that, if end to end transmission power in model 1 and model 2 is 100 mW then in the network of 10 nodes, end to end TX power in our model 3 will be approximately 51 % less than reference model 1 (approximately 49 mW) and 24 % less than that of reference model 2 (approximately 76 mW). Moreover according to figure, in the network of 10 nodes, our model 3 has probability of channel availability approximately 53% more and 46% more than reference models 1 and 2 respectively. Similarly according to figure, in the network of 10 nodes, model 3 has probability of PU presence approximately 42% less and approximately 67% less than model 1 and 2 respectively. For ETX, it is approximately 57% and 52% lower for model 3 as compared to reference models 1 and 2 respectively.

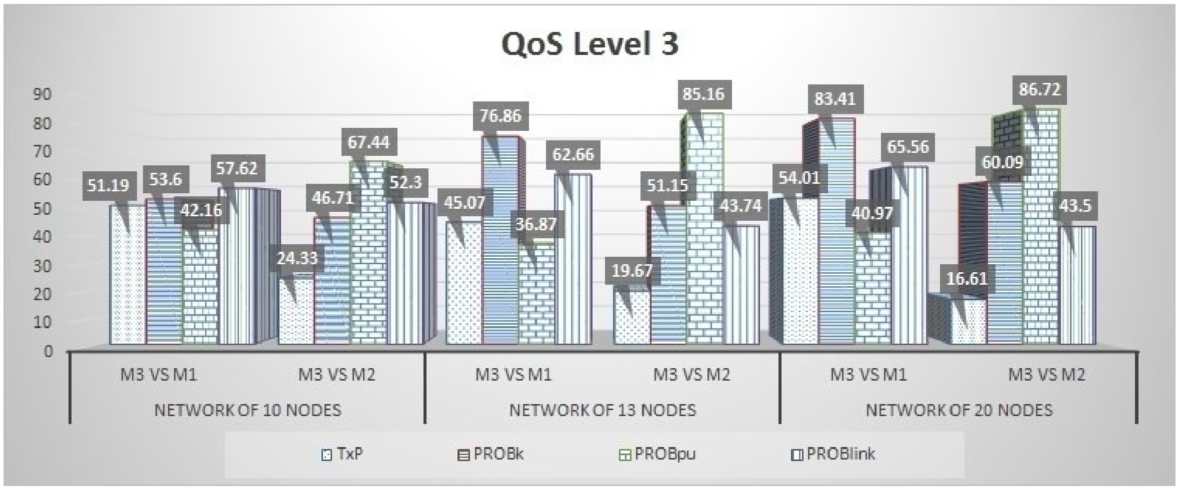


Figure 4.15: Average % difference between Transmission Power, $PROB_K$, $PROB_{PU}$ & $PROB_{link}$ of Our Model 3 & other reference models for QoS Level 3

We compare reference models 1 and 2 with our model 3 in terms of reachability (route to destination exists) for different networks for QoSLevel3. For each network as mentioned above, we look for percentage number of times destination is not reachable from different source nodes. Figure 4.16 indicates that, route to destination is always reachable in our model for QoSLevel3 if we consider in all the networks each node has at least one neighbor node.

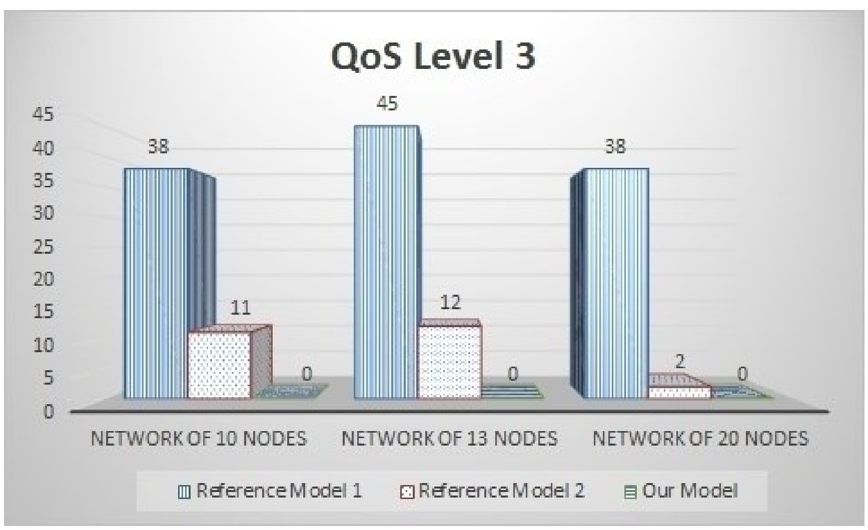


Figure 4.16: Percentage number of times destination is not reachable from source node for QoS Level 3

4.5.5 Summary

In this section, each model is discussed with an example under QoS level 2. Finally, all the models are compared to each other on the basis of end to end transmitted power, probability of channel availability, probability of PU presence and ETX. Comparison shows that our model 3 performs better than other reference models.

4.6 NS2 Simulation

In this section, general discussion on overview of NS2 simulation tool, network topology and routing protocol is provided. Simulation environment/parameters are listed and are explained in detail. Eventually, section is concluded with analysis of simulation results which includes discussion on AWK scripting and various performance metrics such as packet delivery ratio, end to end delay, throughput, and percentage packet loss, which were not possible in a MATLAB environment.

4.6.1 About NS2

Network simulator (version-2), widely known as NS2, is simply an event-driven open source packet-level simulation tool that has proved useful in studying communication networks. It provides standard experiment environment. Also it supports various protocols such as TCP, UDP etc, various traffic models such as CBR, FTP etc and mainly enables graphical monitoring tools (NAM, XGRAPH). With the help of NS2, we can simulate wired and wireless networks.

4.6.2 Network topology and routing protocol

Figure 4.17 shows a network topology generated for simulation purposes with node locations in the network.

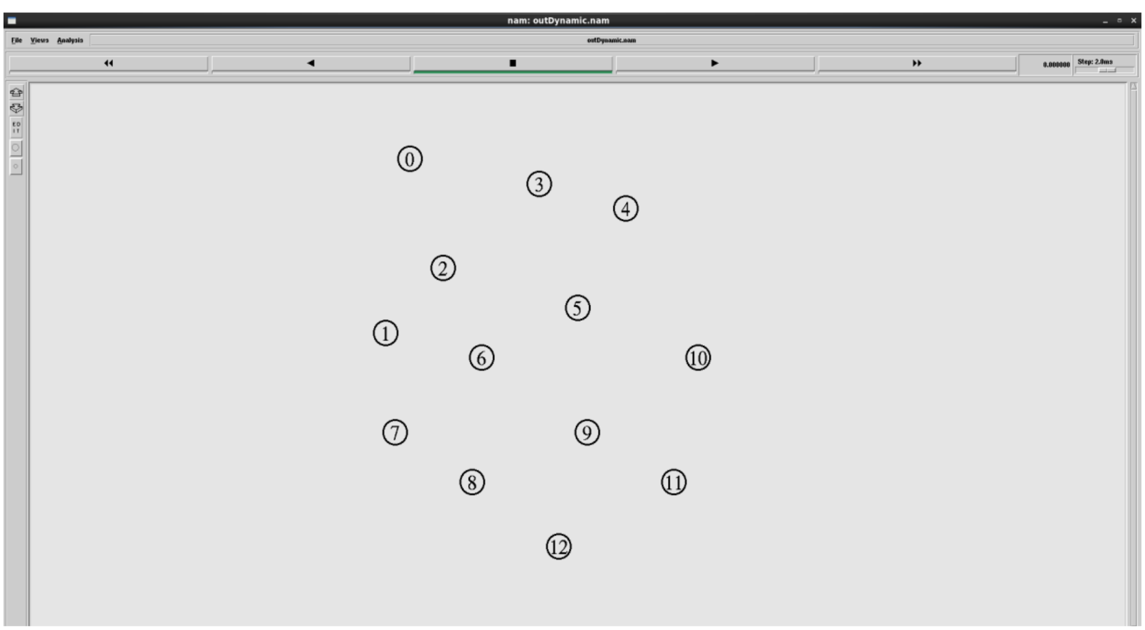


Figure 4.17: Network topology

We regenerate the same topology of network that we used in Chapter 3. An area of 100m * 100m is considered as a simulation ground. Profile exchange routing protocol abbreviated as PERP is used along with the location service to exchange profiles between PU and SU. Profile exchange flow is mentioned in chapter 3. NS2 is configured with CRCN patch and on the top of that we include 'PERP' routing. We use the methods provided under 'PERP' routing protocol to build the routing table entries. Once, table is prepared, packets are routed from source node to destination.

4.6.3 Simulation environment

Table 4.48 summarizes all the parameters that have been used in the simulation. Before we start the actual simulation, we need to define the values for the components in the NS2. These components are nothing but the simulation parameters listed in the Table 4.48.

Parameter	Value
Channel Type	Channel/WirelessChannel
Radio propagation model	Propagation/FreeSpace
Network Interface Type	Phy/WirelessPhy
MAC Type	Mac/802_11
Interface queue type	Queue/DropTail/PriQueue
Antenna Model	Antenna/OmniAntenna
Max. Packets in queue	50
# of mobile nodes	13
Routing protocol	PERP
X- dimensions of topology	100
Y- dimensions of topology	100
# of channels/radio	20
Simulation time	100
Packet size	512 bytes
Application	FTP

Table 4.48: Simulation Environment

In order to review the performance of algorithm and for the purpose of analysis, simulation creates two files.

a. *NAM:* It is an animation tool for viewing the network simulation traces. The topology which we can see in Figure 4.18 is a NAM view of the network simulation.

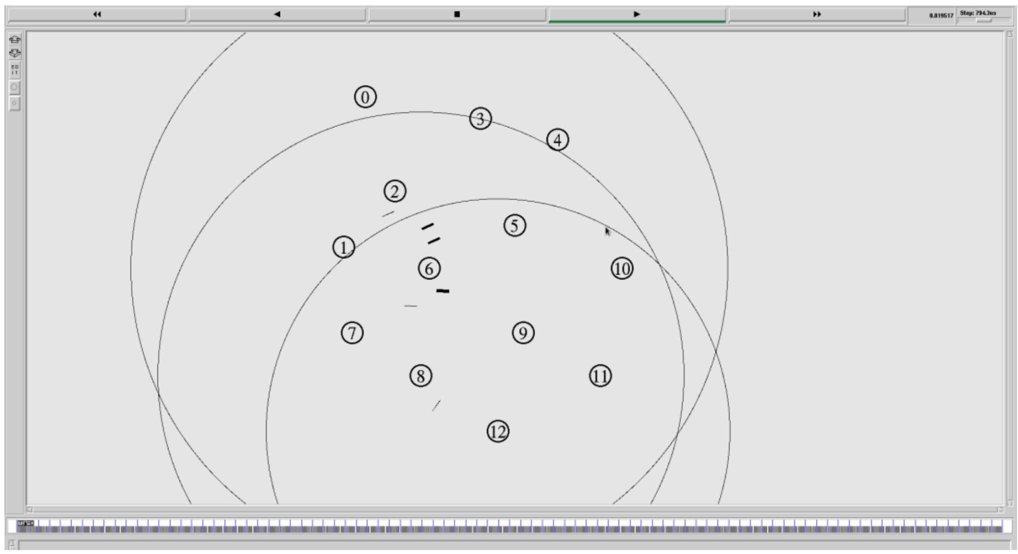


Figure 4.18: Network simulation/ packet trace.

b. *Trace File:* It contains the detailed packet information e.g. send time, receive time, node id at which send or receive event happened, packet size etc. Trace file helps to analyze the performance of communication model. Sample trace file details are listed as in Figure 4.19.

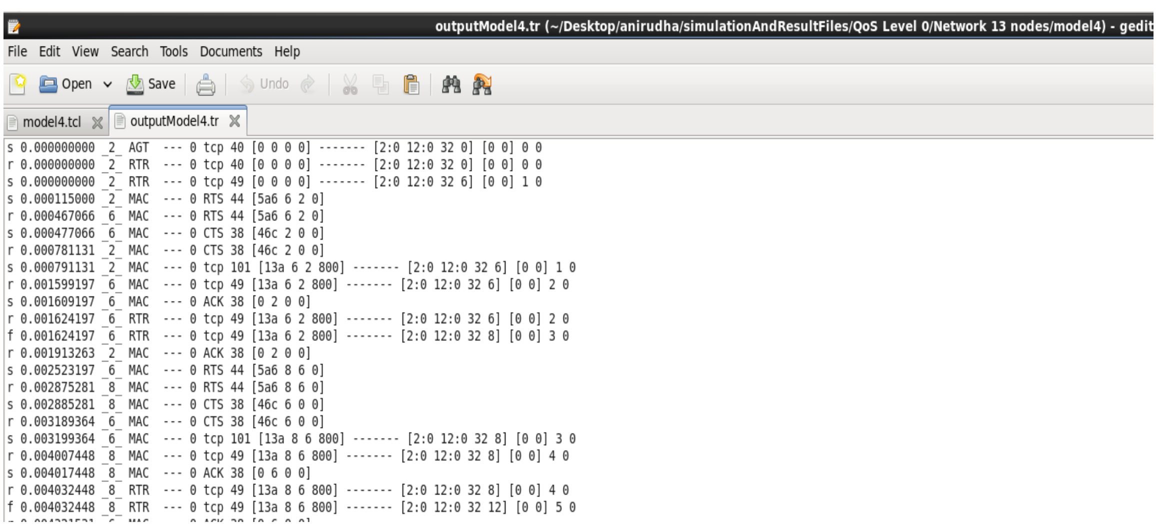


Figure 4.19: Trace file details

4.6.4 Analysis of simulation results

In this section, we discussed in brief the AWK scripting and analysis of few performance metrics such as packet delay, packet delivery ratio, percentage packet loss and throughput.

4.6.4.1 *AWK scripting*

NS2 produces simulation results in terms of trace files, which contains information in terms of fields in rows and columns. Each field has a specific meaning. E.g. first field in a row indicates the time at which specific event of 'send' or 'receive' has occurred.

AWK scripting is used to access this structured set of information to manipulate data. This is described using Figure 4.20.

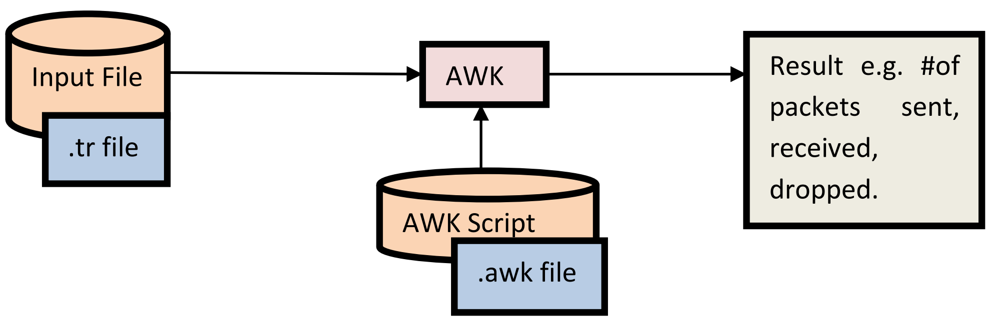


Figure 4.20: AWK scripting

4.6.4.2 *Performance Metrics*

In order to evaluate the performance of network, packet delivery ratio, end to end delay, throughput and % packet loss are considered. These performance metrics are evaluated against 3 different networks namely networks of 10, 13 and 20 nodes.

Our model 3 is compared with reference model 1 as the routing technique followed in both the models is same and its table driven routing where route for each node is stored in a table and accessed whenever required. However, routing technique followed in reference model 2 is on-demand where source node starts looking for next hop if it has packet to send.

4.6.4.2.1 Packet delivery ratio

It is the ratio of # of data packets successfully delivered to all destination nodes to the # of data packets generated by source node.

$$packet\ delivery\ ratio = \frac{\text{\# of data packets deliverd successfully to destination}}{\text{\# of data packets generated by source node}}$$

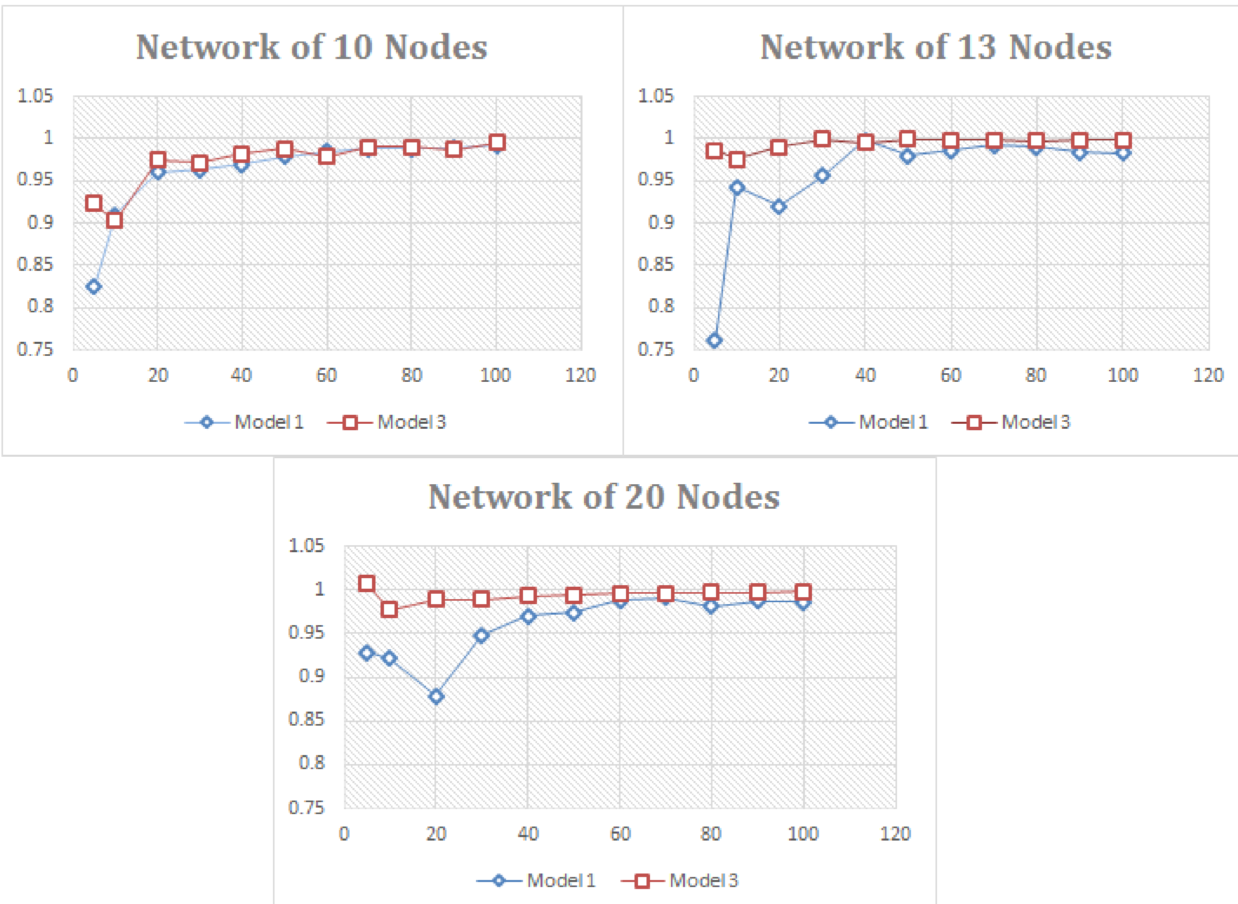


Figure 4.21: Packet delivery ratio for network of 10, 13 and 20 nodes

From Figure 4.21, it is clear that packet delivery ratio is better in case of our model (model 3), which means more number of packets are delivered successfully to the destination in our model than model 1. And as simulation time increases gradually, number of packets delivered successfully to the destination increases as well.

4.6.4.2.2 End to end delay

It is the time taken between generation of packet in a source node and the successful delivery of that packet at destination node. For representation, we analyze the average end to end delay between source and destination node.

Avg. end to end delay

$$= \frac{\sum(\text{Time at which packet has been received at destination} - \text{time at which it is sent from source node})}{\#\text{ of packets received}}$$

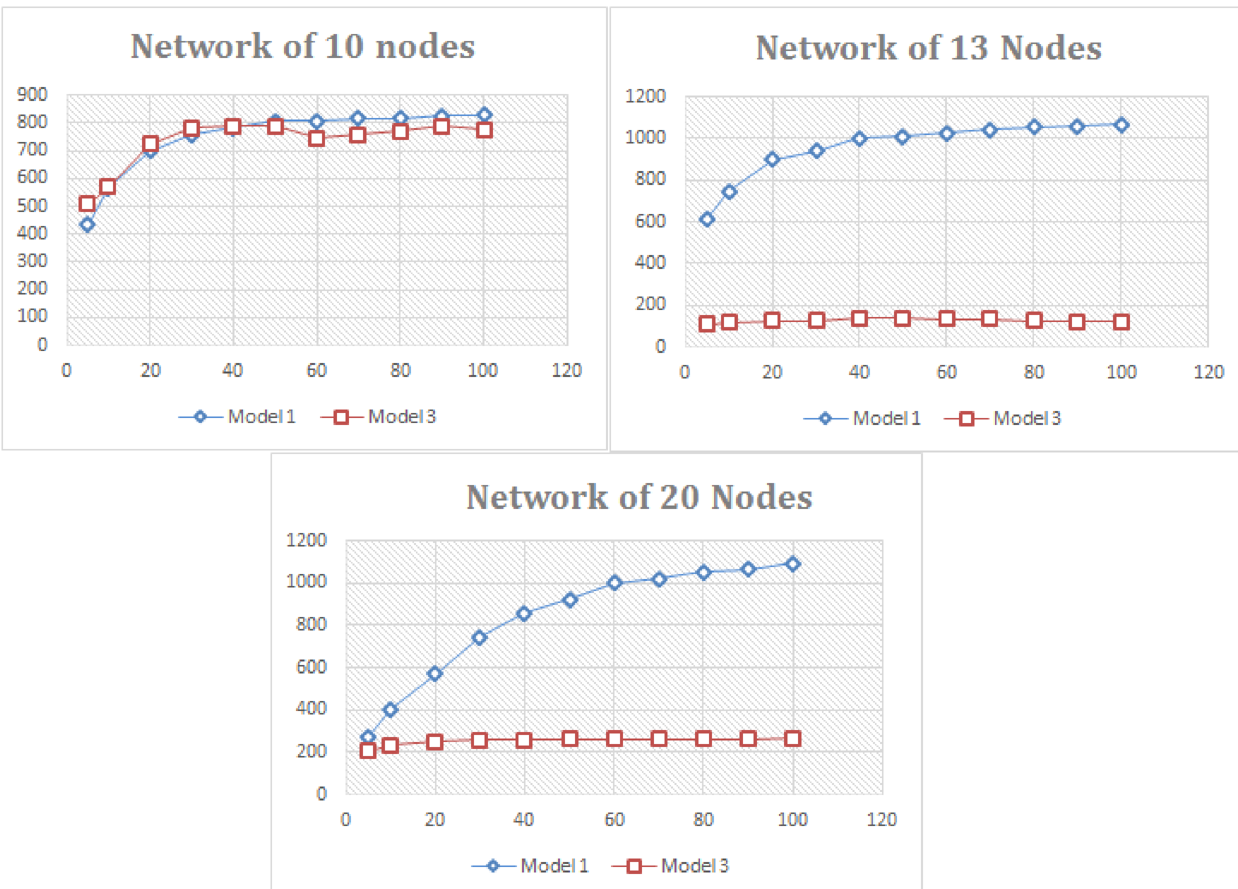


Figure 4.22: Average end to end delay in the network of 10, 13 and 20 nodes.

From Figure 4.22, it is clear that, average end to end delay is less in case of our model. That means, average time required to send a packet successfully from source node to destination node is less in case of our model than model 1. And as simulation time increases end to end delay is maintained at constant level.

4.6.4.2.3 Throughput

It is the amount of information received at the destination per second. It can be calculated by the summation of size of packet received at the destination divided by the time it takes to reach to destination.

$$\text{Throughput} = \frac{\sum(\text{size of the packet received at destination})}{\sum(\text{Time taken by the packet to reach to destination})}\ (\text{bps})$$

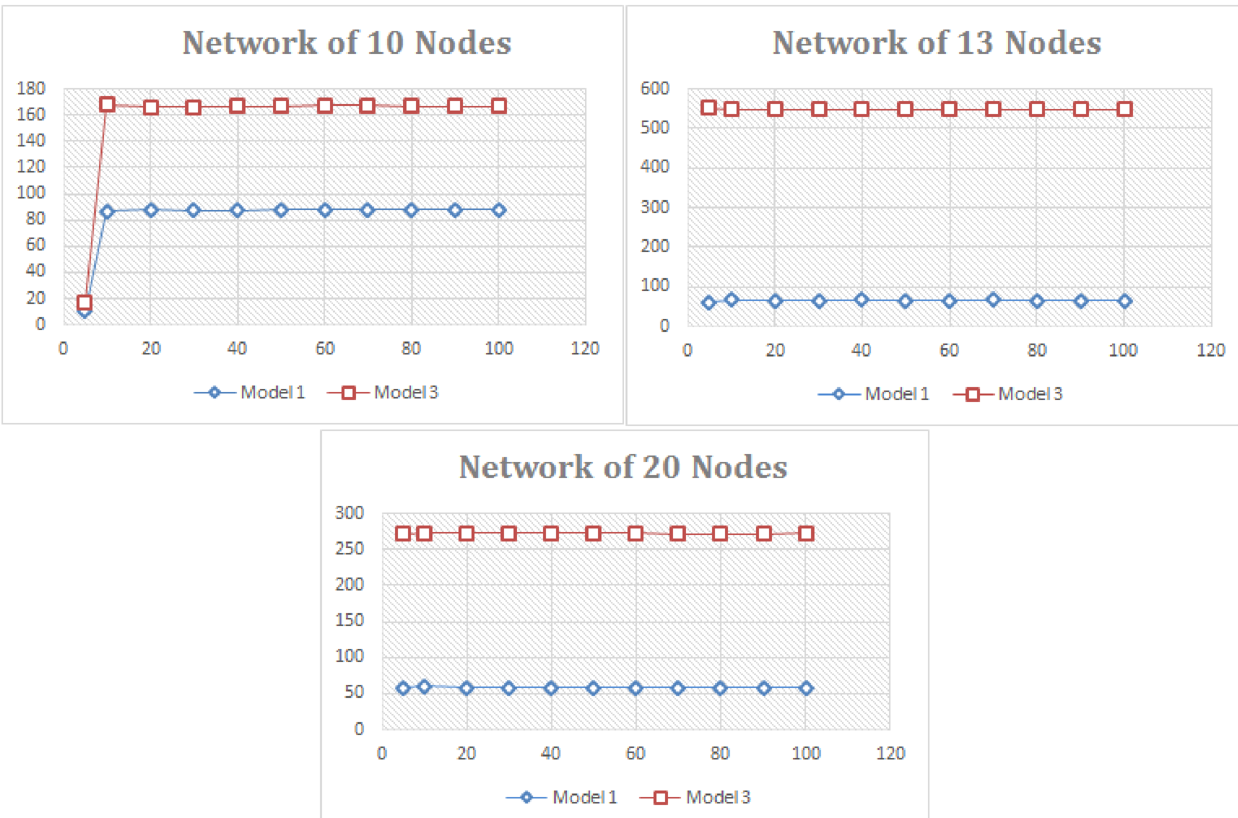


Figure 4.23: Throughput of network with 10, 13 and 20 nodes.

From Figure 4.23, it is clear that, throughput of the communication is better in case of our model. During the start of the simulation as bandwidth utilization is less, throughput is less; but once simulation time increases, bandwidth utilization will be more and hence, throughput will increase and reaches to saturation level and becomes constant.

4.6.4.2.4 Percentage packet loss

It is the ratio of difference between number of packets sent and received to the total number of packets sent from the source node.

$$\% \text{ packet loss} = \frac{\#\text{ of packets sent} - \#\text{ of packets received}}{\text{Total number of packets sent}} * 100$$

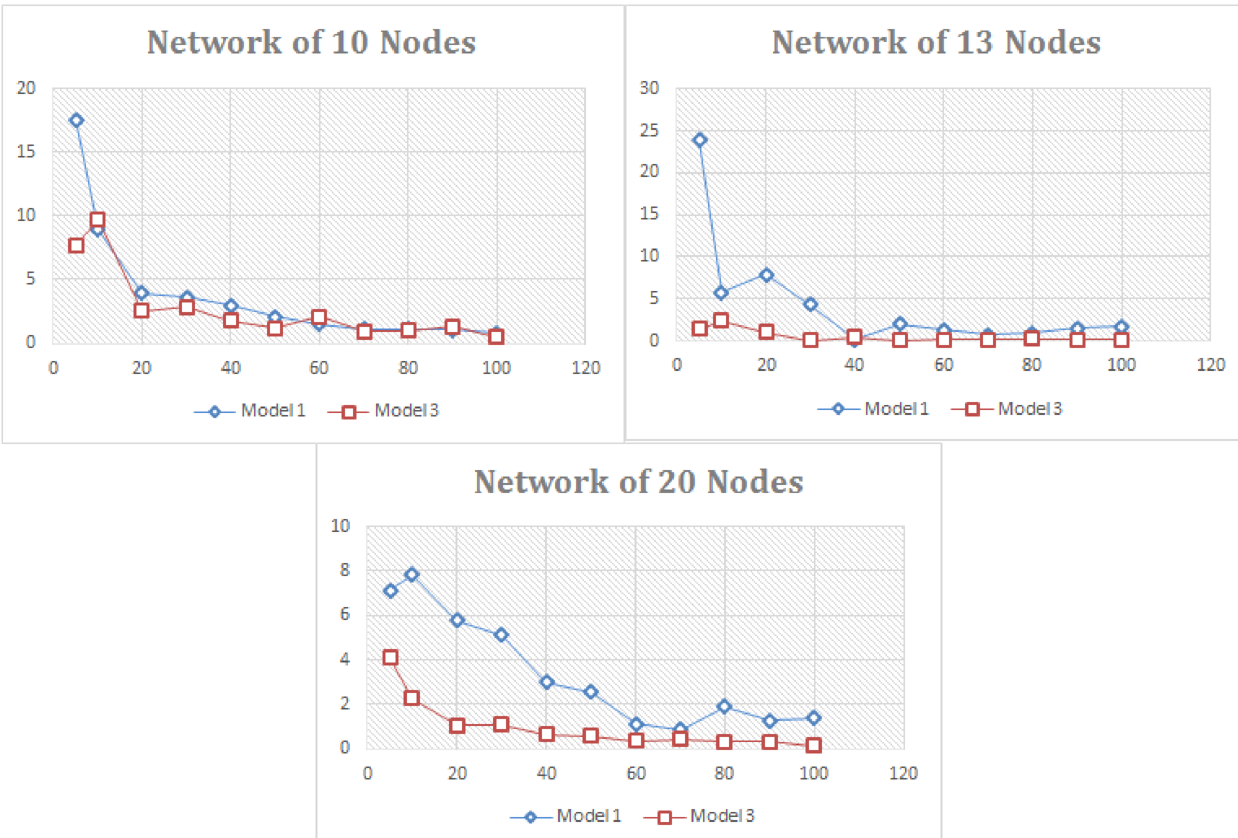


Figure 4.24: % packet loss in the network of 10, 13 and 20 nodes.

From Figure 4.24, it is clear that, percentage packet loss is lower for our model which means more packets are received at the destination if our model is used in comparison to other models studied.

4.7 Summary

As seen from Figures (4.21, 4.22, 4.23, 4.24), model 3 performs better than reference model 1 in terms of transmission power, end to end delay, throughput and % packet loss as performance parameters.

Chapter 5
Conclusion and Future Work

5.1 Conclusion

The problem of developing an efficient QoS based route management in a cognitive radio network is studied in this thesis. Two models described in literature for route management are studied and a route management algorithm is designed by considering various QoS metrics that can manage the spectrum efficiently and help to enhance the network performance.

In this thesis, first model considers multiple metrics while finding route. It considers channel availability, PU presence and link loss as metrics to find path to destination. However they did not consider distance (indirectly transmission power between nodes) as a metric. Second model considers only distance as a metric to find route. Hence, we combined the features of both models which consider distance, channel availability, PU presence and link loss in finding route. Issues of routing in reference models such as excessive control overheads on network, long routes to destination (hop count), resource consumption, route to destination not reachable, complexity, and link stability during communication are addressed in two parts.

In the first part, proposed working model makes use of functionalities of profile exchange mechanism and location services to lower down the excess overhead on network by reducing number of control and profile exchange messages and it helps to reduce the information exchanged with profile exchange messages. In the second part, route management algorithm is designed which selects a routing path with low end-to-end transmission power, high probability of channel availability, low probability of PU presence and low ETX, to increase life span of users in the network, to decrease the delay, to stabilize wireless connectivity and to increase the throughput of the communication respectively based on the QoS level requested by a SU as compared to other models considered in this thesis. Our model's complexity is lower than reference model 2 and similar to reference model 1, therefore delay in route discovery is same or lower than other reference models. Our model lowers down the probability of future packet loss due to route to destination not available.

Eventually, performance of the network is studied by simulating the network in NS2 under simulation environment with the help of end to end delay, throughput, packet delivery ratio, and % packet loss. Proposed model performs better than the other two reference models and is shown in the simulation results.

4.2 Future Work

For future work, few ideas could be applied to enhance the efficiency of route management in cognitive radio networks.

A. QoS Levels: Four QoS levels are introduced; it can be extended to more levels. Moreover, this thesis work can be extended to find the optimal value of the weights assigned to each QoS metric.
B. Security: A way to suppress selfish and malicious behaviors in cognitive radio networks can be considered to enhance the system performance.
C. Game Theory: It can be applied in order to improve routing algorithm performance by taking routing decisions.
D. Distributed approach: In order to reduce the network overhead further distributed approach can be implemented where there will be no need to update the changes in the environmental conditions to central entity. Or hybrid framework can be implemented where for intra cluster operation central mechanism is used and for inter cluster operations distributed approach can be used.
E. Developing multiple routing paths, route maintenance and or recovery in case of failure, mobility of PUs and SUs can be considered.
F. Price: New model can be developed for spectrum trading for various QoS level requirements.

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