



OPTIMISING APPLICATION PERFORMANCE WITH QOS SUPPORT IN
AD HOC NETWORKS

By

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I would like to dedicate this thesis to my loving parents who sacrificed their lives for my education.

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(Jims Marchang)

ABSTRACT

The popularity of wireless communication has increased substantially over the last decade, due to mobility support, flexibility and ease of deployment. Among next generation of mobile communication technologies, Ad Hoc networking plays an important role, since it can stand alone as private network, become a part of public network, either for general use or as part of disaster management scenarios.

The performance of multihop Ad Hoc networks is heavily affected by interference, mobility, limited shared bandwidth, battery life, error rate of wireless media, and the presence of hidden and exposed terminals. The scheduler and the Medium Access Control (MAC) play a vital role in providing Quality of Service (QoS) and policing delay, end-to-end throughput, jitter, and fairness for user application services. This project aims to optimise the usage of the available limited resources in terms of battery life and bandwidth, in order to reduce packet delivery time and interference, enhance fairness, as well as increase the end-to-end throughput, and increase the overall network performance.

The end-to-end throughput of an Ad Hoc network decays rapidly as the hop count between the source and destination pair increases and additional flows injected along the path of an existing flow affects the flows arriving from further away; in order to address this problem, the thesis proposes a *Hop Based Dynamic Fair Scheduler* that prioritises flows subject to the hop count of frames, leading to a 10% increase in fairness when compared to a IEEE 802.11b with single queue. Another mechanism to improve network performance in high congestion scenarios is network-aware queuing that reduces loss and improve the end-to-end throughput of the communicating nodes, using a medium access control method,

named *Dynamic Queue Utilisation Based Medium Access Control* (DQUB-MAC). This MAC provides higher access probability to the nodes with congested queue, so that data generated at a high rate can be forwarded more effectively. Finally, the DQUB-MAC is modified to take account of hop count and a new MAC called *Queue Utilisation with Hop Based Enhanced Arbitrary Inter Frame Spacing* (QU-EAIFS) is also designed in this thesis. Validation tests in a long chain topology demonstrate that DQUB-MAC and QU-EAIFS increase the performance of the network during saturation by 35% and 40% respectively compared to IEEE 802.11b.

High transmission power leads to greater interference and represents a significant challenge for Ad Hoc networks, particularly in the context of shared bandwidth and limited battery life. The thesis proposes two power control mechanisms that also employ a random backoff value directly proportional to the number of the active contending neighbours. The first mechanism, named *Location Based Transmission using a Neighbour Aware with Optimised EIFS for Ad Hoc Networks* (LBT-NA with Optimised EIFS MAC), controls the transmission power by exchanging location information between the communicating nodes in order to provide better fairness through a dynamic EIFS based on the overheard packet length. In a random topology, with randomly placed source and destination nodes, the performance gain of the proposed MAC over IEEE 802.11b ranges from approximately 3% to above 90% and the fairness index improved significantly. Further, the transmission power is directly proportional to the distance of communication. So, the performance is high and the durability of the nodes increases compared to a fixed transmission power MAC such as IEEE 802.11b when communicating distance is shorter. However, the mechanism requires positional information, therefore, given that location is typically unavailable, a more feasible power control cross layered system called *Dynamic Neighbour Aware – Power controlled*

MAC (Dynamic NA -PMAC) is designed to adjust the transmission power by estimating the communicating distance based on the estimated overheard signal strength.

In summary, the thesis proposes a number of mechanisms that improve the fairness amongst the competing flows, increase the end-to-end throughput, decrease the delay, reduce the transmission power in Ad Hoc environments and substantially increase the overall performance of the network.

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Abbreviation

CP: Contention Period

CFP: Contention Free Period

LAN: Local Area Network

HIPER-LAN: High Performance Radio LAN

MANET: Mobile Ad Hoc Networks

QoS: Quality of Service

VANET: Vehicular Ad Hoc Networks

TDMA: Time Division Multiple Access

CSMA: Carrier Sense Multiple Access

CSMA/CD: Carrier Sense Multiple Access with Collision Detection

CSMA/CA: Carrier Sense Multiple Access with Collision Avoidance

CSMA/VT: Carrier Sense Multiple Access with Virtual Time

RTT: Round Trip Time

LR: Loss Rate

TTL: Time To Live

TCP/IP: Transmission Control Protocol (**TCP**) and the Internet Protocol (**IP**)

MAC: Medium Access Control

OLSR: Optimised Link State Routing Protocol

DSDV: Destination Sequenced Distance-Vector Routing

AODV: Ad hoc On-Demand Distance Vector

DCF: Distributed Coordination Function

NAVs: Network Allocation Vectors

DIFS: DCF Inter-Frame Spacing

SIFS: Short Inter-Frame Spacing

EIFS: Extended Inter-Frame Spacing

RTS: Request To Send

CTS: Clear To Send

ACK: Acknowledgement

MTU: Maximum Transfer Unit

MCCA: Mesh Coordinated Channel Access

IEEE: Institute of Electrical and Electronics Engineers

EY-NPMA: Elimination-Yield Non-Pre-emptive Priority Multiple Access

EDCA: Enhanced Distributed Channel Access

FIFO: First In First Out

CBR: Constant Bit Rate

EXP: Exponential Traffic

SINR: Signal to Noise Ratio

BER: Bit Error Rate

UDP: User Datagram Protocol

HBDFS: Hop Based Dynamic Fair Scheduler

SDTQ: Single DropTail Queue

QU-EAIFS: Queue Utilisation with Hop Based Enhanced Arbitrary Inter Frame Spacing

EAIFS: Enhanced Arbitrary Inter Frame Spacing

CW: Contention Window

LBT-NA : Location Based Transmission using a Neighbour Aware

CS: Carrier Sense

CCA: Clear Channel Assessment

PLCB: Physical Layer Convergence Protocol

NA-PMAC: Neighbour Aware- Power Control Medium Access Control

GPS: Global Positioning System

Chapter 1. Introduction

1.1. Wireless Ad Hoc Networks

The ever growing demand for communication in modern society is simplified by wireless technology, with Ad Hoc networks being an excellent example. An Ad Hoc network is formed between two or more nodes without the need of any central controller. Ad Hoc networks have been gaining popularity in recent years due to the speed of configuration and ease in deployment, but providing Quality of Service (QoS) and optimising the utilisation of the limited network resources remain a challenge. Ad Hoc networks follow the OSI or TCP/IP layered architecture (Sun Microsystems Inc., 1995), but crossing between layers would optimise the utilisation of network resources more efficiently.

In terms of single hop communication using a wireless Access Point (AP), interconnection with devices in the Local Area Network (LAN) is restricted by area coverage and limited shared resources. The IEEE 802.11 standard defines two categories of wireless LAN: infrastructure and Ad Hoc based (Katz, R.H., 1994). Infrastructure-based wireless LANs use one or more mobile stations (MSs) connecting via an access point (AP). APs are not typically mobile and they are responsible for connecting any MSs within their sensing range, as the MSs connectivity is limited to a certain area. On the other hand, Ad Hoc networks are not supported by any infrastructure. In an Ad Hoc Network each mobile station is independent and each station can be in one of three modes: sending, relaying or receiving. All the mobile devices involved in Ad Hoc network coordinate and cooperate among themselves when communication takes place between any source and a destination pair without any central controller or any infrastructure as shown in Figure 1.1. Since each node is an independent entity and is capable of connecting to any other node, setting a such network

is easy. Being independent of any form of fixed infrastructure, Ad Hoc networks are more flexible. Such networks will fail, if and only if all the participating nodes fail or all the other nodes are out of radio range. Ad Hoc networks can work in isolation or can be incorporated within an infrastructure network.

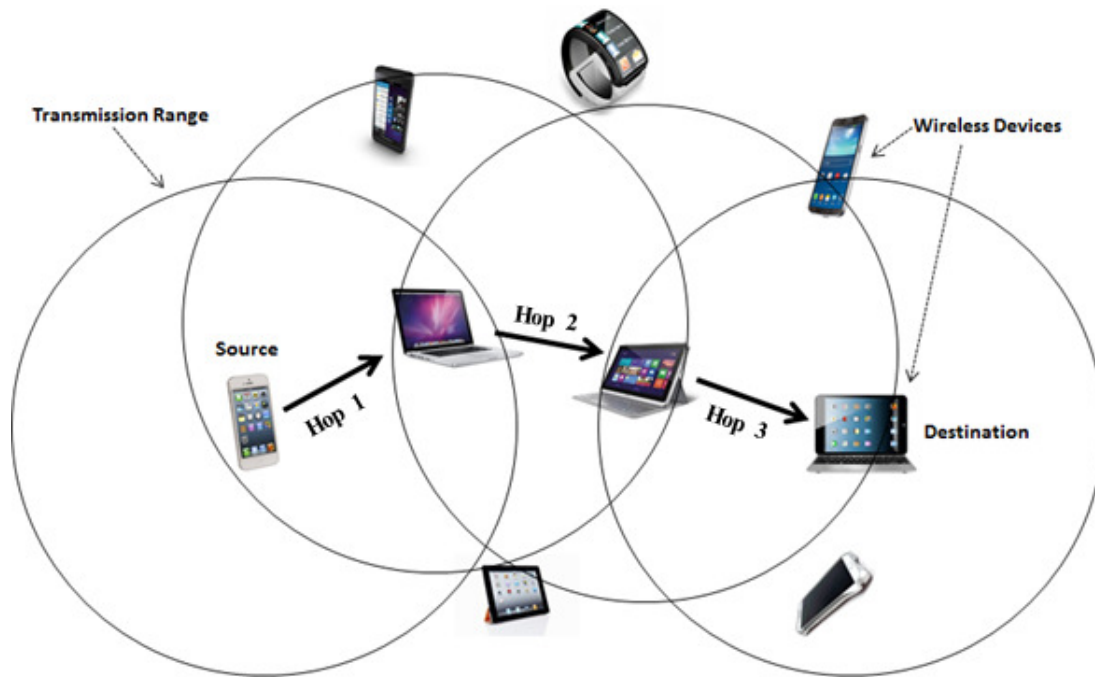


Figure 1.1: Multihop Ad Hoc Networks

1.2. Ad Hoc Network Challenges

Interference and hidden nodes of Ad Hoc networks affect bandwidth sharing due to the variation in the number of participating nodes and node transmission power. Thus, provisioning QoS and optimisation are challenging in this context because of the lack of central controller, node mobility, and frequent changes of network topology, interference and limited resource availability (Ramanathan *et al.*, 2002). (Reddy *et al.*, 2006) surveyed the issues and solutions of wireless Ad Hoc networks and discusses how an Ad Hoc networks

suffer heavy performance degradation due to the hidden node problems, which leads to high collision rates, so aiming to reduce collisions is another aspect of the research. (Kosek-Szott, K., 2012) highlighted the hidden node problems and concluded that they cannot be resolved in a traditional method when antenna are directional, multiple channels are considered and when the transmission power of different active nodes varies. Throughput analysis of directional antennas is described in (Chen *et al.*, 2013). Mobility leads to rapid changes of connectivity and in the worst case, complete isolation from the network, in the context of the user expecting reliable connectivity, despite the rapid changes in link state and route states. Efficient power management to reduce interference and increase the reuse factor of each of frequency channel is highly advantageous in optimising the performance of the network. In view of satisfying the required QoS, providing fairness within same traffic type to support satisfying end-to-end throughput at the user application level is also important. Other issues which involve critical challenges are optimising the network performance and supporting delay sensitive data to ensure QoS, network security, connection and interoperation with heterogeneous MESH networks and scalability issues. Recent advances are discussed in (Basagni *et al.*, 2007; Juan Zheng *et al.*, 2012). The paper of (Conti *et al.*, 2014) also discuss a new challenge of Ad Hoc networking where mobile phone sensing with a mobile phone cloud technique is considered for cloud computing.

1.3. Application Area of the Thesis

The focus of the thesis is to design mechanisms to improve QoS in terms of providing higher end-to-end network performance, ensuring fairness among the contending traffic, remove or avoid hidden node issues and save battery life for Ad Hoc networks. The application of the thesis is mainly focused on linear and random node deployment with restriction on node mobility on a flat surface. In order to meet the real application

environment, various types of traffic and range of packet sizes are considered. It is not possible to achieve high network performance with fairness by avoiding packet loss with low delay or jitter, all at the same time. So, the thesis aims to provide a trade-off between throughput, packet loss, delay and fairness to optimise the utilisation of shared resources.

1.4. Contributions of the Thesis

The thesis contributed in five main aspects in ensuring high performance, avoiding hidden node issues, saving energy, and providing fairness. Firstly, in order to provide fairness among the flows with packets with various hop count, packets are scheduled based on the transited number of hop. Secondly, the end-to-end network performance during network saturation is increased by using a fast packet forwarding technique. But during network saturation reducing packet loss to increase the end-to-end throughput compromised the average end-to-end delay or jitter of the packets in a multi hop environment. Thirdly, in order to further increase the network performance, transmission powers of the active nodes are controlled based on the distance of communication and reduces the interfering range to increase the probability of concurrent transmission. In order to avoid hidden nodes, transmission powers are also dynamically adjusted based on the activity of the neighbours. Fourthly, an accurate deferring mechanism is designed by observing the busy state of the channel to ensure fair channel access and lastly, a backoff mechanism based on the number of active surrounding neighbours is also designed to avoid unnecessary deferring during contention.

1.5. Projected Solutions to Provide QoS

This thesis aims to improve the fairness among multiple flows of traffic, improve end-to-end throughput and provide better overall network performance. This thesis aims to

investigate the relationship of hop count of the path length and the end-to-end throughput. When additional flows are introduced along the same path of another flow, it is challenging to maintain a good degree of fairness among the flows, so a dynamic hop based scheduler is proposed to increase the degree of fairness among the contending flows. Packet loss will be significant when congestion occurs, especially for real time streams that do not adapt to network conditions. The second part of the project aims to enhance the end-to-end performance of the network by following a fast forwarding technique when the queue gets congested towards the next hop which is less or not congested. In a situation when two contending nodes have the same queue utilisation, nodes will allocate a higher probability of accessing the shared channel to traffic that transited a higher hop count.

Interference range is directly proportional to the transmission range and, given the channel is shared, simultaneous communication and bandwidth reuse is difficult when fixed transmission methods are used. In a fixed transmission range methods, following the IEEE 802.11 standard, transmission power does not vary with the distance between even if the communicating nodes are close, communication takes place with a fixed high transmission range, and thus unnecessarily disturb the surrounding with higher area coverage, wastes energy and stopped other active node from participating by deferring channel access. To address this issue, the thesis proposes a distance and signal-dependent transmission power control mechanism to enhance the overall network performance and increase battery life. Using large backoff values in low node density scenarios leads to poor results, therefore the thesis also proposes a backoff mechanism based on the number of active nodes within the transmission range. Overall, the thesis aims to provide a higher degree of fairness among multiple contending flows, higher end-to-end throughput and to increase the overall network performance by using only the necessary energy during communication.

1.6. Thesis Outline

The introductory chapter is followed by a state of the art literature review in Chapter 2. The motivation and the problem statements of the thesis are elaborated in Chapter 3. A new scheduler to provide fairness among multiple flows is then presented in Chapter 4 and Chapter 5 proposes two variants of Medium Access Control (MAC) based on the utilisation status of the active queue and a hop based Enhanced Arbitrary Inter Frame Spacing. In order to achieve a higher degree of parallel transmission and increase the overall network performance in the resource constrained Ad Hoc network, two variants of power controlled MAC are designed in Chapter 6. The first designed of the power control MAC is based on location information and the activity of the neighbours and the variant is based on estimation of transmission power based on the overheard signal strength. In both the cases, the backoff mechanism is based on the number of the active contending nodes within its transmission range. The performance of the designed power controlled MACs is discussed and analysed in detail in Chapter 7. The thesis is completed with a conclusion and future directions in Chapter 8.

1.7. Summary

User mobility is made possible only due to wireless communication technology. Wireless communication is growing at a steady pace and allows the user get connected anywhere and at any time with lots of flexibility. Multihop Ad Hoc networks are a type of network whose application is immense due to its ease in deployment and lack of infrastructure. Multi hop wireless communication is still maturing, but ensuring QoS remains a challenging task due to the lack of central controller and limited shared resources apart from inherent problems of hidden nodes, mobility and interference. Amid the challenges, the

project aims to provide fairer access, higher end-to-end throughput and improved the overall network performance.

Chapter 2. Ad Hoc Networks and Challenges in supporting QoS

2.1. Ad Hoc Networks Application

Ad Hoc Networks have a vast range of applications from military communication in battlefield and isolated areas and sensor networks for remote data collection, to emergency scenarios, including disaster recovery, earthquakes, or traffic control. In addition, Ad Hoc networks can also be used for educational purposes and for decentralised communication and network access in public places.

2.2. Evolution of Ad Hoc Networks

The idea of multihop mobile Ad Hoc networks emerged in the 1970s when Bluetooth (IEEE 802.15.1) for personal area network was realized, where user devices were allowed to communicate within a hop. Research for multi hop became more popular when IEEE 802.11 standards for wireless LAN became reality with high-speed connectivity within its transmission range (Basagni *et al.*, 2004, Imrich *et al.*, 2003). The success of direct communication between wireless entities was then extended from single hop to multihop communication. The MANET research group focuses on establishing the network without any form of infrastructure and no need of any authority for controlling and managing such network, but with full TCP/IP support. The following sections describe the four main types of Mobile Ad Hoc Networks (MANETs) - *MESH network*, *Sensor network*, *Opportunistic network* and *Vehicular networks* and challenges and new research direction in such areas are presented by (Conti *et al.*, 2014).

2.2.1. MESH Networks

The backbone of such network is formed by using dedicated mesh routers which are generally fixed. Wireless mesh networks generally consist of mesh clients, mesh routers and gateways. The clients are often tablet, laptops, cell phones etc., while the mesh routers forward network traffic to and from the gateways which may be connected to the outside world through internet. A multihop routing strategy is used for establishing a route among the routers and the mobile users. Mobile nodes are allowed to connect to any one of the wireless router for end-to-end communication. One of the routers can be connected to the internet and act as the gateway to the Mesh network and via this router all the mobile nodes connected to the Mesh can access resources from the outside world. It is still a challenge to support node's mobility across the Mesh access points when seamless transfer and support QoS are taken into account. Discovering and maintaining a path with QoS support and sustaining the required QoS for the user application during node's mobility is still difficult. In order to support the service requirements of the users, different solutions in Mesh networks are provided by (Basagni *et al.*, 2013; Bakhshi *et al.*, 2011; Skalli *et al.*, 2007; Franklin *et al.*, 2012).

2.2.2. Wireless Sensors

Wireless sensors are multihop Ad Hoc networks designed for data collection and monitoring, therefore the design of such networks is focused on efficient MAC and routing protocols to support QoS, reflected in optimal battery life and information delivery. The collected information from the sensors is passed on to the sink node (gateway) with a multihop mechanism and then eventually the information is directed towards the Internet for remote access. Sensors are intended to collect data with flexibility in deployment at any place, battery life is critical since nodes will not be collected if deployed in hazardous areas. Different authors have conducted surveys and

propose optimisation solutions for wireless sensors in (Akyildiz *et al.*, 2002; Konstantopoulos 2013; Vieira *et al.*, 2003; Munir *et al.*, 2010).

2.2.3. Opportunistic Networking

Typically, mobility is a significant issue within a multihop wireless communication network in the context of maintaining QoS for user application. Opportunistic networks exploit this issue by creating contact opportunities that can be used to connect parts of the network that are otherwise disconnected. Unlike MANETs, a route to the destination node is not a prerequisite and nodes are allowed to carry along the buffered frames until a next hop node is discovered to finally forward the data to the destination. This allows data delivery despite not having a direct end-to-end connectivity between source and destination by exploiting the sequence of connectivity graph generated by the movement of nodes (Acer *et al.*, 2011; Ferretti 2013). The performance may not be efficient, but this idea gave rise to Vehicular Ad Hoc Networks (VANET). Routing in such networks still faces acute problems like uncertainty of its connectivity in future and understanding the nature and characteristics of the movement of nodes.

2.2.4. Vehicular Networking

Vehicular Networking is a specialised multihop Ad Hoc network where moving vehicles communicate among themselves. Its main aim is to reduce traffic congestion, supplying carrier traffic information, warnings of obstacles, safety messages in order to reduce high levels of traffic road accidents etc. The paper of (Hossain *et al.*, 2010) presents a detailed survey on applications of vehicular networking. A challenge is in maintaining connectivity in sparse traffic condition.

2.3. Working Principles of Ad Hoc Networks

The general problems faced by multihop Ad Hoc networks are due to limited shared bandwidth, interference, hidden nodes, and mobility. In a resource-constrained environment using Time Division Multiple Access (TDMA), users are forced to wait for their turn even when the assigned slots of other users go unused and this is unproductive in a limited shared bandwidth environment. In an Ad Hoc network, any node may join or leave the network at any time. Moreover, any node can move at any time, so the dynamic requirement of such network is not suitable for TDMA channel access methods, because it needs a controller which will cooperate and coordinate the participating nodes to synchronise and assign time slot. In order to avoid control overhead and adapt to the dynamic participation of the distributed Ad Hoc nodes, a contention based Carrier Sense Multiple Access (CSMA) access mechanism works well for Ad Hoc networks. However, in a contention based channel access, it's hard to provide fair channel access, but TDMA can handle fair channel assignment successfully, depending on the requirement of the service and traffic type. CSMA is a probabilistic media access control where the node having a data verifies the absence of other traffic before sending. There are different approaches for CSMA access methods: non-persistent, 1-persistent and p-persistent. In non-persistent CSMA, the system is less greedy as it waits until the back-off period is over before it senses the channel again. This approach is efficient but delay is high. 1-persistent is the greediest method because as soon as the channel is idle, it starts transmission. If successful, then the delay is minimal, but this approach is not efficient. The last approach called p-Persistent is greedy but tuneable. In this approach, when the channel is idle, each sender transmits with a probability p . When collisions of data packet can be detected during data transmission and the access mechanism follows a non-persistent approach, CSMA can have following access techniques:

- Carrier Sense Multiple Access with Collision Detection (CSMA/CD): Enhances basic CSMA by terminating the transmission as soon as the collision is detected.
- Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA): The channel is sensed and, if a carrier is detected busy then the transmission is deferred by a random interval to avoid collision.
- Carrier Sense Multiple Access with Virtual Time (CSMA/VT): This mechanism is designed to avoid collision when two transmitting nodes generate signals simultaneously. It uses two clocks, a real system clock of the system and a virtual clock. If the channel is busy then the virtual clock freezes and when the channel is idle then it is reset (Molle *et al.*, 1985).

2.4. What is QoS?

Quality of Service in general means that the network aims to provide or guarantees some level of end-to-end service requirement; it is based on certain level of network parameter requirements, which can include bandwidth utilisation (end-to-end throughput), end-to-end delay, delay variation or jitter, probability of packet loss, or fairness. To be resilient and sustainable with the required QoS, the network must be adaptive in response to any sudden changes due to node movement or node failure or obstacle and must be robust with respect to user application demand and changes in the required network metrics.

In ensuring and providing good QoS in a network, there must be a trade-off among the network parameters in terms of delivery rate (throughput), delay, jitter, packet loss rate, and fairness. Providing QoS in a limited shared resource environment with no central controller and dynamic movement of nodes makes Ad Hoc networks very

challenging. In a multihop network, there is relationship between throughput, end-to-end delay and loss rates. When the loss rate is low then delay could be minimal and the end-to-end throughput may be maximised. In a long hop path with a shared channel, in order to experience high throughput, fast packet forwarding technique has to be followed by the relay nodes, otherwise all the neighbouring nodes will compete to access the channel and resulted in high loss of packets especially when network gets saturated and buffer overflow situation arises. So, in designing a network protocols in supporting QoS in a multihop environment, there should be a trade-off among these three network parameters.

Satisfactory QoS typically has the following prerequisites i.e. using the best possible path by the routing algorithm in terms of high end-to-end bandwidth availability or shorter path length, because more hops in a path leads to higher degree of contention and interference. Moreover, end-to-end delay increases as the number of hop between the source and destination increases. The next is the seamless establishment and transfer of new route when a link is broken between the source and the destination due to node mobility or node failure. Last, but not the least important concerns are that, configuration and scheduling policy of a queue, and the access mechanism. Scheduling policy and the access mechanism are the most crucial policies to aggregate and maximize the throughput, by minimizing to a tolerable delay and tuning to least possible data loss rate. Since, Ad Hoc networks use a limited shared bandwidth, reuse factor of frequency is low. Higher the path length, the higher is the resource requirement and lower the end-to-end throughput, due to sharing of limited available resources and overall increased in interfering area along the route. Increasing the transmission power will reduce the communicating path length, but an active node will affect the transmission of others previously unaffected nodes. Therefore, there should also be a trade-off between the transmission range and path length for optimising the performance of the network. A

higher transmission power may lead to a shorter life span of active nodes and it leads to high interfering space in the surrounding area. However, lower power of transmission may lead to higher number of hop count to reach the destination. Either way, every approach must aim to optimise the overall network performance and high end-to-end throughput with a support of good QoS.

The transport layer protocol sets the relationship between the per-flow throughput, delay and the data loss rate. The main network parameters necessary for satisfactory QoS are *throughput*, *delay*, *jitter*, *packet loss rate* and *fairness* as explained by (Floyd 2008). The loss rate at different hops along the route may be different, but the bottleneck that is formed along the path is of interest, because the source should not send data at a rate higher than processing capability of the bottlenecked node or the overall loss rate will continue to escalate.).

- Throughput

In multi hop Ad Hoc networks, since the bandwidth is shared, resources are limited and, since there are no central controllers, achieving high end-to-end throughput is a challenging task. The demand of the throughput varies depending on whether the traffic is real-time voice, real-time video or best effort traffic. (Floyd *et al.*, 2007) analysed and evaluated the throughput in terms of data transfer rate by considering a significant range of data transfer sizes and proposed a quick start of the connection in order to optimise performance of TCP and IP. In such a resource constrained multihop Ad Hoc environment, meeting the dynamic demands of different type of traffic is difficult, so determining an appropriate sending rate over an underutilised network path is necessary to optimise the end-to-end performance (Sarolahti *et al.*, 2007).

- Delay

The end-to-end delay has three components: processing time, transmission time, channel access time and queuing time. During network saturation and buffer overflow situation, queueing delay would be high for a long path length. If the hop count of a path length increases, the aggregated delay along the route increases drastically. The wireless channel is inherently erroneous in nature, which implies a higher retransmission rate compared to wired network. Moreover, the rate of data collision will also be high, if hidden nodes are high; thus, the rate of retransmission may further be raised and increases the delay. Delay per packet can be very sensitive for real time voice data, but may be more tolerable in the case of best effort traffic.

- Packet Loss Rate

When the number of active nodes within a transmission range is high then the degree of contention for channel access is also high. Buffer overflow due to network congestion is also the reason for loss of packets in the network. However, erroneous packets can always be retransmitted as long as the packets TTL and the attempt of retransmission are valid. During buffer overflow, packet loss either requires retransmission, while TCP slows down to readjust, or leads to poor application quality at the receiver for UDP traffic. A principle of congestion control for Ad Hoc network is discussed in (Floyd 2000). When the network is not saturated, increasing the buffer size can also reduce the packet loss rate.

- Delay Variation/Jitter

Real time traffic is particularly sensitive to jitter, so packets delivered too late can be either considered lost or tolerate the substantial impact on the quality at the receiving end-point. The challenges lie in minimizing the variation in the delay of arrival rate:

when the hop count along the path is high, the contention among competing nodes in a shared channel increases and thus it is challenging in minimising the variation of delay.

2.5. Issue of Fairness

Fairness is an important performance parameter, because distribution of resources should satisfy the service level demands of users without starving any node. Fairness can be measured between nodes, corresponding applications or users, sessions of the same flow or different flows. There are different approaches for measuring fairness, some of them are proposed by (Hahne 1986, Kelly *et al.*, 1998, Kelly 2001, Jiang *et al.*, 2005, His-Lu *et al.*, 2004, Zhou *et al.*, 2011, Bharath-Kumar *et al.*, 1981). In the thesis a popular fairness measuring technique proposed by (Jain, *et al.*, 1984) is used. It is a quantitative measure of fairness to avoid discrimination during resource allocation in a shared environment.

2.6. Issues Affecting QoS in Multihop Ad Hoc Networks

The main issues encountered while provisioning QoS in Ad Hoc networks are due to inherent network issues, technological issues and the nature of node positioning or network topology. All the three aspects are elaborated in the following section as explained by (Natkaniec *et al.*, 2013).

- **Inherent Issues:** Ad Hoc networks are inherently affected by the erroneous and unreliable wireless channel, acute application requirements, and difficulty in resource sharing for multiple flows with various network characteristics.
- **Technological Issues:** The technology used in Ad Hoc networks has its own limitations in terms of the type of the channel used and the direction of the antennas.

- **Node Positioning or Topology Issues:** The position of wireless nodes has a direct impact on the network performance. Limitations of the physical mobile node in terms of computational and battery life also affect the overall network performance in long run.

2.6.1. Medium Access Mechanism Issues

Medium access governs the rules for actual sending or forwarding the frames to the next hop. Since Ad Hoc networks are distributed in nature and each node is independent, coordinating among the participating nodes is difficult and providing end-to-end fairness among the multiple active flows is a challenging task.

- *Lack of Centralized Coordinator:* A network is dynamically set up by exchanging information with nodes within its transmission range. It uses the concept of relaying the information to the nodes within its transmission range. So, coordination among the nodes is done in a distributed manner.
- *Fairness Issues:* It is the challenge of the channel access mechanism so that no nodes are favoured over others. Neither should a node capture the channel nor should any node be starved. At the least, traffic of same class must be given the same access probability.
- *Synchronization Issues:* Since node location is distributed, synchronisation is difficult to achieve, but each node must involve in synchronising by coordinating and cooperation other endpoints.
- *Power Control:* Each node must be able to adapt with changes and vary its transmission range for better connectivity, but increasing transmission range will lead to higher interference. As a result, the MAC protocol must adapt dynamically and must be able to maintain and run the system with an optimal transmission range at all time. A detailed survey of the existing power controlled MAC protocols is elaborated further in section 2.10.
- *Signalling:* It is one important process which could update and inform its surrounding nodes about the network situation. But signalling must be done wisely, so that the control overhead should not decrease the overall end-to-end performance of a resource constrain network.

- *Misuse:* Some nodes may not adhere to the rules of the MAC protocol and this does have an adverse impact in providing good QoS in the network. For example, a node with an overall high data rate that is beyond what the MAC can handle can use up its buffer space and can conceal neighbours from passing through the node.

2.7. Optimising Resource Utilisation in Wireless Networks

The capacity of a wireless network with n randomly located nodes with each node capable of transmitting W bits/sec and provided that the nodes are deployed within a common transmission range, the throughput of a randomly chosen node is given by $\Theta(W/\sqrt{n \log n})$ as described by (Gupta, P., *et al*, 2000). However, the authors assumed that all the nodes are within a transmission range of each other, so in a multihop path, the overall performance would be much lower. If n is the number of nodes per unit area, then the achievable throughput between any source and destination pair is of the order of $\Theta(1/\sqrt{n})$, but mobility can further enhances the overall network capacity (Gupta *et al.*, 2001; Chau *et al.*, 2009), since the degree of interference varies and reuse of frequency may occur. According to (Hwang *et al.*, 2008), the per-node throughput of a static random wireless network consists of n source and destination pairs is $\Theta(1/\sqrt{n \log n})$. It is also found in (Li *et al.*, 2012) that the lower capacity bound depends on path loss exponent, but upper capacity bound does not, moreover it is also revealed that 3-D random or regular wireless networks have lower capacity to that of 2-D network due to higher degree of interference in 3-D. The authors of (Sarıkaya *et al.*, 2012) describe that the maximum allowable traffic to hit the saturation condition can be estimated by calculating the packet delivery and failure probability. The authors of (Comaniciu *et al.*, 2006) also discuss Ad Hoc network capacity for delay sensitive data traffic by relying on signal processing technique which can detect multiuser. The authors

of (Mao *et al.*, 2014) reveal a new evaluation method of the lower bound of the capacity of asymptotic infinite networks with a general node distribution, where the lower bound is dependent on the multiplicative factor of four parameters: firstly, a constant parameter which captures the impact of the distributing nature of the nodes in the network. Secondly, the data rate of the transmitting active node. Thirdly, the parameter $1/n$, where n represents the number of source-destination pairs sharing the network channel capacity and finally, the parameter $1/r$, where r represents the transmission range of the node.

Since the capacity of wireless network is limited and shared, focus should be made on optimising the available shared network resources to enhance the overall network performance. The following sections discuss the performance optimisation techniques used in terms of routing, admission control and MAC protocol.

2.7.1. QoS Based Routing in Ad Hoc Networks

The challenges for QoS routing in wireless multihop Ad Hoc networks is due to its dynamic varying network topology especially when the nodes are mobile. There are number of routing approaches. Some of the popular *Proactive / Table Driven Routing* include an Optimised Link State Routing Protocol (OLSR) is presented in (Clausen *et al.*, 2003) and (Badis *et al.*, 2006) describes an upgraded version of OLSR with QoS support. With respect to *Reactive / On Demand Routing*, different protocols like on-demand highly dynamic destination sequenced distance-vector routing (DSDV) for Mobile Computers is proposed in (Perkins *et al.*, 1994) and the dynamic source routing protocol for mobile ad hoc networks is designed in (Johnson 2003). To avoid the frequent update of route as in DSDV, an Ad Hoc on-demand distance vector routing protocol is proposed in (Perkins *et al.*, 2003) and the same authors proposed another version of AODV with QoS support in (Perkins *et al.*, 2003). One typical example of a *Hierarchical / Hybrid Routing* protocols is proposed by (Sivakumar *et al.*, 1999), where a distributive set of

nodes in the Ad Hoc networks is dynamically selected to form the core, which maintains local topology and performs route calculations. Other routing approaches to support QoS can be based on prediction and location based (Shah *et al.*, 2002). Power aware routing is another approach to sustain the stable and an optimised link (Singh *et al.*, 1998; Toh 2001; Shah *et al.*, 2002). A QoS support routing protocol that guarantees end-to-end delay for IEEE 802.11 is proposed by (Abdrabou *et al.*, 2009) and many other QoS based routing for distributed Ad Hoc networks are also designed by different authors in (De Rango *et al.*, 2012; Krishna *et al.*, 2012; Hanzo *et al.*, 2011; Abdrabou *et al.*, 2006; Baolin *et al.*, 2006; Lei *et al.*, 2005).

2.7.2. QoS Based Admission Control Ad Hoc Networks

Given the channel of the wireless link is shared; each node participating in an Ad Hoc network may receive frames from all nodes within its vicinity. Due to involvement of multiple hops in such network, ensuring end-to-end QoS is challenging, since the availability of bandwidth all along the route will vary so it is mandatory to predict the available bandwidth before admitting new flows, as described in (Yang *et al.*, 2005). In this context, evaluating the bottleneck along the entire route for a dynamic Ad Hoc network is critical, as the packets for an admitted flow may encounter bottlenecks along the route and fail to satisfy the required QoS after being admitted. If a hard QoS requirement is demanded by the source node for its new user application, then it should not be admitted unless end-to-end bandwidth requirement is satisfied (or be admitted with a degraded performance). Since the nodes in an Ad Hoc network are dynamic in nature and battery life is limited, link failure can be frequent, but at the same time bandwidth availability can be dynamic too. Different approaches can be used to measure the level of congestion, to decide if a new flow should be admitted or not. Knowing the network capacity also provides good information for admission control.

An adaptive admission control aiming to provide guaranteed throughput is proposed in (Renesse *et al.*, 2007). The authors of (Kettaf *et al.*, 2006) introduce an admission control that enables on-demand routing with bounded end-to-end delay and a guaranteed throughput. A class based QoS provisioning admission control method is described in (Haq *et al.*, 2004). Some other authors proposed a mechanism that controls the admission based on contention and capacity awareness of the network. Another paper (Calafate *et al.*, 2007) designs a distributed admission control mechanism for mobile Ad Hoc networks with a robustness of using multiple paths and guarantees the end-to-end throughput at the same time. An interference based admission control with a fair channel sharing with guaranteed throughput is proposed is (Sridhar *et al.*, 2006). Some of the recent works on admission control in view of supporting QoS are proposed in (del Pilar Salamanca Azula *et al.*, 2013; Zhao *et al.*, 2012; Alshamrani *et al.*, 2010; Abdrabou *et al.*, 2008; Canales *et al.*, 2007).

2.7.3. QoS Based Medium Access Control

With regards to provisioning QoS, a strict per flow guaranteed end-to-end requirement can be considered or a technique that satisfied a minimum application service requirement. Communication in ad-hoc networks is challenging particularly due to the shared channel, which introduces contention and interference, and the mobility of the nodes, which causes performance degradation and network inconsistency (Zheng *et al.*, 2012). QoS provisioning for a data flow inherently requires an intelligent dynamic resource allocation decision, based on acquiring resource information along the transit route, which should help the contending nodes to achieve higher QoS (Yang *et al.*, 2005). Based on saturated, unsaturated, and semi-saturated network conditions (Yang *et al.*, 2007), controls the throughput of the already admitted flows against the new flows. The situation becomes even more complex, when there are multiple competing data flows.

Requiring fairness leads to a trade-off between overall network utilisation and distribution of traffic between competing flows. Packets are prioritised by (Reddy 2007) using IEEE802.11e together with time to live and hop count to ensure low end-to-end delay and decrease packet loss. However, reordering and selection of packets are required for each individual packet, making it unrealistic from a complexity and processing perspective.

Internet Engineering Task Force standardised these two approaches, one with integrated service architecture called IntServ (Shenker *et al.*, 1994) and the other with differentiated services called DiffServ (Blake *et al.*, 1998). In order to support strict QoS, IntServ follows a specific and a rigid mechanism of access with a corresponding required scheduling technique. So, resource reservation technique is used to fulfil the strict demand of the QoS. A guaranteed QoS can be assured to a limited number of flows due to acute network resources. This deterministic technique restricts the traffic and number of flows, and increases the complexity when optimising the limited available network resources which change depending on the node mobility and node failure. Diffserv considers the approach of prioritizing per-frame basis and it can provide high end QoS and low latency to any critical network data traffic by differentiating the service types. Unlike IntServ, Diffserv can realize the need of various network parameters constrains of critical (voice and video streaming etc.) and non-critical traffic (file transfer and web browsing etc.). Diffserv uses a mechanism that classifies and marks data frames depending on a traffic class. The frame forwarding properties are set based on the class of the traffic, so different forwarding properties can assure transmission with low loss, low latency and varying throughput.

The advantage of Diffserv over IntServ is that it is easier to set up and it does not require any resource reservation for each traffic flow. But in Diffserv it is very difficult

to ensure the end-to-end behaviour of the network. Congestion and dropping of packets has to be handled more sensitively, memory requirement is more costly since every station behaves as a source as it forwards the packet per hop towards the destination. Providing the best possible path is the preliminary requirement to assure QoS, but the actual provision of QoS is to be set at the MAC layer. The access control mechanism can guarantee QoS by prioritizing the data packets based on Diffserv or by reserving resources as in IntServ. Since Ad Hoc networks is distributed in nature and has no central controller, Diffserv suits better for such a dynamic network. The collected packets of various flows in a node should be linked to the scheduling process and the access mechanism for supporting QoS in Diffserv. In IntServ, admission control and reservation policy with its corresponding scheduling technique help in providing strict QoS which can be expressed with quantitative values such as delay, jitter and data rate.

QoS metrics can be defined separately for different layers of the TCP/IP or OSI architecture. Application layer QoS metrics shows the QoS requirements of the user application. Network QoS metrics determines the quality of the end-to-end path from the source to the destination. MAC layer QoS metrics indicates the quality of the link in the network. The QoS of an end-to-end path directly depends on the QoS of each link on the selected path. The most common QoS metrics defined at the MAC layer that should be considered while evaluating QoS-aware MAC mechanism includes: minimum achievable throughput, maximum frame delay, maximum variation of frame delay (jitter), maximum frame loss ratio and ensuring fairness.

2.7.3.1. Distributed Coordinating Function

Most of the MAC protocols proposed are based on DCF because of the distributed nature of the Ad Hoc network. In this network configuration, each node contends for accessing the channel and data is transmitted in an asynchronous manner

using CSMA/CA - before each transmission the node checks the channel condition and if the channel is idle for a certain amount of time then it transmits, else it defers its transmission. There is still a chance of collision due to hidden and exposed nodes and the transmitting node cannot sense the channel during transmission so detection of collision in wireless communication is more complicated than that of wired technology. As a result, successful transmission in DCF relies upon reception of ACK; if an ACK is not received within a stipulated time, then the frame is considered lost and it is retransmitted. In order to avoid collision due to hidden and exposed terminals, control packets called Request To Send (RTS) and Clear To Send (CTS) are used. The actual interaction of any successful transmission of data frame is shown in Figure 2.1. The RTS and the CTS contain a duration field which defines the reservation time of the channel required to transmit the data frame along with its corresponding ACK packet. Any nodes which fall within the transmission range of the sender and overhear the reservation time sets its network allocation vectors (NAVs) accordingly and defers from sending and thus avoid collision. In order to avoid collision, when node A initiates RTS and receives CTS from node B, then node C defers sending to node B as shown in Figure 2.2. The Figure 2.3 shows how RTS and CTS help in allowing parallel transmission when two nodes B and C are within the transmission range of each other, but are intended to transmit to nodes A and D respectively. An Inter Frame spacing time called DCF Inter-Frame Spacing (DIFS) is used for RTS control packet and Short Inter-Frame Spacing (SIFS) are used for DATA, CTS and ACK. If the transmission of frames is erroneous, then an inter frame spacing called Extended Inter-Frame Spacing (EIFS) is used. To further reduce the chances of collision, a random backoff procedure is followed after deferring for an inter frame spacing. In general, a random backoff value is chosen from a range and the generated backoff value defines the random waiting time duration for each sender. For

differentiating the traffic and for assigning different priorities for different traffic different inter frame spacing and backoff are used in Ad Hoc networks.

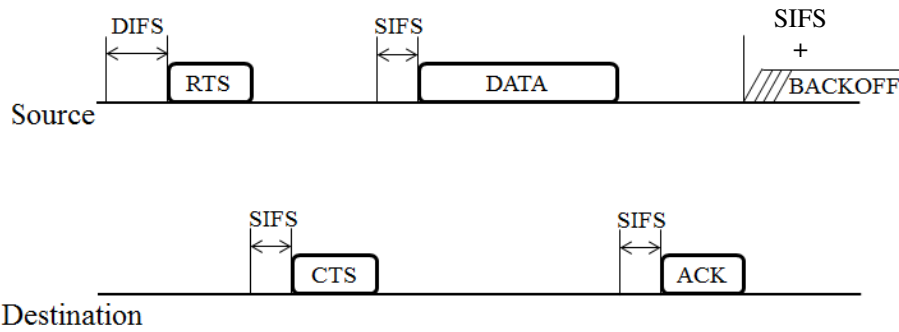


Figure 2.1: RTS-CTS-DATA-ACK interaction.

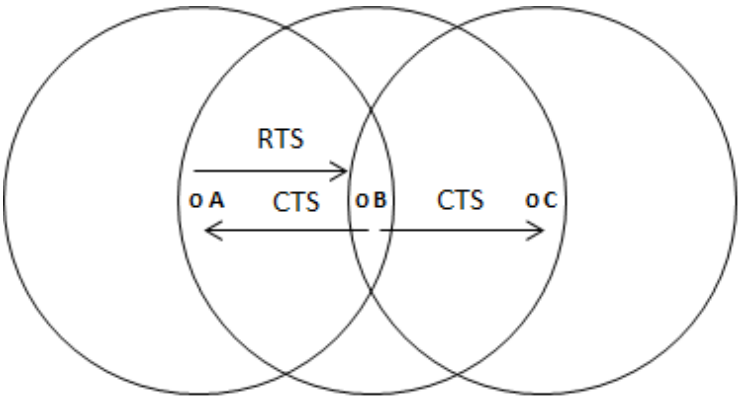


Figure 2.2: Solution of hidden terminal problem.

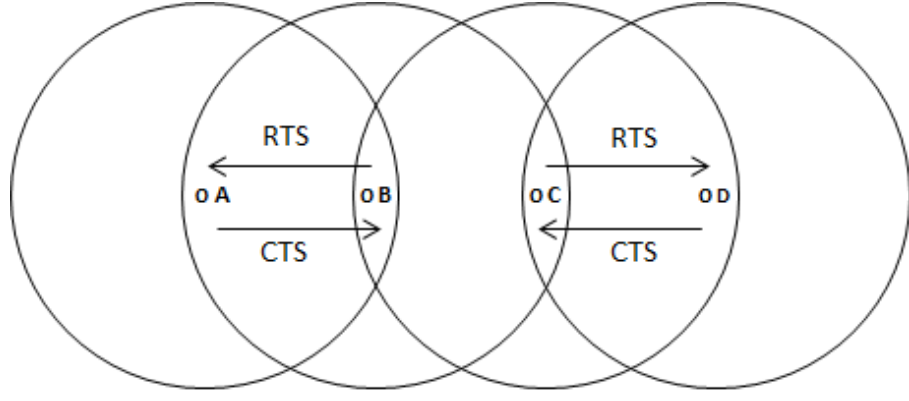


Figure 2.3: Solution of exposed terminal problem.

2.8. Recent Studies in QoS in Ad Hoc Networks

Apart from the dynamic nature of Ad Hoc networks and resource limitations, mobile devices of such networks work with slow processors, relatively small memory and low power storage (Karimi *et al.*, 2009). Communication in ad-hoc networks is challenging particularly due to the shared channel, which introduces contention and interference, and the mobility of the nodes, which causes performance degradation and network inconsistency. The provision of QoS in this environment is challenging and is the subject of considerable research (Hanzo *et al.*, 2009; Xiao *et al.*, 2009; Basagni *et al.*, 2007). The IEEE 802.11 DCF standard does not support QoS, while the IEEE 802.11e standard does support QoS, but it is designed only for a single hop environment and is based only on prioritizing different types of data traffic. QoS provisioning for a data flow inherently requires an intelligent dynamic resource allocation decision, based on acquiring resource information along the transit route, which should help the contending nodes to achieve higher QoS (Yang *et al.*, 2005). Prior studies considered the impact of delay and jitter induced by scheduling techniques (Zorić *et al.*, 2012), nodes mobility and dynamic interference (Renesse *et al.*, 2006), cluster based scheduling (Chao *et al.*, 2002,

Chao *et al.*, 2004), fairness and performance by enhancing random back-off values (Bergia *et al.*, 2008), as well as the overall capacity of the channel (Chen *et al.*, 2004). Among solutions proposed by prior studies (Natkaniec *et al.*, 2013; Kumar *et al.*, 2006; Reddy *et al.*, 2006), possible alternatives are to control or enhance the throughput of a flow by gathering capacity information such as bandwidth and delay at link layer (Kliazovich *et al.*, 2006). Fairness can generally be achieved by using different queues for different activity of the nodes (source or relay), or different queues for each flow with same or different priority while scheduling (Jun *et al.*, 2003).

Quality of Service (QoS) provisioning in Ad Hoc networks remains a challenging issue despite substantial research undertaken over the past decade (Mohapatra *et al.*, 2003; Khoukhi *et al.*, 2013) . Seminal papers have considered the capacity of a wireless network subject to multiple flows (Gupta *et al.*, 2000). Even in this case, due to high interference and limited bandwidth, network environments self-generate bottlenecks along multi-hop paths. The network saturates rapidly and end-to-end throughput decays rapidly with path length (Li *et al.*, 2001).

For a single multi-hop flow in an Ad Hoc wireless network, a node is considered active if it is a source node, a relay node, or a receiving node. In standard IEEE 802.11DCF, all active nodes have equal probability of accessing the medium, and a node with i active nodes within its interference range may gain access to the medium with a probability of $1/i$ when RTS and CTS control frames are not considered. In a chain topology, access probability of each node decreases when the hop count increases since the number of the interfering node increases. For a long chain topology, the highest degree of interference occurs around the centre of the chain and is lower towards either the source or the destination ends of the chain. So, for a single flow along a chain, the queue utilisation pattern will vary with the hop count. This motivates the design of a

medium access mechanism that dynamically depends on the queue utilisation of the participating nodes.

In order to improve the performance of resource constrained Ad Hoc networks, a number of protocols have been proposed by different authors: challenges and prospects of bandwidth allocation are discussed in (Su *et al.*, 2010) and a method of predicting the available bandwidth for optimising per node performance is proposed in (Li *et al.*, 2007).

Significant efforts focused on optimising the performance in multi-hop wireless Ad Hoc networks by controlling congestion and designing efficient MAC protocols. The IEEE 802.11DCF specification provides fairness across the active contending nodes within its transmission range (IEEE 802.11 WG, 1999) but, in order to differentiate services both in terms of throughput and delay and provide QoS, IEEE 802.11e was introduced with some variations in (IEEE 802.11 WG, 2005, Torres *et al.*, 2012; Xiao *et al.*, 2004). In order to enhance the performance of IEEE 802.11e, (Wang *et al.*, 2006) discusses a technique to avoid unnecessary polling of a silent station that generates voice traffic. In order to elevate the end-to-end throughput, hop-by-hop congestion control is discussed in (Yi *et al.*, 2007) and an end-to-end congestion control is also proposed in (Yu *et al.*, 2008). (Kaynia *et al.*, 2011) describes a method to optimise the sensing thresholds of the CSMA receiver and the transmitter by minimizing the outage probability by using SINR (Signal to Noise Ratio). A distributed contention window adaptation technique to adjust the incoming and the outgoing traffic is proposed in (Jung *et al.*, 2010). The paper of (Yu *et al.*, 2008) describes an interesting MAC protocol that allows a concurrent transmission among the neighbours. In order to optimise the contention window usage, the authors of (Deng *et al.*, 2008) also proposed a back-off generator based on contention level and the channel BER (Bit Error Rate) status.

2.9. Comparison of MAC Approaches for Supporting QoS

The mechanism of providing QoS techniques in MAC can follow a number of approaches: backoff differentiation, inter frame spacing differentiating, signal jamming, frame aggregation, dropping frames, changing priorities dynamically, data stream reservation policy, slot reservation scheme and alternating CP (Contention Period)/CFP (Contention Free Period). Backoff differentiation techniques (You *et al.*, 2005, Kosek-Szott *et al.*, 2010, Lee *et al.*, 2007, Geng *et al.*, 2009, Yang *et al.*, 2004, Seth *et al.*, 2011) and IFS differentiating methods (Chou *et al.*, 2003, Geng *et al.*, 2012, Bianchi *et al.*, 2003) are easy to implement, and waiting overhead is higher in backoff differentiation techniques compared to IFS differentiating methods. Jamming methods (Natkaniec *et al.*, 2002, Sobrinho *et al.*, 1999, Sobrinho *et al.*, 1996, Pal *et al.*, 2002) are also easy to implement and easy to detect the bursts, but energy consumption is high. Data frame aggregation methods (Garcia-Luna-Aceves *et al.*, 1999, Hamidian *et al.*, 2006) reduce contention and control packet overhead, but are appropriate only for small data frames and delay is induced during aggregation. Dropping frames techniques (Sarkar *et al.*, 2007) reduce congestion and delay for fresh frames, but they are not applicable for all types of traffic. (Kanodia *et al.*, 2002) designed a MAC that changes the priority of a node dynamically and the priority of a node is increased as the frame delivery rate increases. The issue with such mechanism is that when the frame delivery rate decreases the priority level of the node also decreases and may result in starvation when the flow encounters additional flows with a higher frame delivery rate. Stream and slot reservation techniques (Wu *et al.*, 2004, Jigang *et al.*, 2006, Cho *et al.*, 2011, Ahn *et al.*, 2000, Zhang *et al.*, 2007, De Rango *et al.*, 2007, Kamruzzaman *et al.*, 2010, Rozovsky *et al.*, 2001) can assure bounded throughput and delay, but additional signalling overhead is high and maintaining updated reservation table is costly.

Alternating CP/CFP methods (Sheu *et al.*, 2001; You *et al.*, 2002; Sivavakeesar *et al.*, 2004) segregate the periodic and the burst traffic, but implementation is complex and coordination of the AP and the users required during the contention free period. Despite lot of work carried out in designing MAC to support QoS, many authors failed to investigate in improving end-to-end throughput in a high path length where the source saturates the network by generating high data rate.

2.10. Radio Transmission Challenges

In a wireless communication, the performance is extensively affected not only by the capability of the device but also the environment and the surrounding in which the nodes are deployed. In a real life implementation, node deployment cannot be on a flat surface at all times and surrounding terrain and obstacles limit the connectivity and the performance of the wireless network. In a radio model, considering the nodes with same circular transmission range on a flat surface with a symmetric links may not happen in a real wireless application (Kotz *et al*, 2004) due to the nature of the environment. It is also not necessary that the transmission of the radio signal is circular in nature and all nodes may not have an equal radio range during communication. Thus, when the transmission range varies, node A may reach node B, but node B may not be able to reach node A due to asymmetric links. When a radio model considers the account of antenna height and orientation, terrain and obstacles, surface reflection and absorption etc., then the radio transmission model is more realistic. On the other hand, simple radio models may not be able to capture the complex environment (Zhou *et al*, 2004). The average signal strength fades with distance according to the power-law model considered, but (Rappaport, 2002) claimed that in a real environment, obstruction, reflection, refraction, and scattering may

impact the performance of the channel. Moreover, common simplified mobility and radio propagation models are not robust when nodes are deployed indoors (Cavilla *et al.*, 2004).

2.11. Power Controlled Medium Access Control Protocols

Different approaches were investigated by various authors to reduce interference and improve the performance of the overall network by controlling the transmission power. A power controlled MAC named POWMAC is discussed in (Muqattash *et al.*, 2004) and (Muqattash *et al.*, 2005) the authors use the RTS and the CTS control frames for advertising the signal strength and exchange N pairs of RTS/CTS messages for securing N concurrent transmissions. It also introduces an additional control frame and access windows to determine when to send the data concurrently, thus this approach involves a significant control overhead. In order to reduce the signalling burden, (Li *et al.*, 2009) proposed an adaptive power control MAC by using only the RTS and CTS for collecting transmission power of the active neighbours and interference level; in order to validate its claims, the study assumes that the transmission range and the carrier sensing range are identical, which is rather artificial as the carrier sensing range is typically greater than the transmission range. Such approaches use a maximum transmission power for RTS and CTS frames, but use only the required power for Data and ACK frames, so the probability of collision is high at both the sender and the receiving ends. To reduce the degree of collision in such power control approaches, a new power controlled MAC is proposed in (Kim *et al.*, 2006) which utilises the fragmentation mechanism of IEEE 802.11 MAC and controls the transmission power based on the fragmentation technique. In this mechanism, all the RTS, CTS, and ACK frames corresponding to fragmented data frames are sent with maximum transmission power except the last one, to reduce collision with the surrounding active neighbours. The limitation of this approach is that

fragmentation does not always occur unless the packet size reaches the Maximum Transfer Unit (MTU) of the link.

The energy utilisation model can be different from one perspective to another. Energy utilisation of an active nodes should cover processing power in terms of encapsulation/de-capsulation of packets, encoding and decoding of packet information, idle time, wake up energy if sleep mode is taken into consideration, transmission energy, reception energy, carrier sensing energy and node deferring energy etc. The authors (Ergen *et al*, 2007), (Garcia-Saavedra *et al*, 2011) and (Wang *et al*, 2006) consider an energy consumption model where energy is considered to be consumed during transmission, reception and idle modes. However, the authors (Serrano *et al*, 2015) extensively study the per-frame energy consumption model of IEEE 802.11 devices and concludes that a substantial fraction of energy is consumed even when packets cross the protocols stack. The authors also concluded that the energy consumed by a frame when it passes through the protocol stack is independent of frame size.

(Li *et al*., 2007) proposes a cross layer technique combining scheduling, routing and power control transmission, based on the Time Division Multiple Access (TDMA) mechanism, but in a resource constrained distributed Ad Hoc networks environment using deterministic access like TDMA is highly challenging due to synchronisation issues. In such approach, when the number of the participating nodes in the network changes then a new time allocation table has to be circulated. Moreover when the participating node does not have data to transmit, other nodes have to wait for their allotted turn. The authors of (Wang *et al*., 2008) show that, in order for optimal power control mechanism approaches to improve spatial utilisation, senders should not send with just enough power to reach the next hop node, but they should use higher transmission power. A power control transmission based on the interference and distance

estimation is designed in (Seth *et al.*, 2014), but the approach does not consider an important account where a low power transmissions for short distance and high power transmission with long distance could provide same interference level. Authors of (Shih *et al.*, 2005) propose a collision avoidance MAC based on adjusting the power level of the source node, so that active neighbours can withstand its interference level. (Jung *et al.*, 2002) present a power control MAC where the RTS-CTS are send with maximum power and the DATA-ACK are send with minimum power, but the DATA frame is send with maximum power periodically so that the neighbours within a carrier sensing range can sense its activity. This approach may save power, but the potential benefit of introducing parallel transmission is significantly reduced because nodes overhearing the RTS/CTS will avoid transmission and will wait for the necessary Network Allocation Vector (NAV) to avoid collision. To avoid such problems, the authors of (Varvarigos *et al.*, 2009) introduce a new method where the RTS messages are not sent with a constant maximum power; instead, transmission starts with a lower transmission power, which is also advertised in the message, but the CTS packets are sent with maximum power to alert any neighbours that have data to send. This may subsequently lead to varying transmission ranges from a same node, so active neighbours experience an uneven degree of interference, which may lead to unfair end-to-end throughput. Authors of (Cui *et al.*, 2010) introduce a mechanism where the transmission power is reduced based on the degree of contention by monitoring the contention window. A trade-off between the bandwidth, latency and network connectivity during transmission power control Ad Hoc networks is proposed in (Chen *et al.*, 2003). Focusing on the transmission power control, the study presented in (He *et al.*, 2008) suggests that obtaining an optimal transmission power is an NP-hard problem even if the node has the entire knowledge of the network and uses a deterministic approach to optimise the durability of the battery life. The

algorithm proposed in the study enhances the network performance by generating the minimum power needed by each node during data transmission with the help of location information and by observing its neighbour activity. Most of the authors fail to investigate the impact of hidden and exposed nodes generated due to use of varying transmission power and the issue of fairness needs further investigation.

In reality, it is hard to translate the power controlled algorithms into a corresponding hardware compatible device. There may be a lack of suitable hardware support in wireless cards to implement the power controlled mechanism too. The authors (Shrivastava *et al*, 2007), highlighted that in order to fully realised the importance of power control, the hardware designers need to support various number of possible power levels and the time granularity at which the power control can be implemented. The authors claimed that even if fine-grained power control mechanisms were introduced and made available by wireless card vendors, it will be hard for the mechanisms to properly leverage such degrees of control especially in an indoor environment.

2.12. Recent Standardised MAC Protocols

IEEE 802.11 medium access control MAC) and physical specification for wireless communication has developed from the legacy IEEE 802.11a/b/g to IEEE 802.11EDCA (IEEE 802.11e/QoS) which is a standardised MAC protocol for supporting QoS by means of traffic differentiation. A standard for wireless MESH networks is newly designed named Mesh Coordinated Channel Access (MCCA) (IEEE Standard, 2011). The following are the recently standardised IEEE 802.11 series:

- ✓ IEEE 802.11n: Enhancements for Higher Throughput, (*IEEE Standard, Specifications Amendment 5, 2009*).

- ✓ IEEE 802.11aa: Medium Access Control Enhancements for Robust Audio Video streaming, (IEEE Standard, *Specifications Amendment 2*, 2012).
- ✓ IEEE 802.11ae: Prioritization of management frames, (IEEE Standard, *Specifications Amendment 1*, 2012).
- ✓ IEEE 802.11ac: Enhancement for very high throughput for operation in bands below 6GHz, (*IEEE Standard, Specifications Amendment 4*, 2013)
- ✓ IEEE 802.11ad: Enhancement for a very high throughput in the 60GHz band, (*IEEE Standard, Specifications Amendment 3*, 2012)
- ✓ IEEE 802.11af: Use for television white spaces operation, (*IEEE Standard, Specifications Amendment 5*, 2013)

2.13. Conclusion

This chapter covers the various aspects of supporting QoS in wireless Ad Hoc networks. Many protocols have been designed to understand the nature of multihop Ad Hoc networks and support QoS. Some considered route stability and admission control for providing QoS while others explored medium access control by prioritizing the traffic and reducing the jitter. Considerable amount of work has been done for ensuring QoS in Ad Hoc networks, but ensuring good QoS and achieving fairness in multihop environment with a long path is still a challenge due to interference and limited shared bandwidth. After conducting an extensive literature survey, it is found that authors have not ventured into providing fairness based on the hop count of the transiting packets when a flow arriving from far encounters another flow along the same path. It is also found that authors have not studied on how to increase the end-to-end throughput of a high path length in a multihop environment when a source node generates or a relay node receives packets more than it can forward. In a power controlled Ad Hoc networks,

researchers have not studied location based power controlled and the impact varying transmission ranges due to node's location. Controlling the transmission power of a node leads to higher probability of generating hidden and exposed neighbours and fairness of channel access among the contending neighbours will be affected and providing fairness is one of the factors in ensuring QoS in an Ad Hoc networks. Some author use power estimation techniques based on the received signal strength, but the issue of unfair channel access due to varying transmission ranges are not fully addressed. Some authors consider an unrealistic approach by assuming that interference range and transmission range are similar and it is not the case in a real world. Therefore, the following chapter describes the motive behind the thesis in detail.

Chapter 3. Motivation

3.1. Problem statement

Amid the popularity of Ad Hoc networks, assuring Quality of Service (QoS) especially for real time data traffic is still challenging and optimising the resource sharing and utilisation in such network is critical due to interference, hidden nodes and limited shared bandwidth. The initial scope of the thesis is to studying the inherent issues and the problems faced by Ad Hoc networks Prior research has identified and aimed to improve on a series of limitations for Ad Hoc networks. The aim of this section is to outline the extent of the issues with Ad Hoc network environments, as reflected through a series of scenarios.

High hop count induces higher degree of interference and degrades the overall network performance, so this chapter investigates the relationship between the hop count and the end-to-end throughput. This chapter also investigates the impact of loss of packets during network saturation and provides directions on how to elevate the end-to-end throughput by reducing the packet loss rate. Further the chapter studies the impact of using high transmission power and provides mechanisms to increase the probability of concurrent transmission by controlling the power of data transmission. This chapter investigates and highlights the problems faced by standard scheduler like First in First out (FIFO) and the standard MAC protocols like IEEE 802.11b along with the drawbacks of the existing mechanisms provided by various authors. It also provides new directions to optimise the overall network performance. Thus, the thesis aims to optimise the overall network performance in a limited shared resource in heavily saturated networks and ensure fairness when transmission power is controlled in Ad Hoc networks.

3.2. Assumptions

The study is tested using a network simulator called NS2. Due to the limitation of the simulation tool and its environment, a simple wireless communication model with a perfect radio propagation channel is considered with the following assumptions:

- i. The surface of communication is flat.
- ii. A radio's transmission area is circular.
- iii. If node A can hear node B, then node B can also hear node A (symmetry), provided nodes don't move and uses a same transmission power.
- iv. If node A can hear node B at all, node A can hear node B perfectly.
- v. Signal strength is a function of distance.

One of the main drawbacks of using a simulator is that, during performance evaluation, it is not possible to capture all the real life effects of the surroundings on the wireless channel. Moreover, due to considering simplified models in NS2, the effects of obstruction, reflection, refraction, and scattering effects in wireless communication are also not captured entirely. Such limitations are also highlighted by (Cavilla *et al*, 2004). In reality, the radio propagation may not be circular and signal strength may not be a function of distance due to various environmental and surrounding effects on the wireless channel as mentioned by (Kotz *et al*, 2004). Therefore, the study in the thesis may not capture all the effects that could be experienced by a wireless channel in real life deployment. However, the study in the thesis is focused on how to provide fairness among the multiple competing flows, aim to reduce buffer overflow to yield higher end-to-end throughput and control the transmission power to generate higher probability of concurrent transmission by addressing the hidden node issues to ensure fairness. Thus, the impact of the limitations of the simulator will exist, but the study will still be valid

because the nodes are deployed in an open flat surface with no obstruction. Moreover, node mobility is restricted once deployed. If node mobility and uneven landscape with obstruction is considered then the evaluated performance may vary.

3.3. Hop Count and Fairness

In order to demonstrate the various issues related to supporting high network performance in Ad Hoc networks, a simulation based on NS2 with the network parameters listed in Table 3.1. In this study, NS2 is preferred to that of NS3, because it is well established and stable simulator in terms of the TCP/IP network architecture and the modules of each layer are bug free, whereas NS3 still faces issues with bugs in various modules, since it is developed recently. The TCP variant used in this thesis is Congestion Avoidance, which reduces sender's window size by half at experience of loss, and increases the sender's window at the rate of about one packet per *RTT*. The communication parameters such as Transmitter Gain (G_t), Receiver Gain (G_r), Height of Transmitter (h_t), Height of receiver (h_r), Frequency (f), wavelength (λ) of the corresponding frequency, System Loss (L), where the values of the antenna parameters of G_t , G_r , h_t , h_r , f and L are 1.0dBd, 1.0dBd, 1.5m, 1.5m, 914.0×10^6 Hz and 1.0 respectively. Since the study is focussed on fairness, buffer overflow, concurrent transmission and hidden node issues, so the bandwidth is not a factor in the study, so instead of using 2.4GHz, 914MHz is considered. During the study of network saturation when buffer overflow occurs, the size of the buffer is irrelevant, because during network saturation, there are more incoming packets then the capacity of the buffer space, so a buffer size of 100 and 200 packets are considered. Initial scenarios of the network topology is arranged and aligned with nodes spaced by 200m as shown in Figure 3.1, so an active node's interference range covers up to two hop neighbours. This linear

topology is setup to understand the effect of the end-to-end performance over the number of hops of any linear path. It also helps in understanding the packet forwarding rate along the path and study the loss rate at the same time during network, as the packets move towards the destination. The authors (Li *et al*, 2001) studied that the ideal capacity of a long chain of nodes in isolation should be $1/4$ of the raw channel bandwidth. However, simulation shows that chain capacity for 802.11 MAC achieves only $1/7$ of the channel capacity despite using a greedy sender, because nodes early in the chain starve later nodes due to interference. A greedy sender generating packets more than the node could forward leads to buffer overflow and contention with the next hop neighbours leads to further loss of packets. This study explores on how to limit loss of packets in such scenario in order to enhance the overall end-to-end throughput. Novel research solutions are proposed and analysed in chapter 4 and chapter 5 to ensure fairness in linear chain topology and delivering high end-to-end network performance respectively.

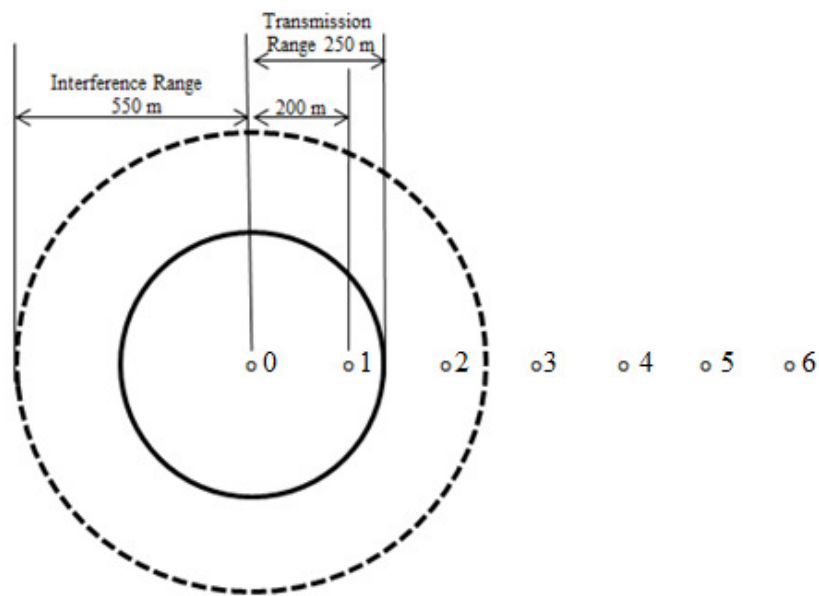


Figure 3.1. Topology settings of the Ad-Hoc Network

Parameter	Value/protocol used
Grid Size	2000m x 2000m
Routing Protocol	AODV/DSDV/DumbAgent
Queue Type	DropTail
Queue Size	100/200
BasicRate	1Mb/s & 2Mb/s
Bandwidth/DataRate	2Mb/s
SIFS	10 μ s
DIFS	50 μ s
Length of Slot	20 μ s
Default Power (Pt_)	0.28183815W
Default RXThresh_	3.652e-10W for 250m
Default CSThresh_	1.559e-11 W for 550m
Transmission Range	250m
Interference Range	550m
CPTthresh_	10.0
Max _{Retry}	7
Simulation Time	1000s
Traffic Type	UDP with CBR, TCP, EXP
Packet size	250/500/750/1000/1500 bytes

Table 3.1: Network Parameters.

In order to test the performance and saturation points of a chain network topology of different path length, simulations of a single flow using the standard DropTail queue were first performed using AODV routing protocol. Simulations of 1000 second with a queue size of 200 using UDP with CBR traffic of packet size 500bytes were carried out for 32 different source data rates starting from 32kb/s up to 1024kb/s to determine the throughput for path lengths starting from one hop to six hops. The result is shown in Figure 3.2 and there are a number of conclusions from this data. Firstly, for a single hop, the throughput is directly proportional to the data rate of the source. Even in the case of a single flow, the generated traffic creates self-contention and interference along the path, leading to a saturation of throughput. The saturation values are shown in Figure 3.3,

indicating that the throughput is inversely proportional to hops. The overall packet loss is increased as the path length increases.

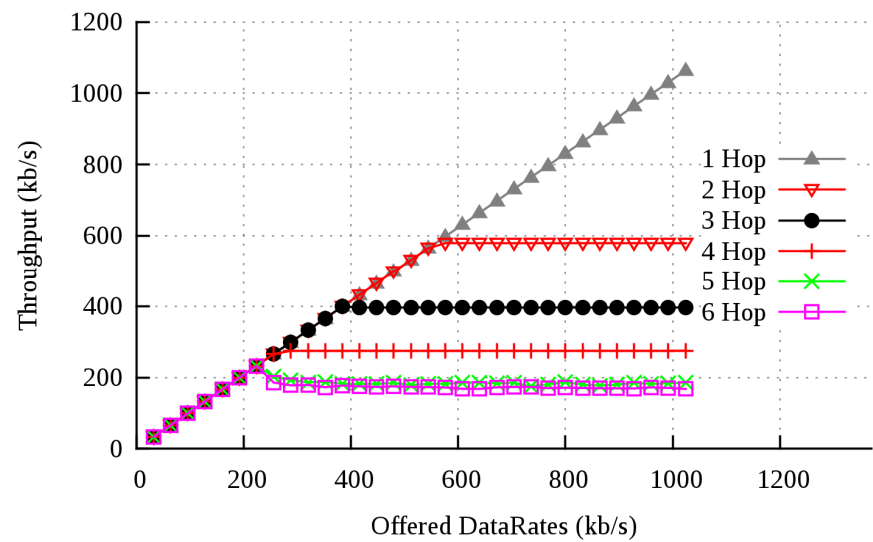


Figure 3.2. Throughput Vs Hops

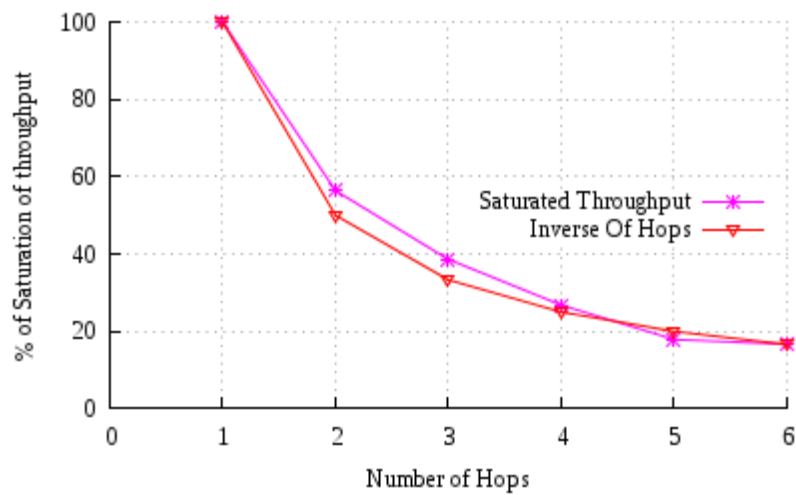


Figure 3.3. Saturation points of the throughput Vs number of hops

Legacy IEEE 802.11 standards provide equal probability of accessing the network for all the contending nodes of any traffic types. IEEE 802.11e was designed to ensure

QoS and prioritize services, and it can differentiate between different types of network traffic classes by assigning priorities, but the performance is poor. Typical end-to-end throughput of IEEE 802.11b traffic flows is higher than IEEE 802.11e flows, but the QoS-aware protocol is able to discriminate the traffic according to its classes. Neither the IEEE 802.11 standards nor IEEE 802.11e care about the traffic that transited multiple hops and the path length of the source and the destination pair. There is contention at each hop, so as the path length increases the overall contention increases. Thus, increasing path length enhances the degree of contention, so is the overall interference in Ad Hoc networks. So, it is expected that network will saturate faster as the hop count of the path length increases.

To investigate in a more quantitative manner, consider two data flows as in Figure 3.4, where, f1 is a flow generated by node A in all the scenarios of the given chain topology and f2 is a flow generated by node C, D and E in scenario (I), scenario (II) and scenario (III) respectively of the same figure. The two data flows (f1, f2) are generated from different sources, transit different path lengths, and transport different data rates. A set of network simulations were run to determine how the bandwidth is shared when the sum of the data rates of the two flows are fixed, while varying the ratio between the two flows. The total fixed load (sum of the data rates of f1 and f2 is fixed) for each simulation set is given in the first column of Table 3.2.

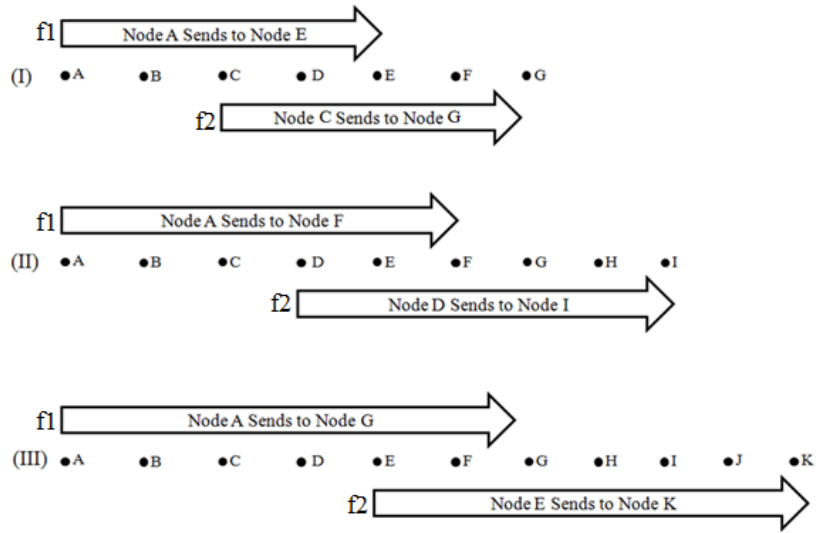


Figure 3.4: Simulation Scenarios with multiple flows and (I) Four hop path length, (II) Five hop path length, and (III) Six hop path length.

For each simulation, Table 3.2 records the average values of the data rates of the sources with flows (f1,f2) for the two competing flows to lead to equal throughput at their respective destinations. The results clearly show that when two data flows compete, the flow generated locally (f2 in this case) takes over the other flow and in order for the two flows to generate a comparable fair throughput, the flow with higher hop count will require a significantly higher source's data rate. However, when the network is not saturated both the flows (f1,f2) shared the channel perfectly, otherwise f1 has to be generated with higher data rate to compete with flow f2.

Total Loads (kb/s)	Scenario I. (f1,f2) kb/s	Scenario II. (f1,f2) kb/s	Scenario III. (f1,f2) kb/s
132	(68,64)	(68,64)	(68,64)
332	(212,120)	(248,84)	(248,84)
632	(509,123)	(554,78)	(563,69)
932	(815,117)	(851,81)	(851,81)
1056	(941,115)	(977,79)	(977,79)

Table 3.2: Per flow offered load for Ideal fairness.

In order to elaborate and understand the issue of starvation of a flow arriving from far when a new flow is encountered, a chain topology of Figure 3.4 with a node placement of 200m apart is considered with two CBR flows where node A sends to G (flow f1) and node E sends to K (flow f2) using IEEE 802.11b with a Single Drop Tail Queue (SDTQ).

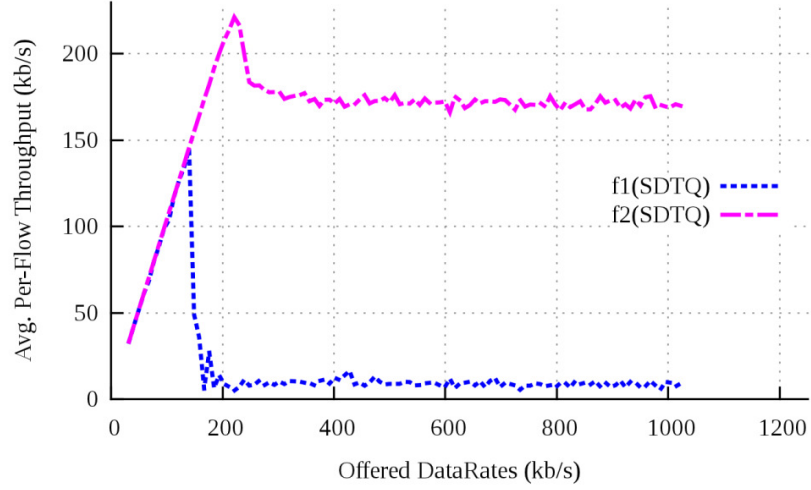


Figure 3.5: Performance of Multi Flows in a Multihop Chain Topology.

The simulation results in Figure 3.5 shows that the f1 arriving from far is taken over by f2, which is introduced along the path of f1. When the data rate of the source of flow f1 is over 150kb/s, the end-to-end throughput drops to 10kb/s despite increasing the data rate of the source, which is due to the presence of f2 generating packets at a higher rate unlike the flow arriving at a low rate from the distant f1 source. The fairness index is calculated by using the Jain's fairness index (Jain *et al.*, 1984) i.e. (3.1), where x_i represents the i^{th} flow and the result is shown in Figure 3.6. In a Jain's fairness index when the number of flows $n = 2$, a fairness index of 50% implies that one flow starves and the other flow has captured the channel.

$$f(x_0, x_1, x_2, \dots, x_n) = \frac{(\sum_{i=0}^n x_i)^2}{n \sum_{i=0}^n x_i^2} \quad (3.1)$$

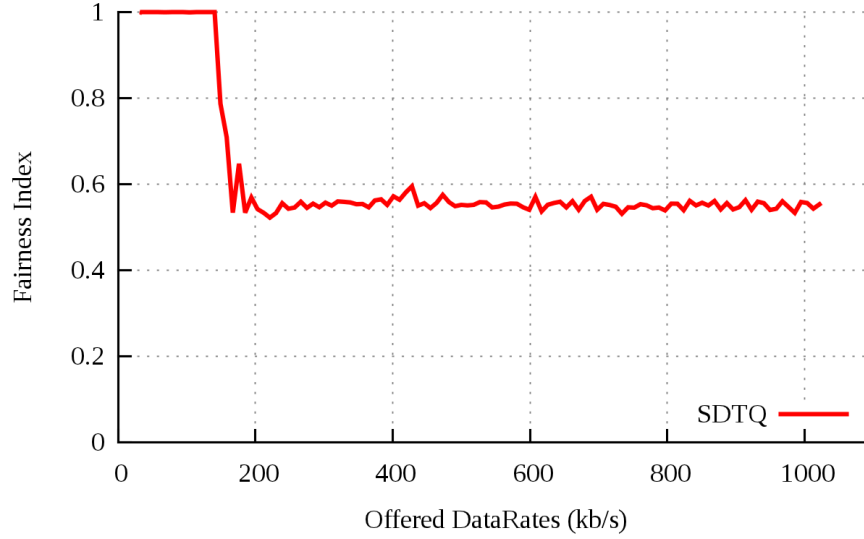


Figure 3.6: Fairness index of Multi Flows in a Multihop Chain Topology.

If hop count is not considered then the traffic that transited multiple hops would not be able to compete in presence of locally generated packets. As a result, a fair scheduler must take into account the hop count of packets. While a number of studies have considered designing MAC considering the hop count, there has not been any attempt to explore this relationship as part of a scheduling mechanism. This thesis aims to elevate the traffic that transited multiple hops and arriving from far hop by designing a dynamic scheduler based on hop counts, which will be fully introduced in chapter 4.

3.4. Saturated Network Vs End-To-End Throughput

Much effort have been given in optimising the performance in multi-hop wireless Ad Hoc networks by controlling congestion and by designing efficient MAC protocols. The IEEE 802.11b specification provides fairness across the active contending nodes within its transmission range (IEEE 802.11 WG, 1999). In order to differentiate services

both in terms of throughput and delay and provide QoS, IEEE 802.11e (IEEE 802.11 WG, 2005) was introduced with some variations in (Xiao 2004, Torres *et al.*, 2012), but has an inherent limitation - the traffic of the same class are given same priority irrespective of the network condition. In order to elevate the end-to-end throughput, hop-by-hop congestion control is discussed in (Yi *et al.*, 2007) and an end-to-end congestion control is also proposed in (Yu *et al.*, 2008), but the loss of packets due to network saturation is not addressed explicitly. A distributed contention window adaptation technique to adjust the incoming and the outgoing traffic is proposed in (Jung *et al.*, 2010), but it did not address the issue of buffer overflow due to network saturation. A MAC protocol that allows a concurrent transmission among the neighbours is designed by (Yu *et al.*, 2008), but it does not guarantee success in packet delivery during parallel transmission because packet collision may occur if the transmitting nodes experienced intolerable interference. In order to optimise the contention window usage, the (Deng *et al.*, 2008) proposed a backoff generator based on contention level and the channel BER (Bit Error Rate) status. A method to optimise the sensing thresholds of the Carrier Sensing Multiple Access (CSMA) receiver and the transmitter is designed by (Kaynia *et al.*, 2011) by minimizing the outage probability using SINR (Signal to Noise Ratio) to improve the network performance.

In a long chain topology, the highest degree of interference occurs around the centre of the chain and is lower towards either the source or the destination ends of the chain. So, for a single flow along a chain, the queue utilisation pattern will vary with the hop count.

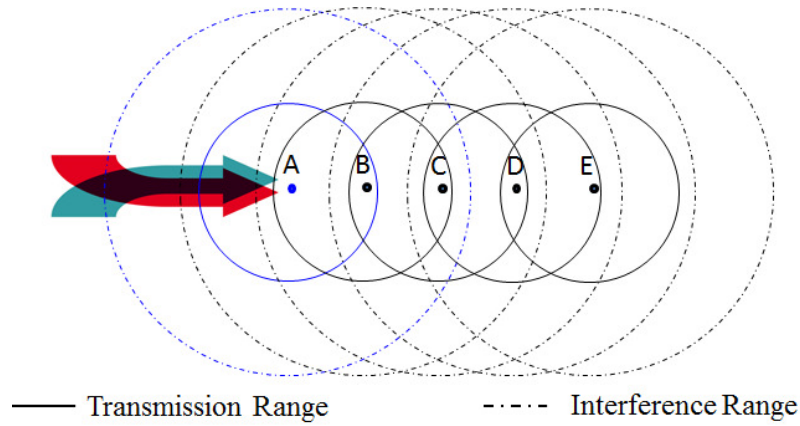


Figure 3.7: A chain topology with four hop network

In the given long chain topology of Figure 3.7, if node A sends data to node E, as the number of hop increases, the degree of interference and the number of contenders also increases, and it gets harder to push the packets forward towards the destination. When node A uses the channel, node B and C have to defer transmission, due to interference range overlap. In such a distributed network and shared channel mechanism, real time traffic with a high data rate of constant bit rate generated at node A will lead to buffer overflow as the access of the shared channel by node B or C would force node A to defer accessing the channel. Thus, a ripple effect of deferring up to two hop neighbours is formed when a node becomes active as a sender or as a relay node in a shared channel of multi hop network and the network self-limits the end to end throughput.

At network saturation, losses of data in the network are mainly due to the queue being full, no route availability or retry count exceeded. Other kinds of drops are due to collision and packet error, but such packets are retransmitted if the TTL (Time To Live) and retry count are still valid. Problems induced by physical limitations like bandwidth, transmission range and interference range cannot be resolved easily, but the MAC

algorithm can be adjusted to control the access mechanism in such a way that overall packet drop is reduced and the network performance is elevated, which is the aim in addressing QoS support in the thesis.

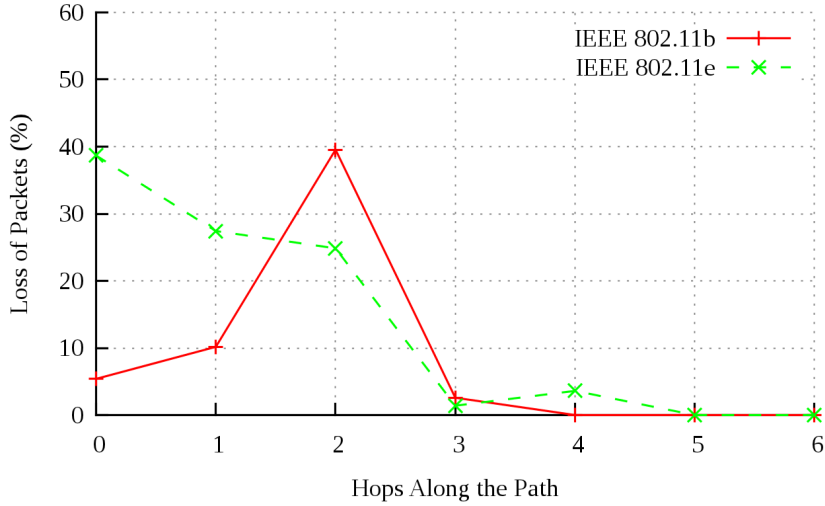


Figure 3.8: Loss of Packets over Hop

When a six hop chain path is considered with a CBR application of 416kb/s (it is the data rate of one of the saturation points of a 6 hop path length), loss rate is low at the source, but there is a heavy loss of 40% after two hops away from the source in IEEE 802.11b as shown in Figure 3.8. It is because the interfering range of the source covers up to the second hop and thus the contention around the source. Moreover, the queue of the source and the relaying two hops are overflowed because when the source tries to forward packets, the next hop relaying node also compete to access the channel to forward the packet and ends up building the queue utilisation in the process and resultant in heavy loss of packets. In case of IEEE 802.11e, there is a loss of approximately 40% at the source; such variation of loss is governed by the medium access mechanisms of IEEE 802.11b which gives equal access probability for all contending nodes and IEEE 802.11e which also provides same access probability within the same priority class. If packets

could be forwarded at a higher rate as the hop count of the path increases, the end-to-end throughput will be increased.

The degree of interference experienced by each active node along the path is different. So, the queue utilisation pattern along the path is also expected to vary. Heavy loss at the source is due to slower rate of transmission compared to the arrival rate from the source application since the channel is shared. The source generates data continuously or discretely, but the MAC layer must pass on the packets to the next hop. If the outgoing packet rate at MAC layer is lower than the application rate, then the local queue will progressively fill up, subsequently leading to packet loss. If the active congested node could capture the channel at a higher rate compared to other active nodes witnessing a lower degree of congestion, then the overall packet drop will be reduced and can expect a higher end-to-end throughput. In this context, a dynamic MAC protocol based on active utilisation of queues should be designed and explore its end-to-end performance. In one way or the other, availability of cross layer network parameter information is mandatory, when the network resource utilisation is to be optimised. For instance for the MAC layer to know the queue status; the current utilisation of queue needs to be shared with the MAC layer. Chapter 5 proposes a cross-layer MAC protocol based on the utilisation of queue and is compared with a variant that considers a dynamic Inter Frame Spacing (IFS) based on the hop count of the transiting packet.

3.5. Issue of Extended Inter-Frame Space

During frame collision or capture or if the receiving frame is erroneous, the receiving node defers access for a fixed Extended Inter-Frame Space (EIFS) time, which equates to $EIFS = SIFS_{time} + DIFS_{time} + Tx_Time_{ack}$ without knowing the actual duration to defer. The reason for the standard IEEE 802.11b using a fixed EIFS is to

provide an opportunity for a fast retransmission of the error frame. However, deferring for a fixed EIFS when the node receives erroneous frames within an interference range makes it impossible to defer the channel access for an accurate duration when the frame type is not known. In fact, $\text{EIFS} \gg \text{DIFS} > \text{SlotTime} > \text{SIFS}$, and waiting for an inaccurate fixed defer time when the erroneous frame is not an ACK is not the right approach. (Li *et al.*, 2005) proposed an enhanced carrier sensing mechanism where deferring the channel access is based on observing the length of the frames and correspondingly identifying its type to provide fair access among the flows in the network, but the author considered a fixed maximum Data length; the study however did not deal with the capture scenario when two signals are received. The concept of using optimised EIFS during packet collision, erroneous frames, or frame capture scenarios are taken into account while designing the new location based power controlled MAC in Chapter 6. Thus, the need for a new optimised EIFS is addressed to provide fairness and avoid starvation when an active node falls within an interference range of another and it is discussed in detail in Chapter 6.

3.6. Reducing Transmission Power Unfairness

Using a fixed and a high transmission power is unnecessary when the communicating nodes are closer to each other. A large transmission power leads to increasing interference, reduces the probability of parallel transmission in the shared channel environment, and decreases the battery life. If transmission power is controlled, then only the required power is used in communicating between two nodes, reduces the interference range, increases the probability of parallel transmission while communicating shorter distances and saves battery life. So, it is vital to control the power

of transmission to enhance the overall network performance and increase the durability of the battery life.

A throughput-oriented MAC by controlling the transmitting power of the nodes based on game theory is designed by (Wang *et al.*, 2009) to achieve concurrent transmission, but such approach is more on probability rather than deterministic. (Zhiwei *et al.*, 2007) uses a set of power levels, starting with a low transmission power while discovering or sending to the next hop node; if the nodes are unreachable, then a higher level of transmission power is used until it reaches the highest possible transmission power level or until the next hop node is discovered, whichever is earlier; the limitation of the technique is that each node will try with different transmission power levels without knowing whether it will result in successful discovering or sending to the next hop node.

The authors of (Douros *et al.*, 2011, Nuraj *et al.*, 2011 and Patnaik *et al.*, 2004) provide a number of improvements on different power control MAC for wireless Ad Hoc networks, with the proposed approaches using a fixed maximum power transmission for control frames, such as RTS and CTS, and a low transmission range for Data and ACK frames. While achieving their aim, the proposed mechanisms have an inherent limitation as the probability of concurrent transmission is reduced, given a higher degree of nodes will receive the RTS and the CTS control frames.

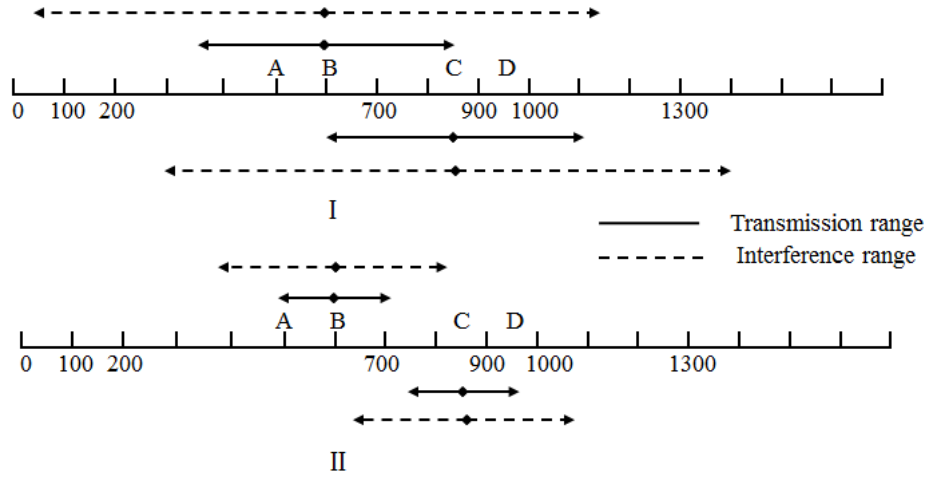


Figure 3.9: (I) Fixed transmission range (II) Location based Power Controlled Transmission.

Standard wireless communication is based on a fixed transmission range, which leads to using a higher than necessary transmission power when the communicating pair are close to each other, where such scenario subsequently leads to significant interference coverage and unnecessary waste of energy. As shown in Figure 3.9 (I), even though node A and node B are only 100m away, when node B communicates with node A with a fixed high transmission power (say) to cover 250m, the activities of node C and node D are disturbed, so these nodes have to defer channel access when node B communicates with node A. On the other hand, considering the same scenario with a power controlled communication based on node's location as shown in Figure 3.9 (II). In such approach, the area of interference decreases, so the probability of concurrent transmission increases and in fact the overall lifespan of a node is expected to be increased. But communication using a fixed minimal power based on the location may lead to an unfavourable situation of unfair access among the contending neighbourhood especially due to hidden nodes. When one node communicates over a longer distance and other neighbour node communicates with a shorter distance due to the positioning of the nodes as shown in Figure 2, where node B communicates to node A and node C communicates with node D

using a transmission power P_1 and P_2 respectively, where $P_1 > P_2$ with distances of $d_{A,B} > d_{B,C} > d_{C,D}$, where d_{ij} : distance between node i and node j):

i. When node A is active, node C and node D are within its interference range. Thus node C and node D are hidden from node A.

ii. When node B is active, node C is within its transmission range, but node D is still hidden and falls within B's interference range.

iii. When node C or node D are active, only node B is disturbed because of the interference range of node C. Thus activities of node A and B hugely disturbed the activities of node C and node D compared to the interference produced by node A and node B upon node C and node D.

iv. Node C is within node B's transmission range, but node B is out of the transmission range of node C. So, node B is not aware of node C even though node C is aware of the activity of node B. In such scenario, the mechanism aims to renegotiate the transmission power of node C while communicating with node D, so that node C is no longer hidden to node B. Thus, node B and node A communicates using transmission power P_1 , node C communicates with node D with a new power P_2' and node D communicates with the initial minimum power P_2 , where $P_1 > P_2' > P_2$ to reciprocate with the distances $d_{A,B} > d_{B,C} > d_{C,D}$.

Hidden nodes affect the network performance by increasing packet collision and introducing unfairness among the traffic flows. Authors of (Kosek-Szott 2012) surveyed the recent development of MAC protocols in terms of solving the hidden node issues. In Figure 3.10, when node A or node B are active, node D could sense the channel as busy but cannot decode packet content, since it is within the interference ranges of node A and B. As a result, the standard carrier sensing IEEE 802.11 mechanisms defer channel access for a fixed Extended Inter-Frame Spacing (EIFS), erroneously assuming the

overheard transmission is an ACK i.e. $EIFS = SIFS_{time} + DIFS_{time} + Tx_Time_{ack}$, although the frame may have been of a different type (such as RTS, CTS, DATA, or Routing). The authors of (Li *et al.*, 2005) proposed an enhanced carrier sensing mechanism where deferring the channel access is based on observing the length of the frames and correspondingly identifying its type to provide fair access among the flows in the network, but the authors considered a fixed maximum Data length. When multiple neighbouring nodes are transmitting, then instead of considering as collision, the overheard nodes measures the incoming signal strength and compared with the background noise to check if the packet can be received successfully. Such situation is termed as packet capture. In this scenario, the IEEE 802.11 standard requires that the node defers for the fixed EIFS, if the newly incoming signal strength is not ten times the ongoing receiving signal strength. The authors of (Li *et al.*, 2005) did not deal with the capture scenario when two signals are received. To address this issue, the thesis introduces an optimised EIFS for packet collision, erroneous frames, or frame capture scenarios and its detail discussion is found in section 6.2.4, and its aim is to improve fairness and enhance the overall network performance.

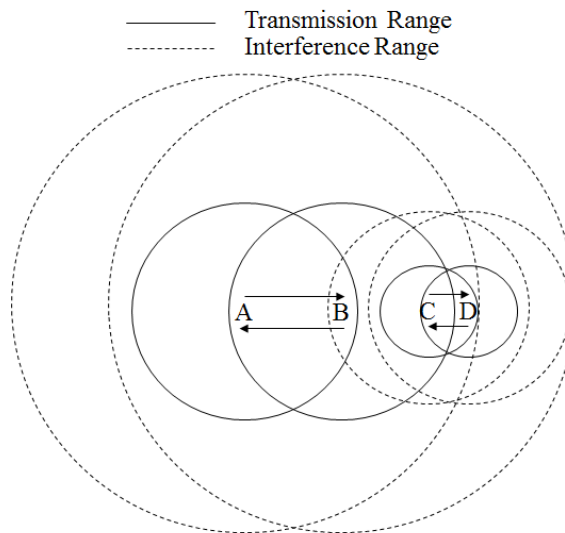


Figure 3.10: Unfair access using minimal power transmission based on location.

A new power controlled MAC is designed in chapter 6 using a location information, an optimised EIFS and a backoff based on degree of contention to be more accurate during transmission power calculation, to support fairer access when multiple flows are involved, to increase the probability of parallel transmission and save battery life. Typically location information is unavailable without a cost, another power controlled MAC is also discussed in chapter 6 where active nodes estimated the transmission power without the need of location information based on the received signal strength.

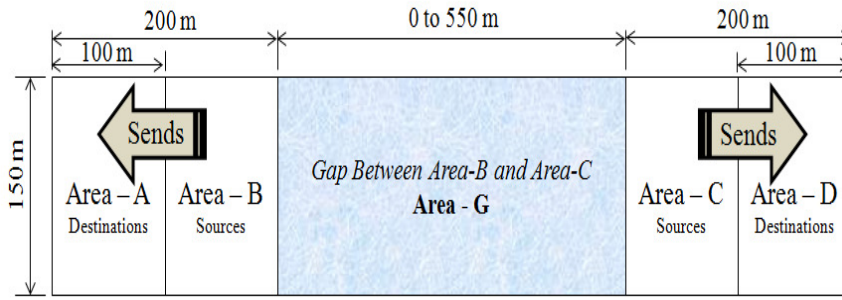


Figure 3.11: Random Network Topology

In order to evaluate the probability of concurrent transmission in a network, a network topology shown in Figure 3.11 is considered where the distance between the sources are increased to demonstrate the impact of probability of concurrent transmission over distance. The scenario includes a 150m wide area with five sections: four of them, are 100m long (Area-A, Area-B, Area-C and Area-D), each containing 10 nodes which are randomly placed, while the fifth section, Area-G, is a separation zone with variable length of [0m; 500m]. Nodes from Area-B and Area-C are used as sources and transmit to destination nodes from Area-A and Area-D with a one hop communication and a

maximum transmission range of 250m. The topology from Figure 3.11 was used to generate 1000 rounds of simulations, each with a simulation time of 1000s, by varying the length of the areal gap Area-G in the [0m;500m] interval in 10m increments. The traffic for the scenario used CBR over UDP flows with a packet size of 1000 bytes.

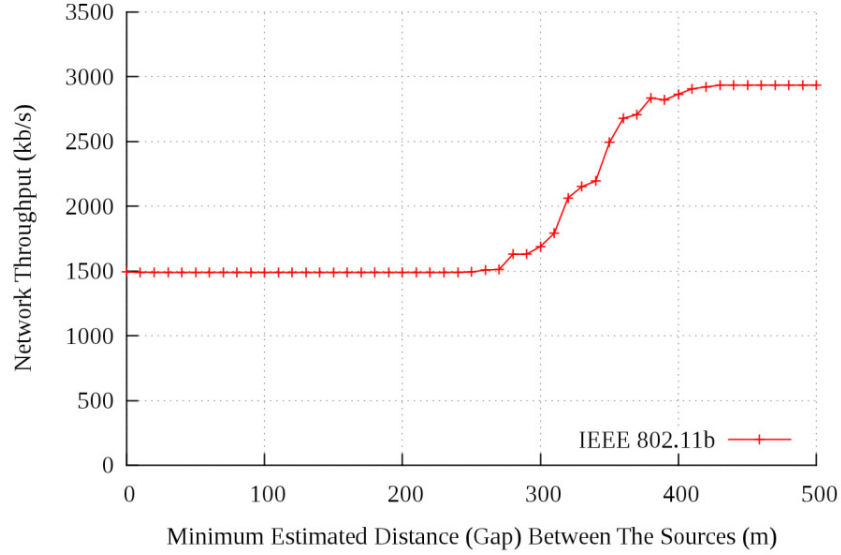


Figure 3.12: Performance as the Distance Between the Sources Increases

In a fixed and a high transmission power with a transmission range of 250m, the random sources do not allow concurrent transmission for an Area-C length under 280m as shown in Figure 3.12,. The probability of concurrent transmission increases with the length of Area-G and, after the length of Area-G is greater than 430m, the random sources of Area-B and the random sources of Area-C do not interfere with each other, so concurrent transmission is achieved. In a real world scenario, the node placement are random and the distance of communication between hop can be small or large, and if transmission power is accurately controlled based on the distance between the communicating pair, then the probability of concurrent transmission would increase whenever the source and the next hop destination are closer.

3.7. Conclusion

Much study has been conducted in optimising the network performance in an Ad Hoc networks, but issues pertaining to fairness when a flow arriving from far hop meets a flow generated locally is not addressed fully. This issue is investigated and a solution to elevate fairness is discussed in chapter 4. In a resource constrained Ad Hoc network limited shared bandwidth, lack of coordination among the contending nodes, high congestion and interference has been a hurdle in enhancing the network performance. It is also found that in a long chain topology when the source nodes generates high data rate, a self-bottleneck is created and heavy loss of packets is encountered since the bandwidth is shared along with the forwarding nodes. In order to reduce packet loss and increase the end-to-end performance in such network, solutions are provided in chapter 5. Power controlled transmission is vital to exhibit concurrent transmission since using a fixed high transmission power leads to high interference in a network using a shared bandwidth. Despite multiple power controlled approaches has been addressed, the issues of the hidden and exposed nodes generated due to use of different transmission powers have not been investigated fully. Therefore, in chapter 6 new power controlled mechanisms are provided and ensure to reduce the hidden or exposed node issues.

Thus, the following chapters describe and evaluate the performance of a number of proposed mechanisms, focusing on the limitations identified in this chapter.

Chapter 4. Fair Scheduler Using Hop Count

4.1. Introduction

Since communication in Ad Hoc networks is distributed in nature and uses a shared channel, there is no mechanism to ensure fairness among the contending nodes and the traffic flows. Thus, provisioning fairness to ensure good Quality of Service (QoS) in such environment is challenging. Providing QoS for a data flow inherently requires an intelligent dynamic resource allocation decision, based on acquiring resource information along the transit route. As discussed in Chapter 3, path length of the communication directly affects the end-to-end performance of the network. So, when a new flow is introduced along the path of an already existing flow then the fresh flow captures the channel and the old flow leads to starvation as it will be discussed in section 3.2 of chapter 3. As nodes route the traffic between source and destination, contention reduces the throughput of a flow as the length of the transited path increases.

In order to elevate the chances of forwarding the flows arriving from far while encounter a new flow, a scheduler called Hop Based Dynamic Fair Scheduler (HBDFS) is designed by considering the path length transited by each flow (section 4.2). This thesis considers different approach where different queue is assigned to every incoming packet based on two factors namely: *hop count of data packets* and *route discovery packets*, where the queue assigned for route discovery takes the highest probability of scheduling and the rest of the queues take turn to schedule based on a round robin fashion. Thus, on each forwarding node, the traffic priority is established based on the number of hops a packet has taken from its source; as a result, distant flows with high hop counts are favoured over new flows with low hop counts. The queue follows a drop tail method rather than

drop head technique, because when the network gets saturated and packets are forwarded to towards the destination, the packets towards the head which are ready to be scheduled have already utilised the limited shared resources in moving towards the head for scheduling or by moving towards the nodes closer to the destination. So, it is wiser to drop the packets which have not utilised the network resources in terms of time, processing power and limited shared bandwidth. The authors (Nichols *et al*, 2012), states that when the queue delay has exceeded the targeted value for at least an interval, a packet is dropped. Moreover, by using a relationship between the drop rate and a throughput with a linear change, the next drop time is decreased in inverse proportion to the square root of the number of drops since the dropping first began. But, when network saturation takes place in a shared bandwidth environment and the source application keeps generating the data to be forwarded like CBR traffic, then the next dropping time will be smaller as buffer overflow began. Thus, in this study, dropping a fresh packet is preferred compared to those packets which has already utilised the network resources. If the packet at the head of the queue is dropped during network saturation and continuous buffer overflow situation, then the fresh packets have to wait afresh in terms of the availing shared network resources to schedule and access the channel to move to next hop, which is wastage of time and resources.

The designed hop-based scheduler is tested against a range of topologies, starting with the basic ones from chapter 3 (Figure 3.4) and Figure 4.2 of this chapter. The result is discussed and analysed in section 4.4 against Single DropTail Queue (SDTQ) and finally, the concluding statements of the findings are provided in section 4.5.

4.2. Proposed Hop Based Dynamic Fair Scheduler

As highlighted in chapter 3, the data rate of a single flow is reduced for each node transited by that particular flow by a factor that can be approximated with the inverse of hops. When two flows arrive at a node after having transited a different number of hops, the traffic of the more distant flow is further affected by the single queue, leading to an uneven distribution of resources across the network.

4.2.1. The New Scheduler

The proposed scheduler consists of eight independent queues, with each queue storing incoming packets based on the type of packet and the transited hop count of the packet. If a node uses a single FIFO queue, then, at network saturation, the probability of establishing a multihop route decreases significantly. It is therefore necessary to provide a designated queue with highest priority, so that route establishment is guaranteed even during network saturation. Moreover, the data rate of a flow slows down as the hop count of the transited path increases, as presented in section 3.2, therefore a fair approach requires multiple queues based on the transited hop count of the packet, otherwise flow with a high hop count are likely to be overtaken by local flows. A separate queue for a source is also necessary, because it is the source that generates data at a higher rate compared to an incoming relayed packets arriving from far hop. As a result, when a round robin scheduling is considered, the freshly generated packets and the packets that have transited a high number of hops will experience same or different scheduling priority based on the assigned weights. Thus, the new proposed scheduler, as shown in Figure 4.1, consists of several queues as follows:

- QR – routing information queue - is a queue reserved for the routing information packets. This queue is given the highest priority in order to guarantee route establishment. If highest priority is not given, then the time-out will occur more frequently when the network gets congested, due to the maximum route request timeout

$\hat{R}_{request} = 10$ seconds and route reply waiting time $\hat{R}_{reply} = 1$ second timers within Ad Hoc On Demand Distance Vector (AODV) routing protocol.

- Q_i , i -hops queue - individual queues for data packets that have transited i hops ($i=0$ for packets generated in the local node). This allows individual control for packets with different hop counts, potentially leading to a better chance of getting scheduled for the next hop and finally proceeding towards their respective destinations. In any practical application queues might be combined to conserve resources. Indeed, in the simulation presented here queue Q_{6+} is used for data packets that have transited six or more nodes in the network. Apart from the assigning special queues for the source and for routing packets, six additional queues are considered one for each corresponding transited hop number, because in a chain topology with a source generating high data rate, a self-bottleneck is created during network saturation and the loss of packets after the sixth hop is literally zero. Thus, by observing the distribution of packet utilization pattern of the buffer of SDTQ along a path, six additional queues along with the source's and the routing queue are considered in the proposed HBDFS scheduler.

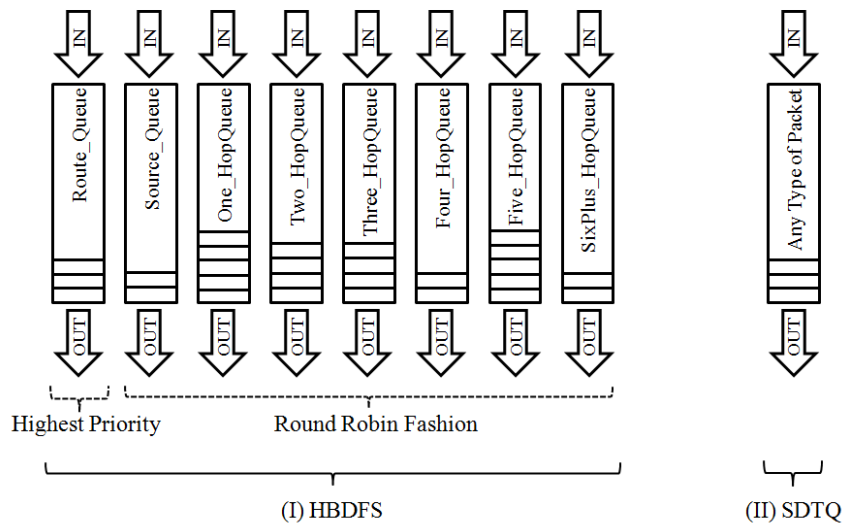


Figure 4.1: (I) Hop Based Dynamic Fair Scheduler (HBDFS) Scheduler. (II) Single Drop Tail Queue (SDTQ) Scheduler.

4.2.2. Scheduling Scheme

The Medium Access Control (MAC) protocol sets the rules on channel access. Since the wireless nodes of an Ad-Hoc network are spatially distributed and use a shared channel, carrier sensing and contending for channel access represent the most effective approaches and are hence used by IEEE 802.11b with RTS and CTS control frames to avoid hidden and exposed nodes.

Whenever a packet is requested by the MAC protocol to send to the next hop, the scheduler first queries the QR queue and transmits any packets available in order to provide highest preference to the routing related information. The scheduler then proceeds to query queues in a round robin fashion. The queue pointer or turn is preserved between calls and when a queue is empty, the next queue with lower hop number is queried and the queue pointer is decremented. If all the seven data queues are empty, the scheduler returns a NULL pointer to the calling MAC protocol. Considering that all the data flowing in the network are equally important, scheduling is done at the ratio of 1:1:1:1:1:1:1, except for QR, which always takes precedence.

4.2.3. Pseudo Code of the Scheduler

Table 4.1 and Table 4.2 describe the pseudo code of the scheduler HBDFS. When a node receives packets to relay or generate to send, the packets are Enqueued at the respective queues in HBDFS based on the number of hops transited. If the receiving packets or generated packets are route discovery related control packets then they are Enqueued in a special queue and provide highest priority of Dequeueing scheduling. The data packets are Dequeued in a round robin fashion to provide same priority over packets travelling with different hops.

PseudoCode for Dequeuing
<p><i>Scheduler preserves the queue pointer x between subsequent calls</i></p> <pre> IF QR_length> 0 return(Dequeue_packet) ELSE IF (Q_i==0, i∈ [0,6]) return(NULL); ELSE FOR(j=0;j<=6;j++) IF Q_x_length> 0 x=(x-1) mod 7 // Sets the turn of the next queue return(Dequeue_packet) ELSE x=(x-1) mod 7 // Sets the turn of the next queue </pre>

Table 4.1:DeQueuing in HBDFS

PseudoCode for Enqueuing
<pre> READ hop_travelled, ptype x=hop_travelled IF (ptype=R_info) Enqueue_packet in QR ELSE Enqueue_packet in Q_x </pre>

Table 4.2: EnQueuing in HBDFS

4.3. Simulation Scenarios

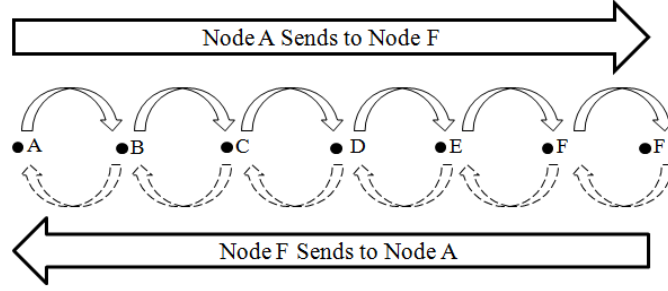


Figure 4.2. Opposite traffic flows in a Six hop path length.

In order to test the effectiveness of the proposed scheduler, the scenario III described in Figure 3.4 of chapter 3 and the topology from Figure 4.2 are considered with two flows. Each simulation lasts for 1000 seconds and an average of 100 rounds of simulation is considered in analysing the result. A comparison is made with the standard DropTail scheduler by considering three different interesting cases as described below:

CASE I (Same per-flow offered load): In scenario III from Figure 3.4, the data flows (f1) and (f2) are generated from source A to destination G and source E to destination K respectively, each with the same data rate which ranges from 32kb/s to 1022kb/s using CBR traffic.

CASE II (Different per flow offered load): In scenario III from Figure 3.4, the data flows (f1) and (f2) are generated from source A to destination G and source E to destination K respectively, with different data rates of CBR traffic. In this case the sum of the data rates of f1+f2 is fixed at 1056kb/s; f1 increases from 32kb/s to 1022kb/s while f2 decreases from 1024kb/s to 34kb/s.

CASE III (Two Communicating Pair): In this case, the network scenario of Figure 4.2 is considered in order to test the degree of fairness when the destination communicates with the source at the same time. Thus, the network scenario with a six hop path length with a CBR traffic flowing in an opposite direction as shown in Figure 4.2 is tested, where node A sends to node F (f1) and at the same time node F also sends data to node A (f2). Since the maximum end-to-end throughput of a six hop chain topology is approximately 200kb/s, the test is conducted with an increasing offered load from 32kb/s to 250kb/s with different packet sizes of 250 bytes, 500 bytes, 750 bytes and 1000 bytes.

4.4. Result and Discussion

4.4.1. CASE I (Same Per Flow Offered Load):

The average throughput of both flows initially increases as the supply data rates increases as shown in Figure 4.3. When the offered load increases beyond 150kb/s, then the average throughput of f1 drops in both the scheduling schemes of SDTQ and HBDFS. The average throughput of the f1 flow, in this region is only 9kb/s for SDTQ and 23kb/s for HBDFS. In a similar manner, beyond an offered data rate of about 250kb/s the throughput of flow f2 converges to an average of 172kb/s and 157kb/s in case of SDTQ scheme and HBDFS scheme respectively.

It can be concluded that, as long as there is enough bandwidth and no congestion in the network, the throughput increases and the media access for the flows is perfectly fair. However, once the network becomes saturated, HBDFS provides a better distribution of throughput in comparison with SDTQ scheduler. Thus, during congestion and saturation, the degree of fairness among the flows is higher in case of HBDFS to that

of SDTQ and, in addition, the flow that has transited a longer path slows down much faster in SDTQ in comparison with HBDFS. From a statistical perspective, there is an increase of 14kb/s corresponding to 155% throughput on average in HBDFS for long transit path flow f1 in comparison to that of SDTQ, improvement that requires a trade-off of only 15kb/s corresponding to -8.7% throughput of flow f2.

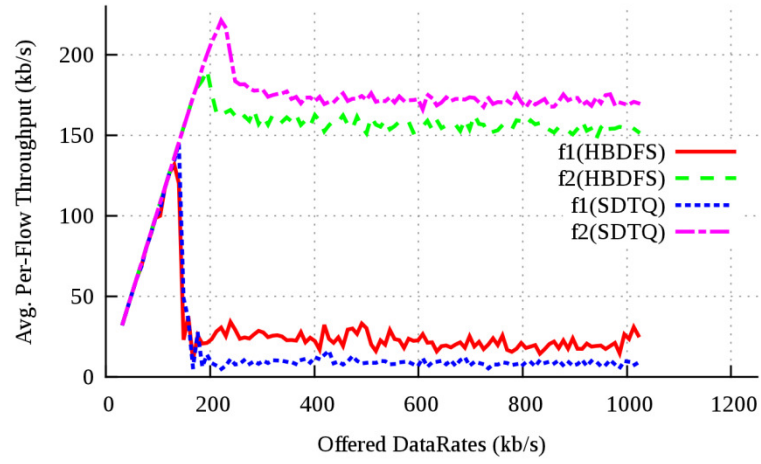


Figure 4.3. Throughput of flow1 and flow2 of HBDFS vs SDTQ in CASE I

The graph of Figure 4.4, describes the fairness between the data flows f1 and f2 of CASE I using Jain's Fairness Index (3.1), and tested with a value of $n=2$.

At the lower data rates, the fairness indexes of both schedulers (SDTQ and HBDFS) are perfect, but as the offered load increases the network becomes saturated, then the fairness index for the two flows when using HBDFS converges to a value of 65% compared to the 55% for the SDTQ scheduler.

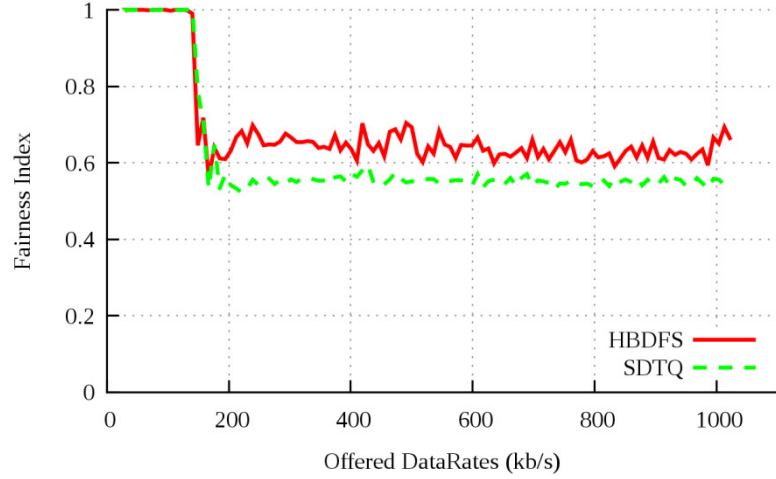


Figure 4.4. Jain's fairness index of HBDFS vs SDTQ in CASE I.

4.4.2. CASE II (Different Per Flow Offered Load):

This case is constructed to observe how performance of data flows, as shown in Figure 4.5, is affected as the ratio of traffic between competing flows varies. Initially, the offered data rate of flow f1 starts with a very low value and the data rate of flow f2 with a very high value, then gradually the data rate of flow f1 increases and the data rate of flow f2 decreases. It is observed that flow f2, which is along the route of flow f1, takes over the channel most of the time even when its source data rate is only around 200kb/s, despite a high data rate (around 850kb/s) of flow f1. As the source data rate of flow f1 goes above 850kb/s and data rate of flow f2 drops below 200kb/s, the performance of flow f1 gradually increases. This indicates that, despite having a source with high data rate, if another flow starts sending data along its route, then its performance is highly degraded. In this case, the synchronizing point (highest degree of fairness in terms of throughput) between the two flows is when the source data rate of flow f1 and flow f2 is around 970kb/s and 80kb/s respectively in both the schemes. It means that, for a data flow that has already transited several hops; a scheduling algorithm must significantly prioritise the respective traffic to be able to compete with the flows generated locally.

On average, the performance of flow f1 in case of HBDFS is much better to that of the SDTQ. And the degree of fairness among the flows f1 and f2 in HBDFS is higher to that of the SDTQ.

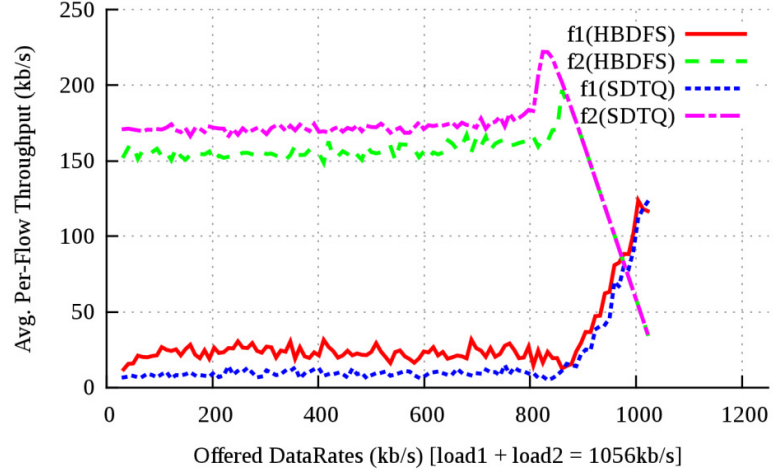


Figure 4.5. Throughput of flow1 and flow2 of HBMQ Vs SDTQ in CASE II

The graph of Figure 4.6 presents the fairness index of flows f1 and f2 of CASE II using SDTQ scheduler and HBDFS scheduler. In this case, the average fairness index of HBDFS outperforms the SDTQ scheduler by approximately 10% when the network becomes saturated. When per flow offered load are similar then the degree of fairness of the traffic flows also increases.

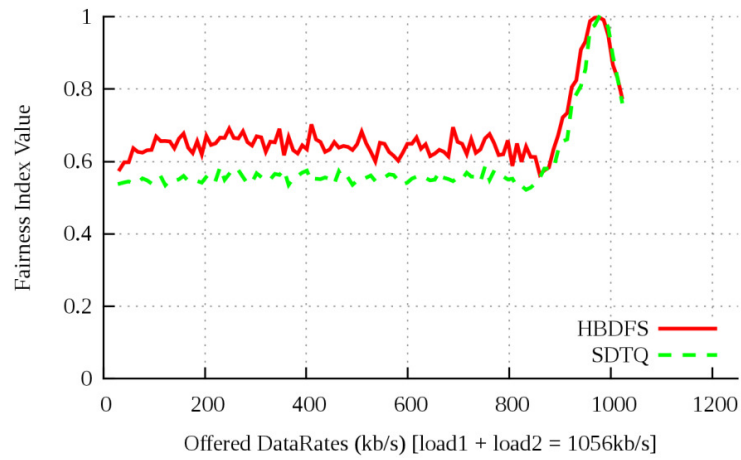
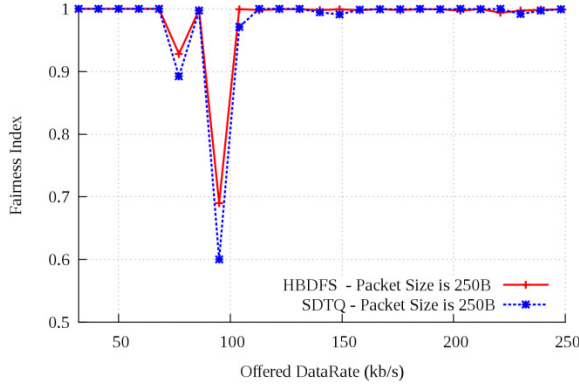
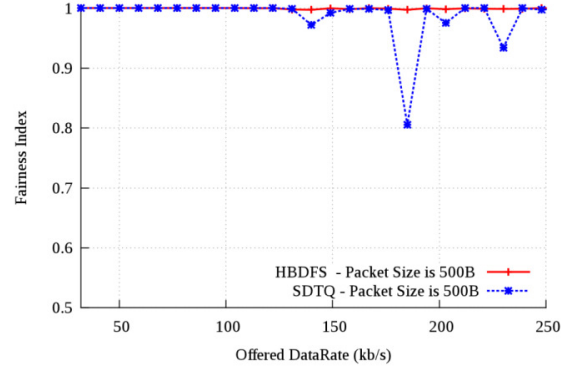


Figure 4.6. Jain's fairness index of HBMQ Vs SDTQ in CASE II

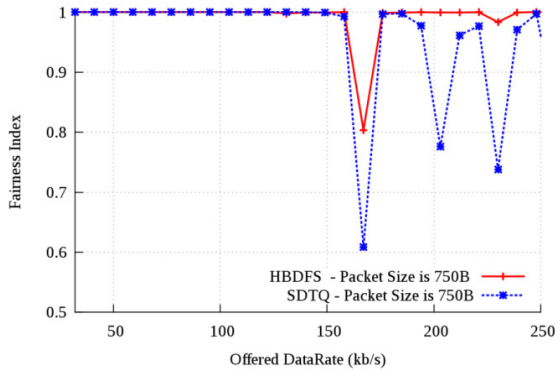
4.4.3. CASE III (Two Communicating Pair):



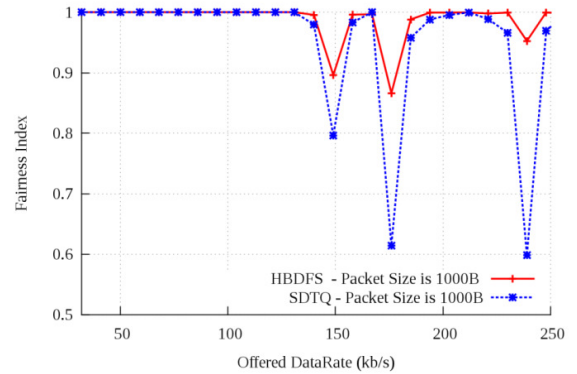
(A)



(B)



(C)



(D)

Figure 4.7. Jain's fairness index of HBDFS Vs SDTQ in CASE III when (A) Packet Size is 250bytes, (B) Packet Size is 500bytes, (C) Packet Size is 750bytes and (D) Packet Size is 1000bytes.

In this case, as traffic flows are generated from opposite directions, the degree of fairness is much better in HBDFS over SDTQ irrespective of the source data rate or the packet size. When the packet size is 250bytes, there is a slight fluctuation in terms of channel sharing when the data rate of the traffic flows are low and the minimum degree

of fairness occurs at round 100kb/s, with only 60% fairness for SDTQ when the lowest degree of fairness is 68% in case of HBDFS. When the packet size of the CBR traffic is 500bytes, the degree of fairness of HBDFS is 100%, unlike SDTQ where the degree of fairness fluctuates and the lowest fairness degree is 80% when the source data rate is around 180kb/s. This shows that when communicating flows are opposite to each other and packet size is an average 500bytes, the flows of the proposed multi queue scheduler HBDFS shares the channel access among the contending flows perfectly. When the packet size is increased to 750B and 1000B, the channel is still shared fairer in HBDFS compared to SDTQ. When the packet size is 750B and 1000B, the degree of fairness is as low as 60% in case of SDTQ, but the lowest point of the degree of fairness in HBDFQ is 80% and above. At certain rates, irrespective of the packet sizes, one flow takes over the other, especially for SDTQ compared to HBDFQ, it is due to lack of prioritising the accesses mechanism after scheduling the packets at the MAC layer. Overall, the fairness of HBDFQ is consistent and does not fluctuate much, irrespective of the offered load and the packet sizes unlike SDTQ, because of scheduling the arriving packets in round robin based on the transited number of hops despite not prioritising packets at the MAC.

4.5. Conclusion

This chapter investigated the issue of using a single queue when dealing with multiple flows with different point of generating data in a chain topology. The flow arriving from further hop count along the path suffers heavy loss when it encounters a fresher flow during network saturation. In order to address this issue of fairness among competing flows a scheduler called a dynamic hop based fair scheduler (HBDFQ) was designed. This scheduler aims to alleviate the unfair scheduling inherent for Ad Hoc wireless networks, when paths of multiple flows overlap. The proposed scheduler

guaranteed route establishment, because a special dedicated queue is allocated for routing related control frames with highest scheduling probability. Assigning different queues for flows with different hops allows the flows to access the channel with a round robin scheduling policy to maintain fairness. Simulation results show that the proposed scheduler HBDFQ shares the channel more efficiently and improves the degree of fairness by at least 10% over a single FIFO queue irrespective of the offered loads.

Since, the study used IEEE 802.11b, even though the scheduler uses a prioritized hop based multiple scheduler, the MAC layer mechanism does not provide any form of priority to the traffic. This way, the performance gain is bounded by the MAC behaviour. It is also observed that, despite the high availability of bandwidth, the throughput in the network is comparatively low. With this in mind, chapter 5 focuses on new MAC protocols based on the utilisation of queue that will to enhance the end-to-end performance of the network and incorporate the importance of hop count in order to alleviate the performance and reduce the average end-to-end delay of packet delivery.

Chapter 5. MAC Based on Queue Utilisation and Hop Count

5.1. Introduction:

In a standard IEEE 802.11b, all active nodes have equal probability of accessing the medium, and a node with i active nodes in its interference range may gain access to the medium with a probability of $1/i$. In a linear chain topology, per node access probability decreases as the hop count of the path length and the interfering nodes increase. As investigated in section 3.3 of chapter 3, during network saturation, the network encounters a heavy loss of packets even in a long a chain topology.

Two MAC variants, *Dynamic Queue Utilisation Based MAC* and *Queue Utilisation with Hop Based Enhanced Arbitrary Inter Frame Spacing MAC* are introduced in section 5.2 and section 5.3 to reduce packet drop rate and increase the end-to-end throughput during network saturation in multihop Ad Hoc networks. Based on the utilisation of the queue, the access probability is dynamically adjusted, so that the highly utilised queue is given a higher access probability compared to the active node with lesser queue utilisation. In case of a similar queue utilisation, a packet with higher hop count is given a higher access probability.

5.2. Proposed MAC Model – Dynamic Queue Utilisation Based MAC

Dynamic Queue Utilisation Based MAC (DQUB-MAC), is derived from the original IEEE 802.11b specification and operates within the context of the RTS/CTS mechanism shown in Figure 5.1. The new protocol dynamically adjusts the probability of accessing the medium according to the buffer utilisation of active nodes. It does this by

varying the [CWMin; CWMMax] interval used in the backoff phase of the IEEE 802.11b protocol. As such, this protocol is explicitly cross-layer and the information concerning the queue utilisation (q_u) is passed to the MAC layer with the help of a new 16-bit field in the IP packet header as shown in Figure 5.2. This information embedded in the packet header could also be useful at the next hop as it makes the node aware of the buffer status of the preceding node.

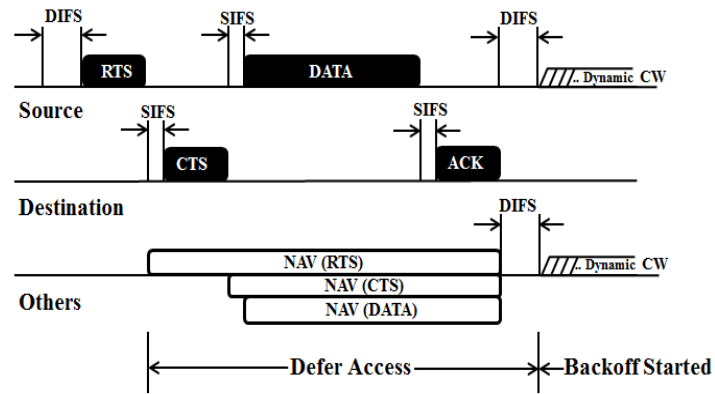


Figure 5.1: Medium Access Control Operation of DQUB-MAC.

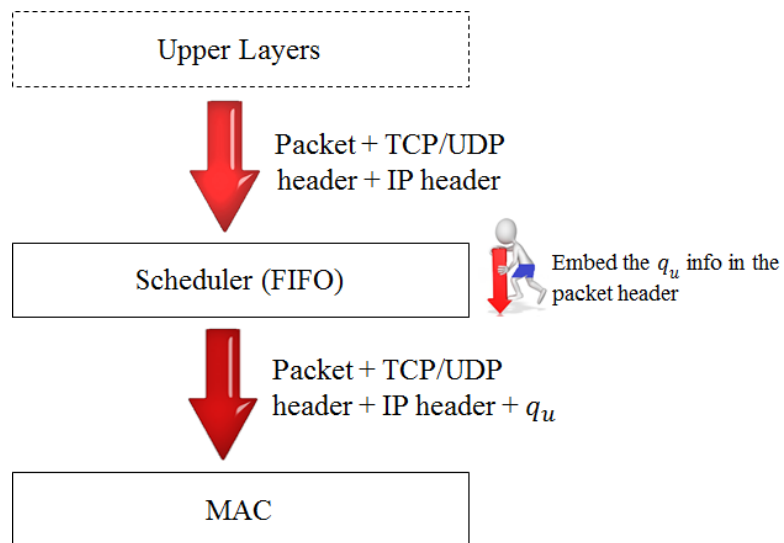


Figure 5.2: Embedding the Queue Utilisation info in the Packet.

The DQUB-MAC assigns a higher medium access probability to nodes with a higher queue utilisation. A node with a full queue has the greatest likelihood of accessing the medium, while a node with an almost empty queue has low probability of accessing the channel. This differentiation increases the probability of frames progressing to the next hop should that node has less congested queue. This optimises the utilisation of the queues and reduces the packet drop along the path, leading to higher end-to-end network throughput.

5.2.1. The Backoff Mechanism of DQUB-MAC

A node running the DQUB-MAC protocol is initialised in the usual way with $[CW_{Min}, CW_{Max}] = [0:8]$. When the node becomes active either in sending, receiving or relaying, the CW range depends linearly on the remaining space in the queue according to (5.1).

$$[CW_{Min}, CW_{Max}] = \begin{cases} \left[2^\alpha \frac{Q - q_u}{\psi}; 2^\alpha \left(\frac{Q - q_u}{\psi} + 1 \right) \right], & r = 0 \\ \left[2^\alpha \left(\frac{Q - q_u}{\psi} + 1 \right) (\gamma); 2^\alpha \left(\frac{Q - q_u}{\psi} + 2 \right) (\gamma) \right], & r > 0 \end{cases} \quad (5.1)$$

In (5.1), Q denotes the maximum size of the queue, and the current utilisation of the queue is denoted by q_u , so $Q - q_u$ represents the remaining number of empty slots of the queue. There are two adjusting parameters, α and ψ ; and they control the width of the range of the contention window and the number of the priority levels respectively. In the present work, $Q=100$ and the adjusting parameter is set to $\alpha= 3$. This allows the contention window range to vary with a factor of 8 for different priority levels and with ψ

= 30 in (5.1) to generate four different priority levels, namely: low, fair, high and very high, corresponding to queue utilisation of 0-29%, 30-59%, 60-89% and $\geq 90\%$ respectively. As a result, the probability of channel access increases proportionally with the queue utilisation. The retry count of a packet is denoted by r and, when the data packet is to be retransmitted ($r > 0$), a new contention window (CW) range interval is calculated as shown in (5.1). This depends linearly on the remaining number of retries given by γ , which is computed as the difference between the retry limit of retransmission, and the current retry number of retransmission. The γ factor increases the medium access probability proportionally to the number of retransmissions when the queue utilisation levels (q_u) of the nodes are similar. The maximum number of retransmissions takes the same value as used in IEEE802.11b following (Nardelli *et al.*, 2012), so that packets with repeated unsuccessful retransmission are discarded after several unsuccessful attempts.

5.3. Queue Utilisation with Hop Based Enhanced Arbitrary Inter Frame Spacing (QU-EAIFS) MAC

The Queue Utilisation with Hop Based Enhanced Arbitrary Inter Frame Spacing (QU-EAIFS) MAC is derived from the original IEEE 802.11b and DQUB-MAC specifications by incorporating the arbitrary inter frame spacing of IEEE 802.11e concepts based on hop counts for QoS support. The QU-EAIFS MAC operates within the context of the RTS/CTS control packet mechanism shown in Figure 5.3. When a node has a packet to send, the protocol dynamically adjusts the probability of accessing the wireless channel as follows: the active node waits for an Enhanced Arbitrary Inter Frame Spacing (EAIFS) based on the hop count of the packet and the priority mechanism uses the current queue utilisation status information of the active nodes. The details of the new features introduced in the access mechanism are described in the following sections.

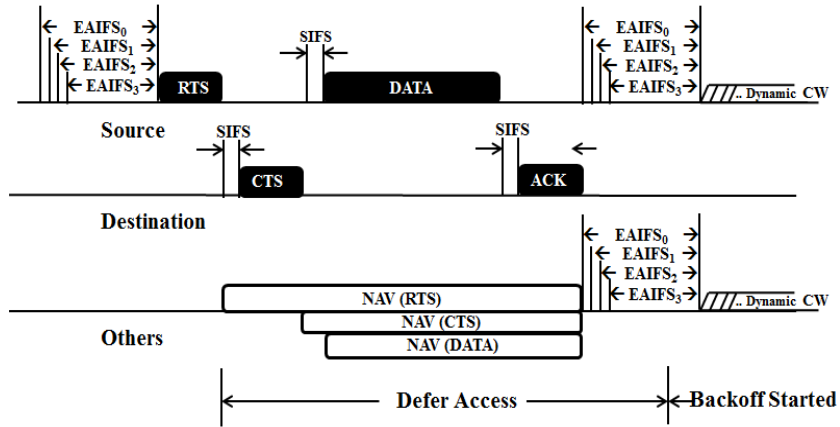


Figure 5.3: Medium Access Control Operation of QU-EAIFS

5.3.1. An Enhanced Arbitary Inter Frame Spacing in QU-EAIFS MAC

Initial Inter Frame Spacing (IFS) includes a waiting time when the node senses the channel as idle. A packet that has already transited several hops will wait a shorter IFS time versus packets generated locally. The new inter frame spacing time is given by $EAIFS_i = \{SIFS_{Time} * (6-i)\}/2$, where i ranges from 0 to 3. The value of $i=0$ when the packet is locally generated, $i=1$ for frames that transited one or two hops, $i=2$ when the frames have travelled three to four hops, and $i=3$ for frames that have transited at least five hops.

5.3.2. The Backoff Mechanism of QU-EAIFS MAC

The second feature of the proposed MAC is prioritising the nodes based on the active current utilisation of the queue by varying CW_{Min} and CW_{Max} ranges during the backoff phase. The backoff slot value freezes, as in IEEE 802.11b standards, when the channel becomes busy, so that it retains the higher chances of access as compared to the fresh packets during next round of contention. The queue utilisation information is

embedded in the packet header while queuing, as shown in Figure 5.2, and the MAC layer extract the queue utilisation information from the packet header while making access decision, following a cross-layer design. When the node has a packet to send, dynamic CW ranges are generated in accordance to (5.2), where the value of CW_{Min} is the same as that of the DQUB-MAC approach.

Similar to the backoff mechanism used in DQUB-MAC, a number of parameters are used as inputs: the queue size, active current queue utilisation, and a factor for generating priority levels are denoted by Q and q_u and ψ respectively. Given a queue size of 100, $\psi = 30$ is used to generate four different priority levels (low, fair, medium and high) and α an adjusting factor which determines the initial width of the contention window with an value of $\alpha = 3$, is used in evaluating the performance of QU-EAIFS MAC. Similar to DQUB-MAC the priorities (low, fair, medium, and high) are based on the queue utilisation of $<30\%$, $30-59\%$, $60-89\%$ and $\geq 90\%$ respectively. The data frame retransmission is triggered for unsuccessful packets until the packet is sent successfully or the retrial limit is exhausted. During retransmission of packets, and a new CW is generated exponentially as the retrial count $r > 0$ increases with respect to each corresponding priority level based on the current status of the queue. The exponential increase of CW_{Min} and CW_{Max} during retrial reduces the probability of collision during high degree of contention. After the fourth retrial attempt, the contention window range freezes at each respective priority and packet retransmission is attempted upto seven more times without further increasing the CW ranges. Even in this case, the maximum number of retransmissions is taken the same value as used in IEEE802.11b standard following the work (Nardelli, P.H., *et al*, 2012).

$$[CW_{Min}; CW_{Max}] = \begin{cases} \left[2^\alpha \left(\frac{Q - q_u}{\psi} \right); 2^\alpha \left(\frac{Q - q_u}{\psi} + 1 \right) \right], & r = 0 \\ \left[2^{\left(\frac{Q - q_u}{\psi} + r + 2 \right)}; 2^{\left(\frac{Q - q_u}{\psi} + r + 3 \right)} \right], & r > 0 \end{cases} \quad (5.2)$$

Thus, in QU-EAIFS MAC, a node having a high degree of queue utilisation has the highest probability of accessing the medium. On the other hand, a node with almost empty queue has the lowest probability of accessing the channel. This method of differentiation increases the probability of forwarding frames, if the node in the next hop has less congested queue. When multiple nodes with similar queue utilisation compete to access the shared channel, a node with packets that have transited a longer path gets higher probability of accessing the channel to the one with packets which has transited shorter path, because traffic which has travelled higher hop waits lesser IFS. The proposed protocol optimises the performance when there is bottleneck in the network due to network saturation by forwarding the packets to the nodes whose queues are less utilised. Thus, this approach optimises the utilisation of the queues and reduces the packet loss along the path, leading to higher end-to-end throughput.

5.4. Setting Up of Network Parameters

In order to test the performance of the newly designed MAC, simulations were carried out using NS2 version 2.35 (NS2), with the network parameters listed in Table 3.1 and the chain topology arrangement of Figure 3.1. Each simulation lasted for 1000 seconds and each result is an average value of 100 rounds of simulations using a DSDV routing protocol with a same basic rate and a bandwidth of 2Mb/s. The majority of simulations are performed using 1000 byte packet size.

Most of the simulations use a regular chain topology based on the node arrangement shown in Figure 3.1 and in later section an extensive random topology simulations are considered to validate the testing. Different length chains are considered in the later section but the first sets of simulations are based on a six hop chain. Node 0 and node 6 act as the source and the destination respectively for a UDP connection supporting a CBR application with a packet size of 1000 bytes.

The first set of simulations measure the throughput per hop as the offered load is increased on the 6-hop chain. The per hop performance for IEEE802.11b, IEEE802.11e, DQUB-MAC and QU-EAIFS MAC are shown in Figure 5.4, Figure 5.5, Figure 5.6, and Figure 5.7 respectively.

5.5. Results and Discussion

The new algorithms DQUB-MAC and QU-EAIFS MAC have been tested and benchmarked against both IEEE802.11b and IEEE802.1e standards in a variety of simulation environments. The purpose of the tests is to evaluate the efficiency in distributing the traffic and queue utilisation, as well as to determine the resulting packet loss in saturated network scenarios. Moreover, some tests of the robustness of the algorithms under less favourable circumstances are also performed.

5.5.1. Performance Evaluation of a Six Hop Chain Topology

In the experiment of Figure 5.4, using IEEE 802.11b, the MAC layer contention among the competing nodes is fair, but interference along the transiting path is different, and the incoming and the outgoing packets of an active node are not controlled. Consequently, it is expected that the packet drop and queue utilisation will not be uniform along the path. The end-to-end throughput starts to saturate when the source node generates data at approximately 290kb/s in IEEE802.11b as shown in Figure 5.4.

The performance deteriorates as the offered load increases, but stabilizes at a data rate of approximately 400kb/s and upwards. The graph also shows the data rates in each node in order to display the bottlenecks. The graph confirms that loss of packets along the route is not uniform and neither is the utilisation of each queue along the path. The end-to-end throughput at the point the network becomes saturated is approximately 200kb/s.

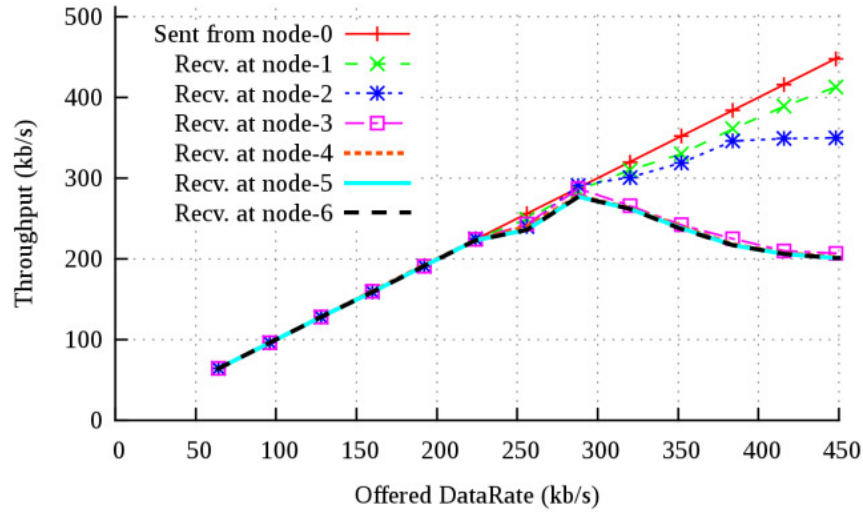


Figure 5.4: Throughput per Hop Vs Offered DataRate, IEEE802.11b on a 6-hop Chain.

The performance of IEEE 802.11e is worse than IEEE 802.11b despite setting the data flow to the highest priority as shown in Figure 5.5. This is due to the fact that the CW window range for this highest priority is only (7, 15), which is too narrow for a saturated network. The end-to-end throughput starts to saturate at 200kb/s, a traffic load much lower to that of IEEE802.11b. Since, the network becomes saturated much earlier, the experiment reveals that there is a heavy loss of packets in an around the source node. This result also shows that the distribution of the queue utilisation is non-uniform along the high hop count communicating path. The end-to-end throughput of IEEE 802.11e after network saturation is approximately 130kb/s, a value approximately 35% lower than IEEE 802.11b. There is a heavy loss of packets in the source, next hop and the second

hop along the path; it is due to the fact that the source node's interference affects the neighbour nodes up to the second hop. Moreover, being an area around the source, there is a higher rate of data to transmit, so the degree of contention is high and thus it leads to buffer overflow.

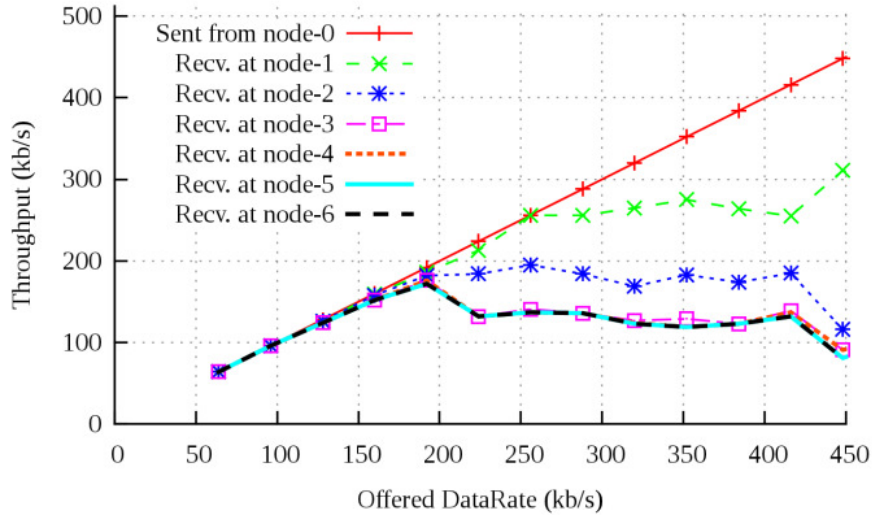


Figure 5.5: Throughput per Hop Vs Offered DataRate, IEEE802.11e on a 6-hop Chain.

The experiment of Figure 5.6 shows that the saturation point of the offered load of DQUB-MAC is similar to that of IEEE 802.11b protocol. However, as the offered load is further increased, the performance does not sink like IEEE 802.11b and IEEE802.11e. Instead, as the queue utilisation along the path is distributed more uniformly in comparison with IEEE 802.11b or IEEE 802.11e, the resulting data rates continue to increase when the offered data rate increases. This is because the nodes with heavily utilised queues are given a higher probability to access the channel than the ones that are less utilised. As a queue fills up, more packets are forwarded towards the next hop nodes whose queues are underutilised, because queues with higher utilisation are prioritised over nodes which are less utilised. In following such accessing mechanism, the packet loss rate along the path is reduced and queue utilisation along the path is more uniform,

hence the end-to-end packet delivery rate is increased. However, those nodes with similar queue utilisation share a same CW range. Nodes with fewer packets will have to wait longer than the ones that are overflowing, therefore the overall packet drop is greatly reduced and in turn the network performance is enhanced. The network becomes saturated with a high end-to-end throughput of approximately 270kb/s. The end-to-end throughput of DQUB-MAC is approximately 35% and 107% higher than that of IEEE802.11b and IEEE802.11e respectively in network saturation.

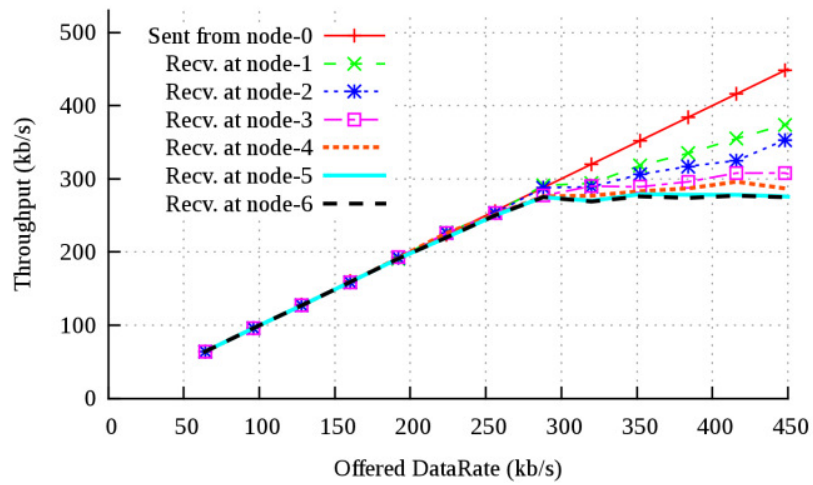


Figure 5. 6: Throughput per Hop Vs Offered DataRate, DQUB-MAC on a 6-hop Chain.

According to Figure 5.7, the saturation point of the new protocol QU-EAIFS MAC is similar to that of IEEE 802.11b. However, as the offered load further increases, the performance of the network does not degrade as in IEEE 802.11b or IEEE 802.11e. In QU-EAIFS MAC, the queue utilisation along the path is distributed more uniformly in comparison with IEEE 802.11b or IEEE 802.11e and the end-to-end performance is retained at higher level when the offered load increases, unlike the standard IEEE 802.11 standards where the performance sinks and stabilizes at a lower point. In QU-EAIFS MAC, the contending nodes share channel access better, unlike IEEE 802.11b and IEEE 802.11e. This is due to the fact that a node with a busier queue gets a higher probability

of accessing the channel than the less congested ones and the traffic with higher hops has a lower IFS waiting time during scheduling. As the queues fill up, there is a higher probability for a node to access the channel and forward the packets to the next hop. When two nodes have similar queue utilisation, the data traffic with higher hops gets the privilege during contention because it waits a shorter IFS waiting time. A node having fewer packets waits longer than the ones that are overflowing, resulting in reducing the overall packet drop and enhancing the end-to-end network performance. The loss rate at the source is high, but the packet delivery rate at the destination is higher, because of providing preference to packets with higher hop count and ensuring higher access probability to nodes with higher buffer utilisation. The network becomes saturated with a high end-to-end throughput at approximately 280 kb/s, which is 40% higher to that of IEEE 802.11b, and 115% higher to that of IEEE 802.11e standard when highest priority level is considered.

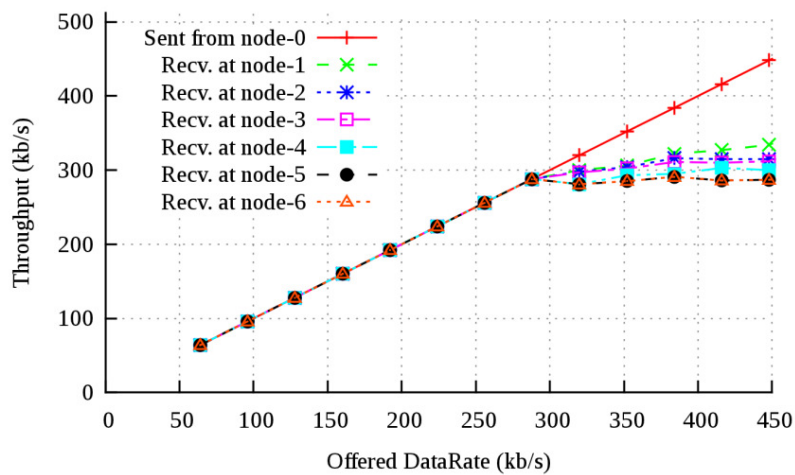


Figure 5.7: Throughput per Hop Vs Offered DataRate, QU-EAIFS MAC on a 6-hop Chain.

5.5.2. Throughput Vs Hop Counts

The graph of Figure 5.8 presents the throughput achieved per hop for a data rate chosen in a saturated region of 416kb/s, which is one of the saturation points in the 6-hop

chain. In the case of IEEE 802.11b, the data rate is halved after three hops; IEEE 802.11e halves the data rate after only two hops from the source. In the case of DQUB-MAC, the overall arrival rate at each intermediate node is much higher than for the IEEE802.11 standards and the data rate never drops by half. This improvement is due to the fact that queues that are either full or highly utilised (in this case queues on the source and the following few nodes) higher access probability to push the packets forward, compared to those nodes whose queues are less populated and are situated closer towards the destination. Since no priority of any form is assigned to IEEE 802.11b, the impact of hidden nodes and buffer overflow degrades the performance of the network after third hop, as is the case for IEEE 802.11e.

The error bar is too small to be visible as shown in the Figure 5.8. During network saturation, the overall average arrival rate is higher for DQUB-MAC, due to the use of fast forwarding technique when queue utilisation is high, unlike IEEE 802.11b or IEEE 802.11e MAC, where heavy loss of packets occurs due to buffer overflow.

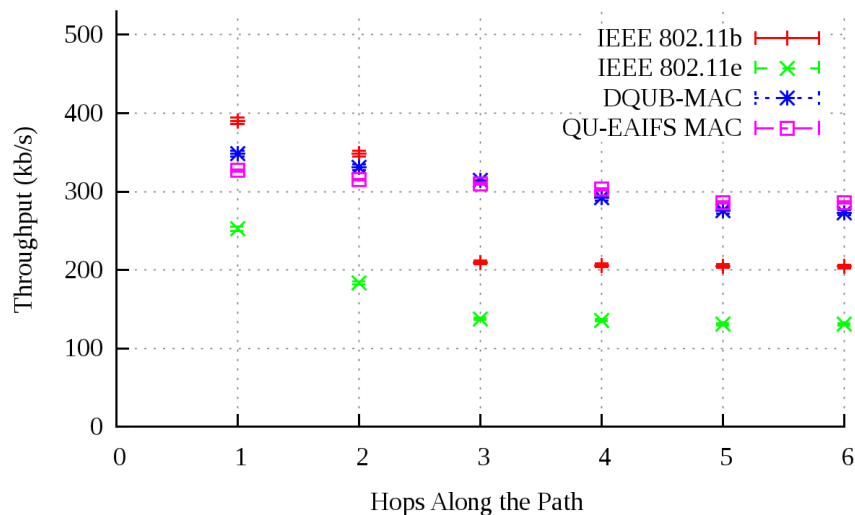


Figure 5.8: Avg. Throughput Vs Hops along the Path.

In the second approach of the new proposed MAC, QU-EAIFS never goes below half at any intermediate node along the source and the destination. In IEEE 802.11b, more packets were forwarded up to the second hop from the source as compared to QU-EAIFS MAC as that in DQUB-MAC, but have a heavy loss thereafter, unlike the new protocol that forwards the received packets gradually with less loss rate along the route towards the destination. Similar to IEEE 802.11b, the QoS MAC IEEE802.11e also suffers a heavy loss as early as the second hop despite receiving a high amount of data upto the first hop from the source. The performance gain in QU-EAIFS MAC compared to the standard MAC protocols like IEEE 802.11b and IEEE 802.11e is due to the fact that the congested queues around the source are given higher priority to forwards the packets towards the destination with less utilised queues and the packets with higher hops waits the least IFS waiting time which gives a good opportunity to forward the older packets than the fresh ones when the contending nodes have similar queue utilisation. Since IEEE 802.11b and IEEE 802.11e do not include any form of priority based on the dynamic situations and conditions of the network like QU-EAIFS MAC or DQUB-MAC, hidden nodes and lack of intelligent decision during contention highly impact the performance of the network. Thus, during network saturation, the overall average arrival rate of QU-EAIFS MAC is higher than that of IEEE 802.11b and IEEE 802.11e. The end-to-end throughput of 6 hop communication with IEEE 802.11b, IEEE 802.11e (Highest Priority Application) and QU-EAIFS MAC are 200kb/s, 130kb/s, 280kb/s respectively. As shown in Figure 5.8, the amount of data forwarded from the source to the next hop is higher in IEEE 802.11b and DQUB-MAC, but the eventual end-to-end throughput at network saturation is higher in QU-EAIFS MAC, which means that there were heavier loss of data along the path in IEEE 802.11b and DQUB-MAC compared to

QU-EAIFS MAC. Concluding, success rate of delivering the data to the destination is higher in QU-EAIFS MAC compared to IEEE 802.11b, IEEE 802.11e and DQUB-MAC.

5.5.3. Per Hop Packet Loss Distribution

In the graph of Figure 5.9 summarises the queue utilisation and distribution improvements brought in by DQUB-MAC, using the per-hop packet loss distribution with an offered load of 416kb/s, which is one of the saturation points of a 6 hop path length. The maximum loss rate at any hop along the route for DQUB-MAC is only 15%, whereas IEEE802.11b and IEEE802.11e have maximum loss rate approaching 40%. In DQUB-MAC, the loss rate is distributed uniformly along the route, while IEEE 802.11b and IEEE 802.11e display an irregular pattern of loss.

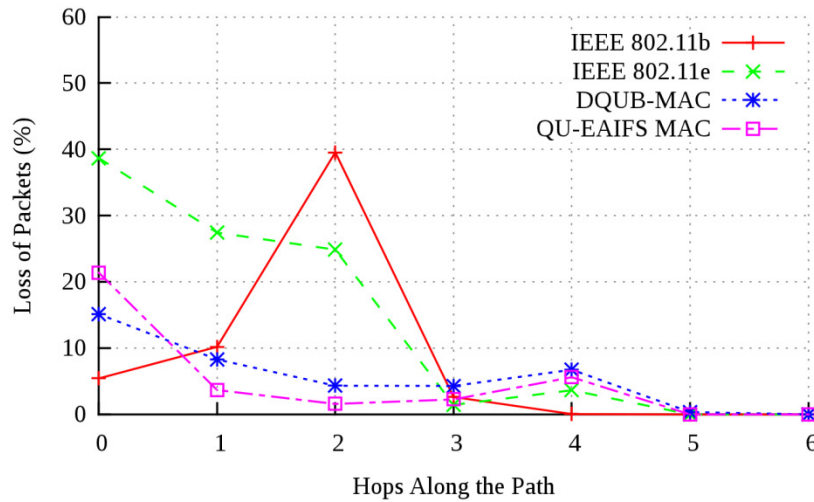


Figure 5.9: Per-hop Packet Loss Distribution.

In Figure 5.9, the per hop packet loss also reflects the queue utilisation status of each node along the route. The graph shows that IEEE 802.11b does not lose as much as the QU-EAIFS MAC at the source, but eventually, as the hop count increases, there is a heavy loss of approximately 40% at the second hop, which is very undesirable because it

has already utilised resources for which the packets will never get delivered at the destination. Such pattern of forwarding higher packets from the source, but experience high loss along the way is also seen in IEEE 802.11e as well. Interestingly, in the case of QU-EAIFS MAC, the loss along the path is gradual and more uniform. In fact, packets are dropped at a higher rate at the source in the case of QU-EAIFS MAC compared to DQUB-MAC. The drop rate stands at approximately 21% at the source in case of QU-EAIFS compared to DQUB-MAC, which has a 15% loss rate. It is preferable to drop packets at the source rather than forwarding towards the destination traffic that is not likely to reach the destination. In fact, the overall loss of packets along the source and destination pair is higher in DQUB-MAC compared to QU-EAIFS, which is less favourable when an end-to-end performance is considered. The chances of forwarded packets getting delivered is very high in DQUB-MAC as well as QU-EAIFS MAC compared to IEEE 802.11b and IEEE 802.11e, which means that forwarded packets faces higher chances of losing along the way in IEEE 802.11b and IEEE 802.11e.

Since IEEE 802.11e is not competitive in terms of end-to-end performance, hereafter the comparison of the proposed MAC protocols, i.e. DQUB-MAC and QU-EAIFS MAC, are benchmarked with IEEE 802.11b.

5.5.4. End-To-End Delay Analysis

Using the chain topology of Figure 3.1 and the network parameters listed in Table 3.1, the average end-to-end delay of a CBR packet with a short path length of 2 hops, an average path length of 4 hops and a long path length of 6 hops are calculated with an increasing offered load.

Here in analysing the delay, instead of testing with different packet sizes, the end-to-end delay is evaluated using different data rates with a fixed packet size of 1000 bytes, so that the rate of generation of packet varies. When the path length of the communication is short (at most 2 hops), the end-to-end delay is not much affected by the increasing data rate of the source in IEEE 802.11b or DQUB-MAC or QU-EAIFS MAC, because the activity of a node affects the neighbours up to two hops. For an average path length of 4 hops, the average end-to-end delay increases as the offered load increases beyond 350kb/s. IEEE 802.11b average end-to-end delay reaches 2 seconds for an offered load of 350kb/s, while DQUB-MAC and QU-EAIFS MAC introduce a similar delay only at data source rates of approximately 480kb/s and 540kb/s respectively. QU-EAIFS MAC introduces a lower overall average end-to-end delay in comparison to DQUB-MAC due to the use of a fast forwarding technique when the utilisation of the queues is high. However, when the offered load is high, the end-to-end delay for IEEE 802.11b slightly improves when compared to DQUB-MAC and QU-EAIFS MAC, as shown in Figure 5.10. This is due to the fact that the source and its neighbours get higher access probability compared to the other relay nodes along the path, so the packets stalls longer along the path.

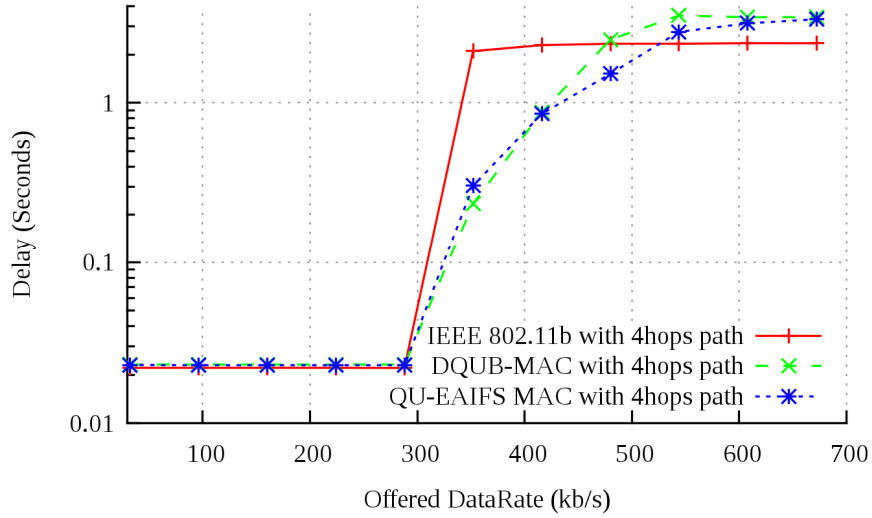


Figure 5.10: The Average End-to-End Delay in a 4 Hop Path Length.

In case of path length of 6 hops, under high contention, as shown in Figure 5.11, DQUB-MAC performs better in terms of average end-to-end delay in comparison to IEEE 802.11b. Moreover, in overall QU-EAIFS outperforms IEEE 802.11b as well as DQUB-MAC, it is due to the fact that QU-EAIFS. At a source rate of 672kb/s and path length is 6 hops, the average end-to-end delay of IEEE 802.11b and DQUB-MAC are approximately 25% and 21% higher to that of QU-EAIFS MAC. This is because, as the path length increases, the queue utilisation distribution along the path is uniform and the smaller waiting time for packets with higher hops in QU-EAIFS MAC. In general, when the offered load of the source is high and path length is also high, DQUB-MAC and QU-EAIFS MAC perform better in terms of average end-to-end delay compared to IEEE 802.11b, due to the fast forwarding techniques used when the queue utilisation is higher. At low data rates, the end-to-end delay is small because there is sufficient bandwidth to share among the contending nodes and the queue hardly gets full to introduce a long queuing delay. However, when the offered data rate is high, more packets are generated at a faster rate at the source than the capacity of the shared channel, so the queuing delay

increases, resulting in higher end-to-end delay in IEEE 802.11b or DQUB-MAC or QU-EAIFS MAC.

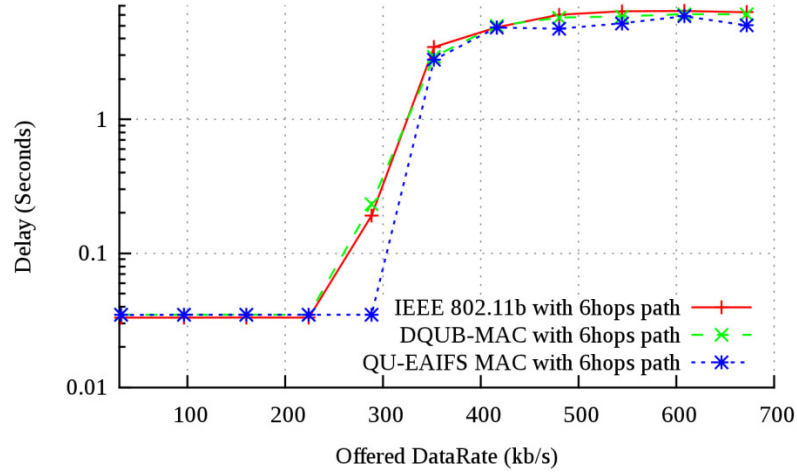


Figure 5.11: The Average End-to-End Delay in a 6 Hop Path Length.

5.5.5. Shorter and Long Chain Performance

This section tests the performance of DQUB-MAC and QU-EAIFS MAC against IEEE 802.11b for a short path length of 2 hops, 4 hops as well as 6 hops path length in a chain topology over different packet sizes ranging from 250 bytes to 1000 bytes, with an offered load of 1024kb/s as shown in Figure 5.12, Figure 5.13 and Figure 5.14 respectively. The end-to-end performance increases with packet size increase, irrespective of the path length in IEEE 802.11b, DQUB-MAC and QU-EAIFS MAC due to reduced overall control overheads in terms of RTS, CTS and ACK when the packet size is larger.

For a small packet size (under 250 bytes), DQUB-MAC and QU-EAIFS MAC gains 3.6% and 4.6% respectively over IEEE 802.11b when the path length is only 2 hops. The performance of DQUB-MAC and QU-EAIFS MAC are similar when the path length is low, because the queue utilisation pattern of the source node and the immediate

next hop neighbours are similar. When the queue utilisation patterns are similar, the channel access priorities of the contending nodes are also similar; this leads to lesser end-to-end performance for both the proposed techniques compared to situation when path length is high. It is because when path length is high, the queue utilisation pattern varies along the source and destination path. In an average path length of 4 hops and a small packet size of 250 bytes, the performance gain of is 10.0% and 7.0% for DQUB-MAC and QU-EAIFS MAC over IEEE 802.11b. When the path length of communication is 6 hops and small packet size of 250 bytes is considered then, DQUB-MAC and QU-EAIFS MAC gains 7.0% and 16% respectively over IEEE 802.11b. Similarly, in a larger packet size and higher path length scenario, DQUB-MAC and QU-EAIFS MAC outperform IEEE 802.11b, as shown in Figure 5.14. In addition, QU-EAIFS performs better than DQUB-MAC, irrespective of the path length, especially when the packet size is large (over 1000 bytes), due to the provision of higher access probability to packets with higher hop count. The performance of the medium access mechanisms used in DQUB-MAC and QU-EAIFS MAC during network saturation is more effective when the path length of the communicating nodes is high. Moreover, using a large packet size reduces the number of control frames and increases the overall network performance.

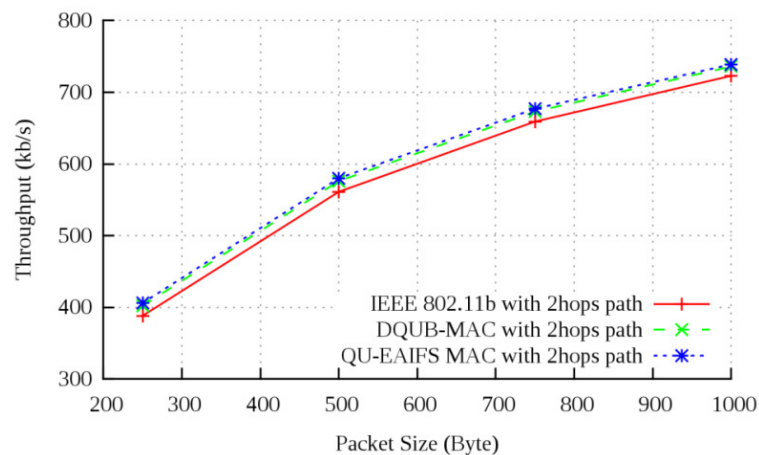


Figure 5.12: End-to-End Throughput Vs Packet Size in a 2 Hop Path Length.

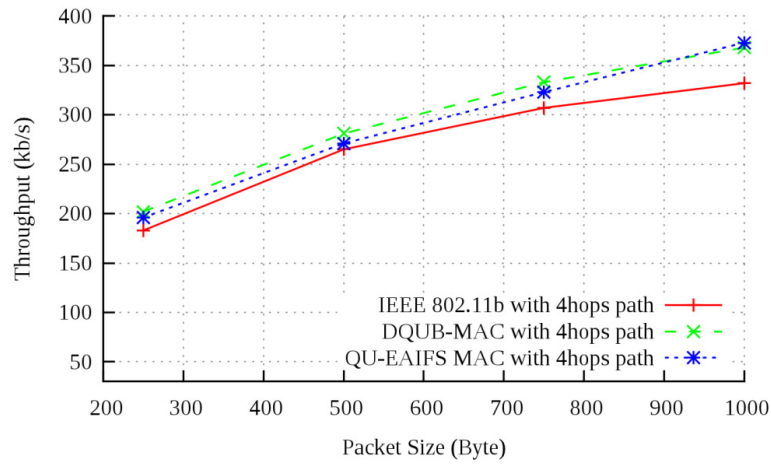


Figure 5.13: End-to-End Throughput Vs Packet Size in a 4 Hop Path Length.

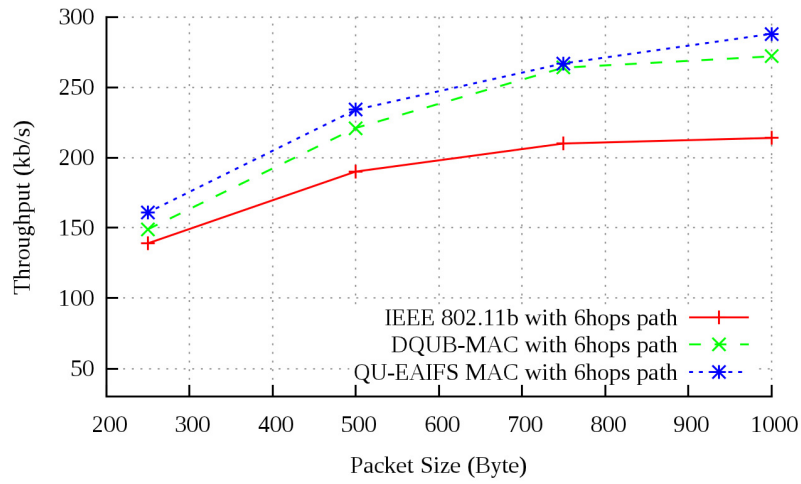


Figure 5.14: End-to-End Throughput Vs Packet Size in a 6 Hop Path Length.

5.5.6. Traffic Flows In Opposite Direction

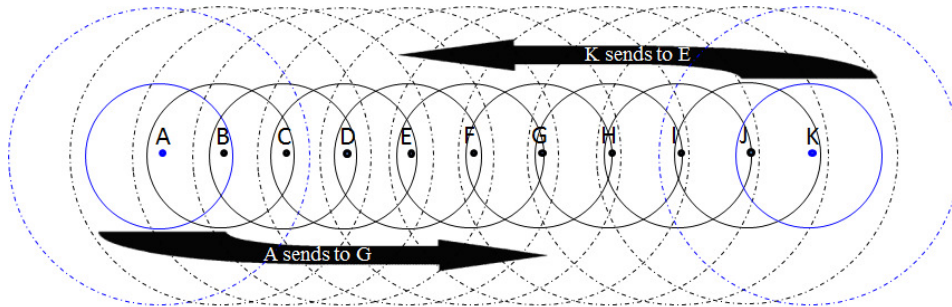


Figure 5.15: A chain topology with 11 nodes, with two flows from Opposite Direction.

In order to test the effect of a flow in presence of another flow arriving from the opposite direction, eleven different nodes are arranged in a chain topology as shown in Figure 5.15. Two sources, placed at the extreme end points of Figure 5.15, are selected as the sources, where node A sends to node G and node K sends to node E, so that the two traffic crosses each other with a crossover of two hops and each flow has to move six hops to reach their respective destinations. Figure 5.16 shows the network performance of the network for an increasing data rate of per flow offered load of the network topology of Figure 5.15 and tested with the network parameters from Table 3.1. Using IEEE 802.11b medium access control, the total network throughput peaks at 425kb/s when the offered per flow load is approximately 250kb/s to 350kb/s, but thereafter, despite increasing the per flow offered load of the network, the total end-to-end network throughput drops drastically and saturates with a total network throughput of around 325kb/s. In the case of DQUB-MAC, the network saturates with a higher network throughput of around 375kb/s. This leads to a performance gain of 15% during network saturation in case of DQUB-MAC over the standard IEEE 802.11b medium access control protocol. In case of QU-EAIFS MAC, the highest peak of network performance occurs when the per flow load is approximately 350kb/s and yields a network throughput of 450kb/s compared to IEEE 802.11b and DQUB-MAC. In case of QU-EAIFS MAC, the network saturates at approximately 425kb/s, so QU-EAIFS gains approximately 15% over DQUB-MAC and approximately 30% over IEEE 802.11b during network saturation due to prioritising the access based on the utilisation pattern of the queue and hop count of the transited packet. Unlike IEEE 802.11b, DQUB-MAC and QU-EAIFS MAC do not rapidly degrade the overall network performance when the offered per flow load increases as shown in Figure 5.16, since the utilisation pattern of the queues along the

path are more uniform and the congested queues forward their packets to less utilised queues. Increasing per flow load does not increase the overall network performance after the peak, but the DQUB-MAC and QU-EAIFS MAC performs better and handles the saturated region more efficiently than IEEE 802.11b.

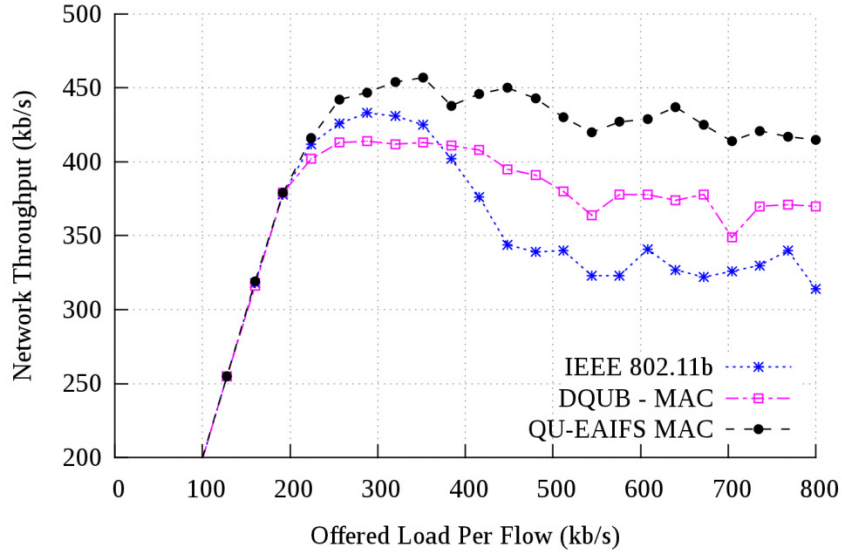


Figure 5.16: Network performance, with two flows running from opposite direction.

5.5.7. Random Topology

In order to validate the scheduler, a topology of 40 randomly placed nodes is considered, as shown in Figure 5.17, by dividing the area into three zones, namely AREA 1, AREA 2 and AREA 3. AREA 1, AREA 2 and AREA 3 are randomly placed with 10 nodes, 20 nodes and 10 nodes respectively. Sources and destinations are also randomly selected from AREA1 and AREA 3 respectively. The source zone and destination zone are placed at least 1000m away from each other, to ensure a significant path length. The same network parameters listed in Table 3.1 are used during the simulation. The actual path taken depends on the routing algorithm, DSDV. Two different sets of simulations are considered: firstly, with a single flow with a random selection of source from AREA 1 and a random selection of destination from AREA 3. Secondly, a case with a multiple

flow (two flows in this case) with a random selection of distinct source and destination pairs from AREA 1 and AREA 3 respectively are considered. A total of 200 different random topologies are considered with a fresh random selection of source and a destination pair(s) at each turn in both the cases. Results include only simulations where a path was successfully established between source and destination.

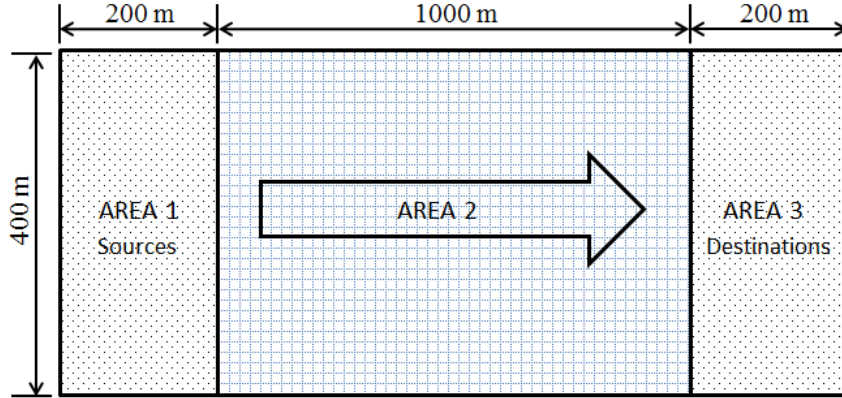


Figure 5.17: Random Topology Setup.

5.5.7.1. Exponential Traffic

The random topology setup in Figure 5.17 is also tested with an exponential traffic generator with multiple sources. In this section the system is tested with a network parameters listed in Table 3.1 of chapter 3 with a 1000 bytes packet size and multiple flows of 416kb/s, one of the data rates in saturation point of a six hop path length. Table 5.1 shows that the overall network performance gain of DQUB-MAC and QU-EAIFS MAC outperformed the standard IEEE 802.11b regardless of the burst parameters. When the burst time of the source is higher the performance gain of DQUB-MAC and QU-EAIFS MAC is at least 16% compared to IEEE 802.11b. Even when the idle time is more or equal to the burst time, the proposed mechanisms outperformed the standard IEEE 802.11b, because frame lost rate is low when buffer overflow occurs. The overall gain in network performance shows that during network saturation, the buffer

overflowing nodes fast forward the data frames to the next hop with higher rate, because higher priority is given to nodes with high queue utilisation. Thus, data frames moving towards the destination node with less utilised buffer from a highly utilised buffer leads to less lost and resultant in a high end-to-end throughput.

Burst Time (s)	Idle Time (s)	IEEE 802.11b (kb/s)	DQUB-MAC		QU-EAIFS MAC	
			Performance (kb/s)	Gain in % over IEEE 802.11b	Performance (kb/s)	Gain in % over IEEE 802.11b
1.0	0.5	193.96	226.66	16.85	231.44	19.32
0.5	1.0	209.74	218.08	03.97	221.57	05.64
0.5	0.5	204.84	242.02	18.15	222.20	08.47

Table 5.1: Network Performance using Exponential Traffic.

5.5.7.2. CBR Traffic

The performance of the random topology of Figure 5.17 was tested using a real time data like CBR traffic of 1000 bytes with a fixed data rate of 416kb/s, which is one of the data rates of a saturation point in a 6 hop path length. Since, a saturated network is considered, packet size is not vital in the study, so a random large size of 1000 byte is considered. In the case of a single flow, the correlation coefficient of the end-to-end performance of IEEE 802.11b and DQUB-MAC is +0.78, showing a positive linear relationship. The performance gain of DQUB-MAC and QU-EAIFS MAC over IEEE 802.11b is shown in Table 5.2. The average degree of fairness among the flows in IEEE 802.11b, DQUB-MAC and QU-EAIFS MAC are approximately 97.60%, 97.51% and 99.00% respectively, according to Jain's fairness index.

Protocol	End-to-end throughput in kb/s			Gain	
	IEEE 802.11b	DQUB-MAC	QU-EAIFS MAC	DQUB-MAC over IEEE 802.11b	QU-EAIFS MAC over IEEE 802.11b

Single Flow	192.54	234.50	247.51	22%	28%
Multiple Flows	187.73	224.75	249.98	20%	33%

Table 5.2: Performance Gain of CBR traffic in a Random Topology.

5.6. Conclusion

This chapter proposed a new MAC protocol based on queue utilisation, with two variants called Dynamic Queue Utilisation Based (DQUB) MAC and Queue Utilisation with Hop Based Enhanced Arbitrary Inter Frame Spacing (QU-EAIFS) MAC. In DQUB-MAC, a node with a higher utilisation queue is prioritised over a node whose queue is less utilised. The results show that, while using DQUB-MAC, a more congested queue gets higher probability of forwarding the packets towards the less congested queue and increases the probability of packet delivery rate towards the destination. Moreover, during packet retransmission, the protocol also ensures that packets with higher retransmission count takes priority over packets with lower retransmission count. As a result, during network saturation, a high end-to-end throughput is achieved when for a high path length in case of QUB-MAC compared to IEEE 802.11b or IEEE 802.11e. In a path length with at least 6 hops, the performance gain of DQUB-MAC is 35% better to that of IEEE 802.11b when CBR traffic is used. Moreover, the average end-to-end delay of packet delivery at the destination during high offered load is lesser in DQUB-MAC compared to IEEE 802.11b.

In QU-EAIFS, instead of using a fixed DIFS, a differentiated enhanced IFS based on hop count is used and provides priority during contention based on the utilisation of queue. Thus, the network performance is even higher than DQUB-MAC and IEEE 802.11b. It is also observed that IEEE 802.11b outperforms the network performance of

IEEE 802.11e. In a saturated region, when the path length is high (over 6 hops), the end-to-end performance of the network of QU-EAIFS MAC is high and stands at 40% higher to that of IEEE 802.11b. Moreover, the average end-to-end delay of CBR packets is lower in case of QU-EAIFS MAC compared to that of DQUB-MAC and IEEE 802.11b.

It is also observed that DQUB-MAC and QU-EAIFS MAC are compatible with varying packet sizes, different offered load, different traffic flows including exponential traffic, and varying path length. There is a high degree of stability and consistency in DQUB-MAC as well as QU-EAIFS MAC, even with random topologies. The degree of fairness of DQUB-MAC and QU-EAIFS MAC is comparable to IEEE 802.11b with an overall network performance gain. The next chapter proposes two power controlled approaches, in order to indirectly control the degree of interference by controlling the transmission range. One approach uses location information of the active nodes and the other one uses power estimation based on the received signal strength in order to save energy and increase spatial reuse to increase the probability of multiple transmissions in a limited shared Ad Hoc environment.

Chapter 6. Power Controlled Transmission

6.1. Introduction:

In a resource-constrained Ad Hoc network, interference is a significant limiting factor in achieving high throughput. As the interference range is directly proportional to the transmission range, controlling transmission range of the active nodes dictates the density of parallel or simultaneous communication and subsequently the overall network performance. Using a large transmission range does have its benefits, as it reduces the path length and increases link stability and throughput, but also increases interference and degrades the network performance as the number of active nodes increases. On the other hand, when the transmission range is low, the overall interference decreases but the path length between the source and the destination increases; as a result, the end-to-end throughput may decrease, as discussed in section 3.2, but the level of frequency and space reuse increases, increasing the probability of parallel transmission. One of the biggest challenges in controlling transmission power in Ad Hoc networks is the impact on connectivity and routing. This chapter proposes two different MACs following different approaches, first approach uses location information to control the transmission and the second approach uses power estimation technique based on the received signal strength. Both approaches are tested with a variety of location and power estimation techniques.

The location based power controlled MAC is discussed in section 6.2 and the power estimation technique with its variants are discussed in section 6.3. The discussion in this chapter does not consider mobility, so route maintenance is not considered, but focuses on the MAC mechanisms using a single hop communication to explore the probability of parallel

Data transmission over a defined area. The new mechanism is benchmarked and tested extensively with both fixed and random topologies with random sources and destinations with variants of power controlled MAC mechanisms and a maximum power transmission method like IEEE 802.11b.

When pair of communicating nodes is closer with respect to the maximum transmission range, using a maximum fixed transmission power leads to significant interference and energy waste. Further, if a node communicates with the next hop destination using only the required minimum transmission power, then the area of interference decreases, the probability of parallel transmissions increases, and battery life is extended; the aim of this chapter is to alleviate all these limitations of traditional wireless. When there are active neighbours, each node dynamically estimates an optimal transmission power by considering the signal strength of the neighbours to avoid hidden node issues. This chapter also focuses on drawing a relationship between the amount of energy spent by an active node and the distance between the communicating nodes. In order to decrease waiting time during low congestion, the proposed MAC uses a dynamic backoff ranges based on the number of active neighbours rather than using a fixed backoff ranges.

The remainder of the chapter is structured as follows. Detail discussions of the algorithms of the proposed technique are discussed in the following subsections of 6.2, 6.3 and 6.4.

6.2. Location Based Power Controlled Cross Layer

As highlighted by prior research, the transmission power does have a significant influence on the network capacity, particularly for relatively high node density, due to the high degree of transmission and interference area overlap. To reduce the impact of these

issues, this chapter proposes a new cross layer MAC called Location Based Transmission using a Neighbour Aware with Optimised EIFS MAC for Ad Hoc Networks (LBT-NA with Optimised EIFS MAC). The proposed protocol consists of three parts: power estimator, optimised EIFS, and backoff. Firstly, the algorithm calculates the power for transmission using location information by considering the optimal distance among the active neighbours; secondly, an optimised EIFS is introduced, based on the frame type; lastly, a new random backoff algorithm is implemented, using the number of active neighbour in order to enhance the utilisation of shared resources. The proposed power controlled cross layer MAC is described in detail in the following subsections.

6.2.1. Location Based Transmission Power

The proposed model assumes that each node is aware of its current location with the help of a Global Positioning System (GPS). Since a perfect radio propagation channel is considered, the model does not take into account the effects on signal due to obstruction, reflection, refraction and scattering. Since a perfect channel condition is considered, an additional transmission power margins are not taken into account to accommodate fading or shadowing of the signal. But the proposed mechanism considered frame loss if collision occurs if the receiving signal is not ten times higher than the interfering signal. The mechanism uses a distance path-loss component, but the reception decision is based on the distance and the corresponding received signal strength. Having either position information allows a receiver/sender pair to determine the distance (d) between them and allows the sending node to calculate the required signal power to reach the intended receiver with the required signal strength to successfully receive the data. This leads to a twofold advantage from an efficiency perspective: firstly, it allows using only the minimal required power for communication between the source and the destination, thereby active communicating nodes save power and extend the battery life. Secondly, the interfering range changes dynamically

depending on the distance of communication, so the probability of simultaneous transmissions without interference by other nodes increases. In this study, the energy used by an active node during extracting the location information via GPS is not taken into account mainly because node mobility is restricted once the nodes are deployed whereby constant availability of location information is not required unless the deployed nodes move. Moreover, in this study, availing location information is a one-time event which happened during node deployment and the main usage of energy happens during the communication between the active source, active relay node and the active destination node. So, during a calculation of energy usage of an active node, the study is focused mainly on the amount of energy spent when a node is in a receiving mode or a sending mode by assuming that the amount of energy used in acquiring the one-time location information during node deployment is very minute compared to the energy used during actual data transmission between the communicating pair.

The proposed model does not use any additional control frames for exchanging location information, but new fields are introduced in the RTS and the CTS frames to exchange the location information between the source and the destination. Since the nodes are deployed in flat surface environment, only the *X-Axis* and *Y-Axis* values are exchanged. When a node has a data to send, it starts by broadcasting an RTS frame at full power and the intended next hop receiver replies with a CTS control frame to reserve the channel. When the intended destination node N_D with coordinates (X_D, Y_D) receives an RTS frame from a Source node N_S which is located at (X_S, Y_S) , it extracts the location information and calculates the corresponding Euclidian distance $d = \sqrt{(X_D - X_S)^2 + (Y_D - Y_S)^2}$ between the two nodes. Likewise, upon receiving a CTS message, the source also calculates the distance between the two nodes. As a result, the source and the next hop destination are aware of the relative distance between them upon receiving the first RTS and the first CTS frames. Following the

RTS/CTS exchange, further control frames or data communication between these pair of nodes is carried using the estimated power based on the distance. This thesis assumes a perfect channel condition; otherwise the newly calculated minimum power should be estimated to cover $d+\Delta$ to incorporate the effect of signal fading. After a successful reception of the data frame, an ACK frame is sent by the destination to the source/relay node in order to confirm the arrival of the data with the newly calculated transmission power. In terms of exchanging location information, new fields are added in both RTS and CTS control frames, so an additional overhead of $(4 \times 2 = 8 \text{ bytes})$ each are introduced.

One of the drawbacks of using the newly calculated minimal power communication in a distance-based power controlled mechanism is that a pair of nodes communicating over a higher distance can capture the channel over neighbours communicating with a shorter distance. In order to avoid such situations, when neighbour nodes are active, an optimised transmission power is estimated by considering the distances of all the active neighbours to reduce hidden node issues and provides fair contention among the competing nodes. The optimal distance of node i , $d_{optimal}^i = \text{Max}\{ d_{i,q} \}$ where, $q = \{1, 2, \dots, k^{th}, \dots, N\} - \{i\}$, which are the active neighbours around node i .

$$d_c = (4 * \pi * h_t * h_r) / (\lambda) \quad (6.1)$$

$$P_t = \{P_r * (4 * \pi * d)^2 * L\} / (G_t * G_r * \lambda^2) \quad (6.2)$$

$$P_t = (P_r * d^4 * L) / (G_t * G_r * h_t^2 * h_r^2) \quad (6.3)$$

Since, a flat surface is considered during node deployment, line of sight radio propagation or a ground reflection radio propagation model best fit the scenario. So, a simple Friis radio propagation model is used for a short distance communication and used a Two Ray Ground propagation model, if the distance of communication is far, so that the chances

of receiving signal is increased through light of sight and ground reflection. The transmission power is calculated using (6.2), when Friis propagation model is considered and it uses (6.3) for a Two Ray Ground propagation model. Friis propagation model is ideal for a short distance communication, since line of sight propagation is considered as discussed in (Rappaport, T.S., 2002; Haykin, S., *et al* (2002) and Mark, J.W., *et al* 2005) and these authors also mentioned that Two Ray Ground propagation model is efficient for a long distance communication, due to consideration of the reflected ground signals as well as the line of sight signals. The authors also found out that, using Two Ray Ground propagation model is not favourable for short distance communication due to the oscillation caused by the constructive and destructive combination of the two signals arriving from the reflected ground and the line of sight. Thus, the cross-over distance which shows an approximation of the distance after which the received power decays with its fourth order of the communicating distance is used and the cross-over distance (d_c) is calculated using (6.1). In order to obtain an optimal performance, in this study, Friis propagation model is used when the distance of communication is below the cross-over distance, and the system automatically switches to a Two Ray Ground propagation technique otherwise. The variables P_t and P_r of (6.2) and (6.3) represent the transmitted signal strength and the received signal strength respectively, when the communicating pair are separated by a distance called d . The antenna's transmitter gain, receiver gain, height of transmitter, height of receiver, frequency of the signal, wavelength of the signal and the system loss are represented by G_t , G_r , h_t , h_r , f , λ and L respectively. The algorithm for estimating the transmission power based on the distance of the communicating pair when the activities of the neighbours are taken into account is described in Table 6.2. The Two Ray Ground propagation model also has its own limitations in real life application in comparison to basic Freespace model like Friis as mentioned by the authors of (Sommer, C., *et al*, 2011), and the authors introduced a new

propagation model based on the phase difference of interfering signals and a reflection coefficient which yields a better result for an unobstructed communication between the sender and the receiver. A list of terminologies and the symbols used in this chapter is available in Table 6.1.

P_{type} : Packet Type	P_{recv} : Received power strength.
f_c : Control Frame	$O_{rts_cts}^{i \blacksquare k}$: Node i overheard either RTS or CTS frames from node k .
f_{rts} : RTS Frame	ID_{gen} : Node ID of the frame/packet generator.
f_{cts} : CTS Frame	$Orc_table^{i \blacksquare k}$: This table records the IDs and counts of node k when i overheard.
f_{ack} : ACK frame	$A_i^{\mathbf{x}}$: A table recording the active neighbour of node i .
f_{data} : Data Frame	$A_{i_count}^{\mathbf{x}}$: The number of active entry in $A_i^{\mathbf{x}}$
L_{frame} : Frame length	$O_{dist}^{i \blacksquare k}$: Distance between the active node i and the overheard neighbour node k .
$f_{routing}$: Routing Frame	d_{max} : Maximum Distance of an active neighbour.
$C_{rts}^{i \rightarrow j}$: Counting the number of RTS generated by active node i to j .	Dst_i : Destination of an active node i .
$C_{cts}^{i \rightarrow j}$: Counting the number of CTS generated by active node i to j .	P_{est} : Estimated Power needed/used between the communicating pair.
$R_{rts/cts}^{j \rightarrow i}$: node i receives an RTS or CTS from node j	OP_{est}^i : Optimal Power estimated to reach the farthest active neighbour node from i .
P_t^i : Power of transmission used by node i .	$Table_{Out}$: A table recording the IDs and P_t^i to whom the frame/packet is going out.
P_r^i : Received power by node i .	$Entry_{OutCount}$: Count of the Table record of
P_{max} : Maximum transmission power an active node can use.	$Table_{In}$: A table recording the IDs and P_{est}
P_{thresh} : Minimum threshold power a node can receive successfully.	
$P_{min}^{i \rightarrow j}$: Minimum power required to communicate from node i to node j .	

$d_{optimal}^i$: Farthest distance among all the active nodes within a transmission range of node i .	from whom the frame/packet is arriving.
d_{ij} : Distance between node i and j .	$Entry_{InCount}$: Count of the table record of $Table_{In}$.
$P_{optimal}$: It's the power to reach the farthest active node within its transmission range.	$O_p^{i \blacksquare k}$: Overheard signal power by i when k communicates with other nodes (say) m .
D_{of_k} : Destination of node k .	

Table 6.1: List of symbols and terminologies used

$$\begin{aligned}
 &\text{If } [d_{optimal}^i < d_c] \text{ then} \\
 &\quad M = (4 * \Pi * d_{optimal}^i) / (\lambda) \\
 &\quad P_{optimal} = (P_{min} * M^2 * L) / (G_t * G_r) \\
 &\text{Else} \\
 &\quad P_{optimal} = (P_{min} * (d_{optimal}^i)^4 * L) / (G_t * G_r * h_t^2 * h_r^2)
 \end{aligned}$$

Table 6.2: Calculating Optimal Transmission Power

6.2.2. Use of Calculated Transmission Power

In order to limit the transmission range, every node is allowed to use the maximum standard transmission power (P_{max}) = 0.28183815W, which can cover a maximum fixed transmission range of 250m (default standard values as described in NS2 for a fixed transmission range). The interference range is higher than the transmission range and it covers a radial distance of 2.2 times of the transmission range as per the standard value described in the NS2 simulator. So, a node sending a data with a transmission power of 0.28183815W generates an interference range up to 550m and thereafter the signal strength is negligible. The threshold value of the signal strength to be considered within a transmission

range is, $P_{thresh} = 3.652e-10W$ and a signal received with a power of at least $1.559e-11W$ is considered to be within an interference range as described in NS2.

The aim is to analyse the spatial reuse and probability of parallel transmission in a single hop shared channel environment, so a routing protocol called DumbAgent is used since it sets up a link for a one hop communication and it works as shown in Figure 6.1. Route discovery packets are always sent with maximum transmission power since the node has no information about the location until RTS/CTS packets are exchanged and this provides the highest probability of discovering the next hop neighbour. Following a successful exchange of the first RTS and CTS frames of the two communicating pairs, thereafter the frames are then sent with reduced power, optimised for a radius equal to the distance between the corresponding endpoints and in presence of multiple active neighbours, optimised transmission power ($d_{optimal}^i$) is considered. The detail algorithm on how the transmission power is adjusted based on the type of packet, activity of the neighbours and the communicating distance between the nodes is described in Table 6.3.

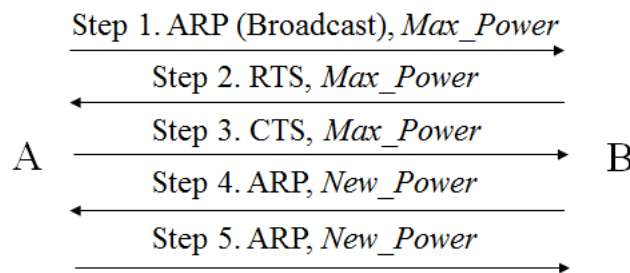


Figure 6.1:Route Discovery Using DumbAgent.

When node i wants to send data to node j

```

If [ $P_{type} == f_{rts} \parallel P_{type} == f_{cts}$  ]
  If [ $C_{rts}^{i \rightarrow j} == 1 \parallel C_{cts}^{i \rightarrow j} == 1$ ]
    If [ $R_{rts/cts}^{j \rightarrow i} == \text{Yes}$ ]
      If [ $d_{optimal}^i > d_{ij}$ ]
         $P_t^i = P_{optimal}$ 
      Else
         $P_t^i = P_{min}^{i \rightarrow j}$ 
    Else
       $P_t^i = P_{max}$ 
  Else
    If [ $d_{optimal}^i > d_{ij}$  ]
       $P_t^i = P_{optimal}$ 
    Else
       $P_t^i = P_{min}^{i \rightarrow j}$ 
Else if [ $P_{type} == f_{data} \parallel P_{type} == f_{ack} \parallel (P_{type} == f_{routing} \ \&\& \ R_{rts/cts}^{j \rightarrow i} == \text{Yes})$ ]
  If [ $d_{optimal}^i > d_{ij}$  ]
     $P_t^i = P_{optimal}$ 
  Else
     $P_t^i = P_{min}^{i \rightarrow j}$ 
Else
   $P_t^i = P_{max}$ 

```

Table 6.3: Algorithm for Adjusting the Transmission Power.

6.2.3. Recording the Neighbours Information from RTS and CTS

A record of the active RTS and CTS frames of all the active neighbour nodes is maintained by each node as shown in Table 6.4. The activity of the neighbour information is updated after every interval of T seconds and here $T=1$ second is considered. During updating the active neighbour table, the algorithm removes any records with a timestamp older than a threshold T seconds. The neighbour table updating algorithm is shown in Table 6.5 and it is done in order to maintain the freshness of the network condition and remove stale entries of inactive neighbours. In a neighbour table, an active node i , records the activity of each overheard (It's a situation when node i is within the transmission range of another active node

k , when k communicates with m) active neighbour by listening to the RTS and the CTS frames. The optimal distance of the node i , $d_{optimal}^i$ is also calculated while updating the neighbour record.

When node i overheard node k communicating to node m

```

If [ $P_{type} == f_{rts} \parallel P_{type} == f_{cts}$ ]
If [ $O_{rts\_cts}^{i \blacksquare k} == 0$ ]
     $Orc\_table^{i \blacksquare k}[0].ID_{gen} = Src\_ID$ 
     $Orc\_table^{i \blacksquare k}[0].Count = 1;$ 
     $O_{rts\_cts}^{i \blacksquare k} ++;$ 
Else
    For [ $t=0; t < O_{rts\_cts}^{i \blacksquare k}; t++$ ]
        If [ $Orc\_table^{i \blacksquare k}[t].ID_{gen} == k$ ]
             $Orc\_table^{i \blacksquare k}[t].Count ++;$ 
            If [ $Orc\_table^{i \blacksquare k}[t].Count > 1$ ]
                If [ $A_{i\_count}^{\mathbb{N}} == 0$ ]
                     $A_i^{\mathbb{N}}[0] \leftarrow \left\{ \begin{array}{l} T_{recv}, k, m, X_k, Y_k, O_{dist}^{i \blacksquare k} \\ NAV_k, O_{rts\_cts}^{i \blacksquare k} ++ \end{array} \right\}$ 
                     $A_{i\_count}^{\mathbb{N}} ++$ 
                Else
                    For [ $u=0; u < A_{i\_count}^{\mathbb{N}}; u++$ ]
                        If [ $A_i^{\mathbb{N}}[u].From_{rts\_cts} == k \ \&\& \ A_i^{\mathbb{N}}[0].To_{rts\_cts} == m$ ]
                             $A_i^{\mathbb{N}}[u] \leftarrow \left\{ \begin{array}{l} T_{recv}, k, m, X_k, Y_k, O_{dist}^{i \blacksquare k} \\ NAV_k, O_{rts\_cts}^{i \blacksquare k} ++ \end{array} \right\}$ 
                            Break;
                        Else If ( $u+1 == A_{i\_count}^{\mathbb{N}}$ )
                             $A_i^{\mathbb{N}}[u] \leftarrow \left\{ \begin{array}{l} T_{recv}, k, m, X_k, Y_k, O_{dist}^{i \blacksquare k} \\ NAV_k, O_{rts\_cts}^{i \blacksquare k} ++ \end{array} \right\}$ 
                             $A_{i\_count}^{\mathbb{N}} ++$ 
                        Else
                            Continue;
                    Break;
                Break;
            Else
                Continue;
        If [ $t+1 = O_{rts\_cts}^{i \blacksquare k}$ ]
             $Orc\_table^{i \blacksquare k}[t+1].ID_{gen} = k$ 
             $Orc\_table^{i \blacksquare k}[t+1].Count = 1;$ 
             $O_{rts\_cts}^{i \blacksquare k} ++;$ 
        Else
            Continue;

```

Where,

$$O_{dist}^{i \blacksquare k} = \sqrt{(X_k - X_i)^2 + (Y_k - Y_i)^2}$$

Table 6.4: Algorithm for collecting active neighbour information

```

Initialised:  $d_{max} = 0$ 
For [p=0, q=0; p <  $A_i^{\mathbb{N}}$ .count ; p++]
    If [ $(A_i^{\mathbb{N}}[p].T_{recv} + Interval) \geq Now$ ]
         $Temp\_Record[q] \leftarrow A_i^{\mathbb{N}}[p]$ 
        q++;
    If [p+1 ==  $A_i^{\mathbb{N}}$ .count]
        For [r=0; r < q; r++]
             $A_i^{\mathbb{N}}[r] \leftarrow Temp\_Record[r]$ 
            If [ $d_{max} < A_i^{\mathbb{N}}[r].O_{dist}^i$ ]
                 $d_{max} = A_i^{\mathbb{N}}[r].O_{dist}^i$ ;
 $d_{optimal}^i = d_{max}$ ;
 $A_i^{\mathbb{N}}$ .count = q;

```

Where,

Each record entry of $A_i^{\mathbb{N}}$ consists of $\left\{ T_{recv}, k, m, X_k, Y_k, O_{dist}^{i \blacksquare k}, \right.$
 $\left. NAV_k, O_{rts_cts}^{i \blacksquare k} + + \right\}$

Table 6.5: Algorithm for updating the neighbour information.

In this location based transmission control mechanism, apart from increasing the probability of spatial and frequency reuse, this mechanism can increase the battery lifespan too. In a fixed maximum transmission power approach, the same transmission range is used regardless of the distance between source and destination, which leads to energy waste and unnecessary interference range for short distance communication. In the proposed technique, the source adjusts the transmission power as per the required distance between the communicating nodes, and if there be an active neighbours then it adjust the transmission range up to the farthest active neighbour to enhance a fairer access. The node updates its neighbour records to maintain the freshness of the network condition.

6.2.4. Optimised EIFS (Extended Inter-Frame Space)

When a node i is within an interfering range of other active nodes, then node i would not be able to decode the erroneous signal received, so node i defers channel access and waits for an EIFS. Even when node i is within a transmission range, but receives an erroneous frame and forward error correction (FEC) could not rectify the error, then node i waits for EIFS time, before contending to access the channel for the next round. When a frame is erroneous, it is not possible to know the type of frames directly, so IEEE 802.11 standards use a fixed time to defer channel access in such situation. The fixed deferring time in such situation for an active node is $EIFS = SIFS_{time} + DIFS_{time} + Tx_Time_{ack}$. However, randomly fixing a deferring time without knowing the frame type can lead to deferring blindly without knowing when and how long the actual deferring is required to take part in contending for accessing the channel for the next round. In such situation the hidden node may starve and lead to an unfair channel access during contention. When a node senses activity from two or more nodes at the same time, then before the frames are considered to be lost due to collision, the signal strength of the incoming signals are compared to check if one of the signals outstands the background interfering noise. In this thesis, when one of the receiving signals is ten times stronger than the other, then the frame is received rather than dropping i.e. when $SINR$ (Signal-to-Noise Ratio) $= 10/1$ otherwise, frames are considered to be collided. The phenomenon is known as frame capturing and a capture threshold is denoted by $CPThresh$. If the captured frame is not intended for node i then the node defer the channel access for a fixed EIFS time in IEEE 802.11 standard. If a frame is captured successfully, then the node knows the type of the frame it captured, so the node should not defer channel access using a fixed EIFS time, rather it should defer based on the type of the received frame and whether the overheard frame is for node i or for some other node. The issue of using a fixed EIFS time during frame error or capture situation is that the frame could have been any

other frames other than ACK frame, so deferring for a fixed amount of time in such situation is not an accurate estimation. To tackle this unfavourable situation, this thesis proposes an optimised Extended Inter-Frame Spacing rather than using a fixed EIFS based on frame type and the algorithm aims to use an accurate deferring time by predicting the type of frame by estimating the length of the arriving frame.

When frames are erroneous and if FEC could not fix the errors, it is hard to determine the type of a frame directly. However, in such situation, it is possible to indirectly determine the type of a frame if the length of a frame can be measured. Such approach is applicable if the frame lengths are unique otherwise it will be ambiguous for those frames which have same frame length. Once the route is established, only four types of frames are participated in the communication i.e. RTS, CTS, Data and ACK. In the study, due to embedding location information and frame size information in the control frames, the sizes of these frames are unique. In the RTS frame additional location information is carried so the size of the frame is 52 bytes and the size of CTS frame is 56 bytes, since it carries location information as well as the length of the data frame it received (initially the CTS generator does not know the length of the data frame to be received, so maximum frame size of 1000 bytes is assigned). The size of an ACK is 38 byte. Since the frame sizes of RTS, CTS, and ACK are unique and are known, any frame size larger than any of them can be assumed as a Data frame. In order to calculate the frame length within a carrier sensing range, a node can sense the busy state of the channel by using the CS (Carrier Sense)/CCA (Clear Channel Assessment) mechanism within PLCP (physical layer convergence protocol) (IEEE 802.11 standards, 1999). Here in this work, CS sensing method is used to measure the frame length by measuring the busy state of the channel. When multiple nodes are active, then the signal with higher magnitude is compared with the background interfering noises to check if it satisfies CPT_{thresh} to capture the frame before dropping. Thus, busy duration of the channel in a sensing region is used to

uniquely identify the frame type and the node encountering erroneous frames and captured frame uses the optimised EIFS as described in Table 6.6 and Table 6.7 respectively.

Switch(L_{frame})
CASE 38: f_{ack} // This is ACK frame $Optimized\ EIFS_{ack} = DIFS_{time}$ Break
CASE 52: f_{rts} // This is RTS frame $Optimized\ EIFS_{rts} = SIFS_{Time} + Tx_Time_{cts}$ Break
CASE 56: f_{cts} // This is CTS frame $Optimized\ EIFS_{cts} = SIFS_{time} + Tx_Time_{data}$ Break
Default: f_{data} // This is DATA frame $Optimized\ EIFS_{data} = SIFS_{time} + Tx_Time_{ack}$ Break

Table 6.6: Defer access during packet error

When data communication takes place between nodes i and j , the control and data frames are exchanged in an order of RTS-CTS-Data-ACK. So, when the frame type of an erroneous frame is interpreted correctly based on the length of the frame, the node listening to the incoming frame knows what frames will follow, so deferring time is more accurate instead of using a fixed EIFS. When a node i captures a frame successfully, but the destination of the incoming frame is not i , then access is deferred as described in Table 6.7. If the node i captures the frame and the destination of the frame is node i , then the node i responds to the sender in accordance with the four way handshaking principle i.e. if the captured frame is RTS then node i replies with a CTS frame and so on.

Switch (P_{type})	
CASE f_{rts} :	$Optimized EIFS_{rts} = (3 * SIFS_{time}) + Tx_{Time_{cts}} + Tx_{Time_{data}} + Tx_{Time_{ack}}$
CASE f_{cts} :	$Optimized EIFS_{cts} = (2 * SIFS_{Time}) + Tx_{Time_{data}} + Tx_{Time_{ack}}$
CASE f_{ack} :	$Optimized EIFS_{ack} = DIFS_{Time}$
Default:	$Optimized EIFS_{data} = SIFS_{Time} + Tx_{Time_{ack}}$

Table 6.7: Access Defer During Packet Capturing

6.3. Neighbour Aware – Power controlled MAC (Dynamic NA -PMAC)

This section studies the impact on network performance when transmission is controlled based on the estimated distance between the communicating nodes by measuring the signal strengths. By considering a new backoff based on the number of active neighbours, a new cross layer MAC called Dynamic Neighbour Aware – Power controlled MAC (Dynamic NA -PMAC) is designed where the transmission power is adjusted based on its estimated communicating distance by measuring the overheard estimated power from the neighbours. The designed protocol consists of three parts: firstly, estimating distance of communication based on the received signal strength; secondly, dynamically adjusting the power of transmission based on the received signal strength of the active neighbours and lastly, using a new random backoff values based on the number of active neighbours instead of using a fixed range of backoff value. Despite considering a perfect channel, being a wireless channel the signal may fluctuate and can be affected by external factors and environment, so in this part of the study, instead of using a minimum power to cover the communicating distance (d), a power is calculated to cover $d + \Delta$. The proposed protocol is

tested with a fixed transmission power like IEEE 802.11b, and a variants of estimated power based MACs as given below:

- **MaxRC-MinDA NA-PMAC:** This is a variant of the proposed power controlled Dynamic NA -PMAC MAC where the RTS and CTS are sent with maximum transmission power ($Power_{Max}$) and the Data and ACK are sent with minimum transmission power.
- **Min NA-PMAC:** This is also a variant of the proposed power controlled Dynamic NA -PMAC MAC where the RTS, CTS, Data and ACK are all sent using an estimated minimum power between the communicating nodes.

6.3.1. Estimation Based Transmission Power

This model also considers RTS and CTS control frames by introducing new fields to exchange the initial sending power information. Thus, during transmission, the power at which the signal is transmitted is embedded in these control frames and the sending node records the ID of the destination and the transmission power in a table. Upon exchanging the RTS and CTS control frames, the intended receiver extracts the transmission power of the source (P_t) from the frame and then, after measuring the received signal strength (P_r) at the receiver, a new power is calculated. This new power is strong enough to cover $d + \Delta$ and it is strong enough to communicate and this information is stored in another table. As a result, each node maintains two tables, one for storing the transmission power at which it is sending and the destination node ID and the other for recording the newly calculated transmission power and the originator's ID. By controlling the power between the source and the destination pair, it allows using only the minimal required power for communication between the source and the destination, thereby active communicating nodes save power and extends battery lifetime. Secondly, the interfering range changes dynamically depending on the

distance of communication, so the probability of simultaneous transmissions without interference by neighbour nodes increases. Each node maintains two tables, called $Table_{out}$ and $Table_{in}$. The table $Table_{out}$ has two fields namely: Sender's transmission power (P_t) and Destination ID and $Table_{in}$ stores the newly estimated transmission power (P_{est}) of the incoming signal and the Source's ID.

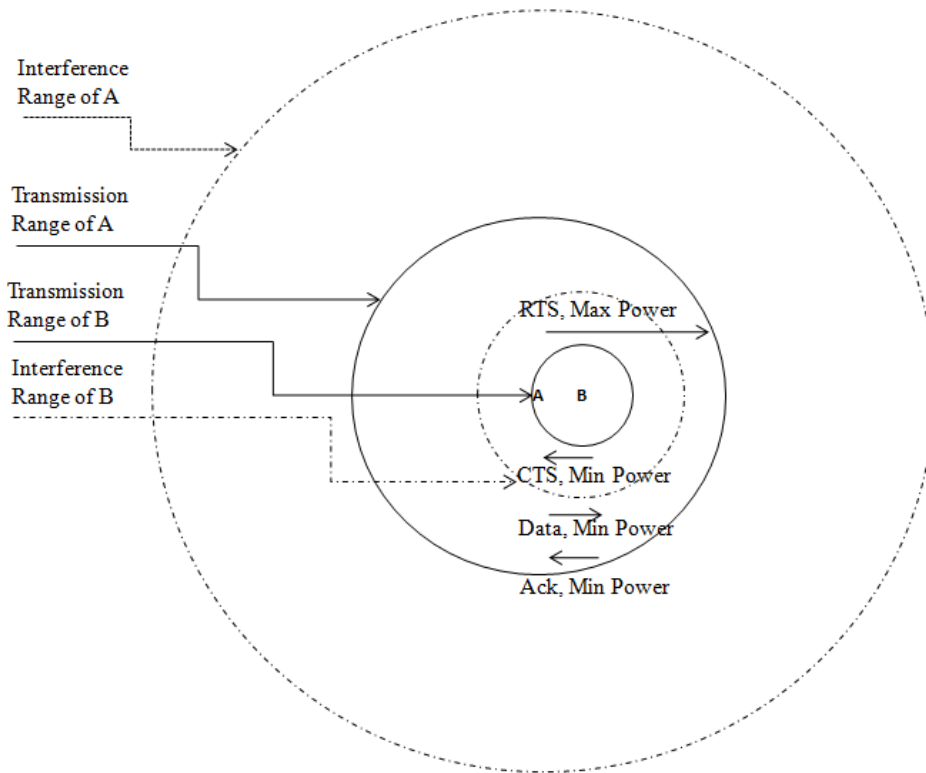


Figure 6.2: Initial stage of power controlled when first RTS and CTS are exchanged.

When node A wants to send data to node B as shown in Figure 6.2, the first RTS frame sent by node A to node B is transmitted using a maximum transmission power (P_{max}) irrespective of the communicating distance between them. When the first RTS is sent by node A, $Table_{out}$ contains P_{max} and B's node ID as the first entry in the table. Upon receiving the RTS frame at node B from node A, node B measures the received signal strength (P_r) and extract the transmission power (P_t) of node A from the RTS frame, then the distance (d)

between the communicating node A and B is calculate using (6.5). After knowing the distance (d) of communication between the source node A, and the destination node B, node B now calculates the power of transmission (P_t) using (6.4) for the distance ($d + \Delta$) so that the receiver receives a signal strength of at least the threshold value $P_{thresh} = 3.652e-10W$. Then the newly estimated minimum power (P_{est}) covers a little beyond node A by a distance of (Δm) from node B and is recorded in the table $Table_{In}$ along with the ID of node A and update the transmission power field of $Table_{out}$ of node B, so that node B uses the updated transmission power information while sending to node A. This increased distance coverage by Δm , helps the communicating nodes uses the reachable transmission power even when node movement takes place before the new transmission power is calculated. When, node B responds to node A with a CTS frame using the newly calculated transmission power, node A can directly update both the tables i.e. $Table_{out}$ and $Table_{In}$ with the transmission power embedded in the CTS frame to reach to node B (considering node A and B are static) or can freshly calculate the transmission power to reach to node B from node A upon receiving every CTS control frames from node B. Now, when node A sends Data to node B and when node B sends ACK to node A, both use P_{est} instead of the fixed maximum transmission power.

	$P_t = P_r d^4 L / G_t G_r h_t^2 h_r^2 \quad (6.4)$	
	$d = \sqrt[4]{(P_t G_t G_r h_t^2 h_r^2) / (P_r L)} \quad (6.5)$	

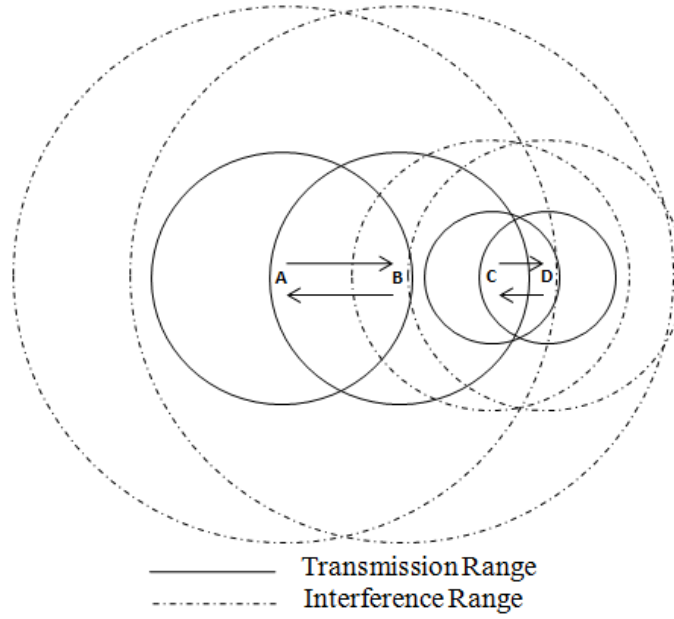


Figure 6.3: When two communicating nodes completed estimating the transmission power.

After the first RTS is delivered to the next hop destination, future control frames and Data between the communicating source and the destination is conducted by using the newly estimated power to cover a distance of $d + \Delta$, when the distance of communication is d . When the communicating nodes are closer with respect to the maximum transmission range, by considering a transmission power that covers only $d + \Delta$ instead of using a fixed maximum power transmission range, the areal coverage of the transmission as well as the interference range is reduced extensively. As shown in Figure 6.3, when there are active neighbours which are transmitting with higher transmission power due to longer distance of communication, such as node B sending Data to node A and a shorter distance of communication such as node C sending Data to node D. In such a situation, node B is exposed to active node C, but node C is hidden to node B. As a result, the activity of node C is directly affected by the activity of node B and fair contention is not possible since node C will defer most of the time because node C can receive data from node B, but when node C tried to access the channel, node B who is not aware of the existence of node C will also try to access the channel to communicate with node A. In order to resolve such partial hidden

nodes, the proposed mechanism notes the signal strength of the transmission power of the active neighbour and when its current transmission power is lower than the active transmission power of the neighbour, it adapts to the transmission power that would cover the neighbour to avoid partial hidden node issue. As shown in Figure 6.4, node C increases its transmission power to reach node B, so the problem of partial hidden issue is removed, but in such situation node D still suffers a disturbance from the activity of node A and B. If the nodes are foreshadowed within an interference range then nothing can be done. Thus the unique approach of this mechanism is that, when node C overhears the transmission power of node B through the RTS or CTS frame (contains a field which carries the value of the transmission power of the sending node), node C estimates the distance of node B based on the received signal strength and increases its transmission power to reach the location of node B, instead of using the transmission power of the overheard node B. In general, if there are N active neighbours around an active node i , then an optimal transmission power i.e. OP_{est}^i , which can reach the most distant active neighbour among the N active nodes is considered to avoid the hidden node issue. As shown in Figure 6.4, despite all the active nodes considering an optimal transmission power, node A remains hidden to node C and D, node D remains hidden to node A and node B, so the issue of hidden nodes persists. So, this transmission power control mechanism removes the partial hidden nodes issue and it does not resolve all the hidden nodes perspective.

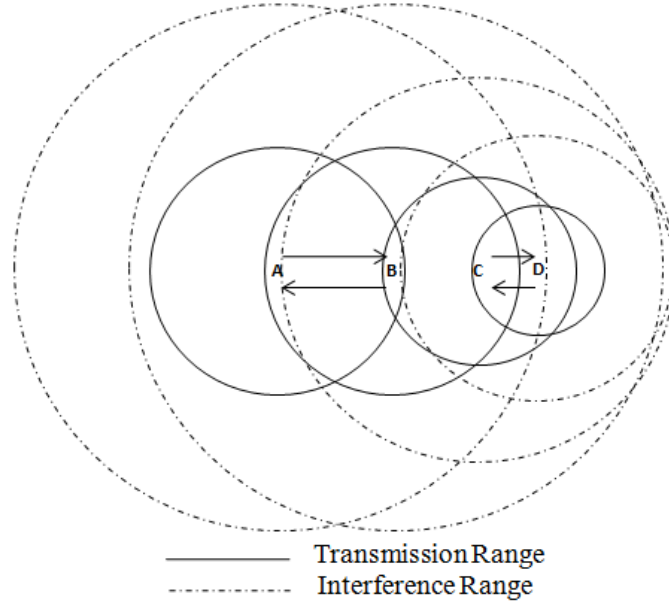


Figure 6.4: Adjusting the transmission power based on the signal strength of the active neighbour.

In analysing the network performance of the designed mechanism, the maximum transmission power considered for each node is $P_{max} = 0.28183815\text{W}$; this power value can cover a maximum fixed transmission range of 250m (default standard values as described in NS2 for a fixed transmission range). The interference range is always higher than the transmission range and, as per the default standard value described in NS2, its radial distance is 2.2 times of the transmission range. As a result, when a node sends Data with a transmission power of 0.28183815W, the active transmitting node covers an interference range of 550m. When the received signal strength crosses the threshold signal strength of $3.652\text{e-}10\text{W}$ then it is considered to be within a transmission range and any measured signal strength up to $1.559\text{e-}11\text{W}$ is considered to be within its interference range.

This proposed mechanism is designed in such a way that it works with any routing protocols and in analysing the network performance, AODV routing protocol is used. All the route request and the route reply control frames are sent using the maximum transmission power i.e. P_{max} .

The Friis propagation model is typically used for short communicating distances and uses a Two Ray Ground propagation model when the distance of communication is far. However, in the analysis, only one propagation model called Two Ray Ground propagation model is used for any distance of communication for maintaining consistency in evaluation. When both propagation models are used, in order to decide which propagation model to be considered, a cross-over distance ($d_c = 4\pi h_t h_r / \lambda$) is calculated; whenever the distance of communication crosses the d_c , Two Ray ground propagation model is used, otherwise Friis propagation model is used.

6.3.2. Estimated Transmission Power

The detail algorithm on how the active node i uses different transmission power is described in Table 6.8. When an active node sends a routing packet, then the node sends with full transmission power (P_{max}) when the packet is an RTS frame then, depending on whether it is generating for the first time for the intended destination or not, the transmission power changes. If the RTS frame generated for an intended destination j is the initial frame of the communication, then node i sends with the maximum transmission power (P_{max}) and the subsequent RTS frame generated from i for the destination j are sent with the newly estimated power (P_{est}). According to the proposed protocol, after the destination node j receives the first RTS,, it estimates the required transmission power to reply to node i . So, the destination node j always transmits the CTS and ACK with the newly estimated transmission power.

When node i sends to node j	
If [$P_{type} == f_{routing}$]	
$P_t^i = P_{max}$	
Else if [$P_{type} == f_{rts}/f_{cts}$]	
If [$Entry_{OutCount} = 0$] then	

```

    If[EntryInCount = 0] then
        TableOut[0].ID = Dsti;
        TableOut[0].Pest = Pmax;
        Pti = TableOut[0].Pest;
        EntryOutCount ++;
    Else
        For[k = 0; k < EntryInCount; k ++]
            If [TableIn[k].ID==Dsti]
                TableOut[k].ID = Dsti;
                TableOut[k].Pest = TableIn[k].Pest;
                Pti = TableOut[k].Pest;
                EntryOutCount ++;
                Break;
            Else
                Continue;
    Else
        For[l = 0; l < EntryOutCount; l ++]
            If [TableOut[l].ID==Dsti]
                For[m = 0; m < EntryInCount; m ++]
                    If[TableIn[m].ID==Dsti]
                        TableOut[l].Pest = TableIn[m].Pest
                        Break;
                    Else if [m + 1 == EntryInCount]
                        TableOut[l].Pest = Pmax
                        Break;
                    Else
                        Continue;
                Done;
            If[TableOut[l].Pest < OPesti ]
                Pti ← OPesti ;

            Else
                Pti ← TableOut[l].Pest;
                Break;
            Else if [l + 1 == EntryOutCount]
                TableOut[l + 1].ID==Dsti
                For[n = 0; n < EntryOutCount; n ++]
                    If[TableIn[n].ID==Dsti]
                        TableOut[l + 1].Pest = TableIn[n].Pest
                        Pti ← TableOut[l + 1].Pest;
                        Break;
                    Else if [n + 1 == EntryInCount]
                        TableOut[l + 1].Pest = Pmax;
                        Pti ← TableOut[l + 1].Pest;
                    Else
                        Continue;
                        EntryOutCount ++;
                Break;
            Else
                Continue;
    Else // Data or Ack
        For [p = 0; p < EntryOutCount; p ++]
            If [TableOut[p].ID==Dsti ]
                If [TableOut[p].Pest < OPesti ]
                    Pti ← OPesti
                Else
                    Pti ← TableOut[p].Pest
                Break;
    Else

```

Continue;

Table 6.8: Algorithm for Adjusting the Transmission Power.

6.3.3. Recording the Neighbours Information from RTS and CTS

Every active or passive surrounding node records the activities of the overheard RTS and the CTS control frames exchanged between the communicating source and the next hop destination. Table 6.9 describes the detail algorithm on how a node captures and maintains the neighbour's activity information. The first RTS overheard from the neighbour node i is ignored, because the subsequent communication will not be using the maximum transmission power (P_{max}), but the newly estimated transmission power (P_{est}). As a result, the activities of only the active neighbours within the newly estimated transmission range are recorded. The node overhearing the neighbour activity records the IDs of the source and the destination pair, the timestamp when the frame was received, NAV duration information and the value of the transmission power. Upon hearing RTS or CTS control frames, the node checks if the frame is intended for this node or not. If the frame was not intended for the node, then the node backs off its activity, and waits for a timeslot equal to NAV (the time required for the communicating nodes to send the packet successfully) and records the detail information about the active neighbour nodes. If the overheard signal is outside the transmission range but within the interference range, then the node defers access for an Extended Inter-Frame Spacing (EIFS). During overhearing from neighbour, if the intended source and the destination nodes of the active neighbours are already recorded then only the time of arrival of the packet, NAV and the signal strength of the transmitted power are updated. During updating the active neighbour table, any records with a timestamp older than T seconds from the current time are removed from the list as shown in Table 6.10. In this study, table

updating time is consider as 1 seconds, it is done in order to maintain the freshness of the network condition and remove any entry of those neighbours which are no longer active.

When node i overheard f_{rts}/f_{cts} when k communicates with m

```

If [ $O_{rts\_cts}^{i \blacksquare k} == 0$ ]
     $Orc\_table^{i \blacksquare k}[0].ID \leftarrow \{ID_j\}$ 
     $Orc\_table^{i \blacksquare k}[0].Count \leftarrow 1$ 
     $O_{rts\_cts}^{i \blacksquare k} ++$ 
Else
    For [ $t = 0; t < O_{rts\_cts}^{i \blacksquare k}; t++$ ]
        If [ $Orc\_table^{i \blacksquare k}[t].ID == ID_j$ ]
             $Orc\_table^{i \blacksquare k}[t].Count ++$ 
            If [ $Orc\_table^{i \blacksquare k}[t].Count > 1$ ]
                If [ $A_{i\_count}^{\blacksquare} == 0$ ]
                     $A_i^{\blacksquare}[0] \leftarrow \left\{ T_{recv}, k, m, \right.$ 
                         $\left. NAV_k, O_p^{i \blacksquare k} \right\}$ 
                     $A_{i\_count}^{\blacksquare} ++$ 
                Else
                    For [ $u = 0; u < A_{i\_count}^{\blacksquare}; u ++$ ]
                        If [ $A_i^{\blacksquare}[u].ID == k \ \&\& \ A_i^{\blacksquare}[u].Dst == m$ ] then
                             $A_i^{\blacksquare}[u] \leftarrow \{T_{recv}, NAV_k, O_p^{i \blacksquare k}\}$ 
                            Break;
                        Else If [ $u+1 == A_{i\_count}^{\blacksquare}$ ]
                             $A_i^{\blacksquare}[0] \leftarrow \left\{ T_{recv}, k, m, \right.$ 
                                 $\left. NAV_k, O_p^{i \blacksquare k} \right\}$ 
                             $A_{i\_count}^{\blacksquare} ++$ 
                            Break;
                    Else
                        Continue;
            Else
                If [ $t + 1 == O_{rts\_cts}^{i \blacksquare k}$ ]
                     $Orc\_table^{i \blacksquare k}[0].ID \leftarrow \{ID_j\}$ 
                     $Orc\_table^{i \blacksquare k}[0].Count \leftarrow 1$ 
                     $O_{rts\_cts}^{i \blacksquare k} ++$ 
                    Break;
            Else
                Continue;

```

Table 6.9: Algorithm for collecting active neighbour information

```

For [ $p = 0; q = 0; p < A_{i\_count}^N; p++$ ]
  If [ $A_i^N[p].Time + Interval \geq Current\_Time$ ]
     $Temp\_Active_i^{Neighbour}[q] = A_i^N[p];$ 
     $q++;$ 
  If [ $p + 1 == A_{i\_count}^N$ ]
    For [ $r = 0; r < q; r++$ ]
       $A_i^N[r] = Temp\_Active_i^{Neighbour}[r];$ 
     $A_{i\_count}^N = q;$ 

```

Where, n^{th} record of the active neighbour table, A_i^N has the following entry:
 $\{T_{recv}, k, m, NAV_k, O_p^{i \blacksquare k}\}$

Table 6.10: Algorithm for updating the neighbour information

In this transmission power controlled mechanism, if communication between the source and the next hop destination are closer than the maximum transmission distance, the overall battery life is extended and the chances of multiple simultaneous transmissions and frequency reuse increases rapidly since the probability of the distances between the two communicating nodes for random positions at a given time changes. The minimum power transmission generates hidden nodes when the distances of the communicating nodes vary. However, by dynamically controlling the transmission power and using an optimal transmission power, as well as considering the signal strength of the neighbours, partially avoids the issue of hidden node while nodes are exposed to other active nodes whose magnitude of the transmission power is high. If there are no active neighbours transmitting with different transmission power levels, then a minimum transmission power $+ \Delta$ is used between the communicating pair. The record of the active neighbours is used in designing a new random backoff values while deferring channel access, so when fewer nodes are active in the surrounding, small random backoff values are chosen otherwise large values are considered. The detail approach of this new backoff values for deferring is described in details in the following section. The activity of each node and its neighbours are updated to maintain the freshness of the network and to maintain the correct information about neighbour activity.

6.4. Neighbour Aware Backoff Mechanism

The approach of considering different backoff values depending on the degree of congestion is more efficient compared to using a fixed random backoff values, because degree of contention is dependent on the number of active neighbour nodes. When an active node has a high degree of active neighbours, then the backoff value is high, otherwise it's low.

Each active node maintains three different levels of contention degree. The degree of contention (C_d) aims to describe the level of congestions in the neighbouring area. $C_d=0$ (Low), if no other active nodes are detected (other than the next hop node responding with a CTS or ACK), $C_d=1$ (Average) when there are two active nodes within its transmission range, and $C_d=2$ (High) if there are at least three active nodes within its transmission range. The degree of contention (C_d) and the retrial number (r) controls the exponential contention window size as shown in (6.6). The contention random backoff value doubles whenever the transmission fails, but the highest possible value of the backoff is bound by the maximum contention window (CW_{max}) size. When the number of active nodes within its transmission range is Low, Average and High; the maximum allowable contention window (CW_{max}) value is 255, 511 and 1023 respectively. If the calculated $CW_{C_d,r}$ goes beyond the given maximum contention window sizes then it takes the provided maximum values (CW_{max}) for each levels. Attempt of transmission of a fresh packet is indicated by $r = 0$ and $r=7$ signified the last retransmission attempt before the packet is dropped.

$$CW_{C_d,r} = \begin{cases} 2^{(3+C_d)} - 1 & ; \quad r = 0 \\ 2^{(3+C_d+r)} - 1 & ; \quad r \geq 1 \end{cases} \quad (6.6)$$

Where: $C_d = \{\text{Low} = 0, \text{Average} = 1, \text{High} = 2\}$

$$r = \{0, 1, 2, \dots, 7\}$$

6.5. Conclusion

In order to increase the probability of parallel transmission, controlling the transmission power of a node is vital. Here, two different approaches of power controlled techniques are designed. Firstly, a power controlled mechanism called LBT-NA with Optimised EIFS MAC is designed based on the location of the nodes. However, location information is not readily available, so another power controlled mechanism known as Dynamic NA -PMAC is proposed and it is based on controlling the transmission power by estimating the received signal strength. In order to estimate the distance of communication more accurately, the initial source's transmission power is provided to the receiver by embedding it in the exchanged control RTS/CTS frame. In both the approaches, a new backoff mechanism is considered, where the channel deferring time during the busy state is directly proportional to the degree of contention.

When transmission power is controlled then the hidden node issue also increases. In order to tackle such hidden node issues, the transmission power is adjusted based on the power at which the neighbours transmit data. Moreover, an optimised EIFS based on the estimated length of the received frame is also taken into account in designing LBT-NA with Optimised EIFS MAC in order to provide fairer access to the competing flows. The following chapter provides the detail discussions and analysis of the proposed techniques by comparing with a fixed transmission power MAC like IEEE 802.11b and a variant of proposed power controlled MACs, where control frames and data frames uses same and different transmission powers.

Chapter 7. Evaluation of Power Controlled Transmission MACs

7.1. Introduction

Two Power controlled MACs are designed in the previous chapter by using location information of the communicating nodes (LBT-NA with Optimised EIFS MAC) and by adjusting the transmission power by estimating the distance based on the received signal strength (Dynamic NA-PMAC). In this chapter, the performances of both power controlled mechanisms are evaluated. The performance analysis of LBT-NA with Optimised EIFS MAC and Dynamic NA-PMAC are discussed in section 7.2 and section 7.3 respectively. In both mechanisms, the energy utilization of senders and receivers are also analysed. The issues of hidden nodes when different transmission ranges are used are also taken into account during the investigation. With a defined space and a random topology, the probability of concurrent transmission of multiple data flows is also analysed using different traffic including CBR, TCP with FTP traffic and Exponential.

There are various energy consumption model, designed by various researchers, including (Bruno *et al*, 2002) and (Carvalho *et al*, 2004) which considers a finite number of states i.e. when the node is active and when it is idle. The authors (Ergen *et al*, 2007), (Garcia-Saavedra *et al*, 2011) and (Wang *et al*, 2006) consider an energy consumption model where energy is considered to be consumed during transmission, reception and idle modes. However, the authors (Serrano *et al*, 2015) extensively study the per-frame energy consumption model of IEEE 802.11 devices and concludes that a substantial fraction of energy is consumed when packets cross the protocols stack. The authors also concluded that the energy consumed by a frame when it passes through the protocol stack is independent of frame size. In this thesis energy of a node is considered to be consumed during reception

mode, sending mode, deferring mode/idle mode and processing. The main studies in the following subsections are focussed on the total amount of energy spend by a source during transmitting data and RTS control frame, energy spend by destination node in responding with CTS and ACK frames, and the total amount of overall energy used during reception, sensing, sending and idle/deferring state by a source and destination nodes. However, in the study the amount of energy spent in the protocol stack is not considered separately, but it is taken into account as part of energy usage during processing the frame.

7.2. Evaluation and Discussion of LBT-NA with Optimised EIFS MAC

The proposed cross layer power controlled MAC was tested in different scenarios and benchmarked against the IEEE802.11b and a Location Based Transmission Neighbour Aware Cross Layer MAC (LBT-NA Cross Layer MAC), a MAC which uses a minimum transmission power and a fixed EIFS during reception of erroneous frames or when frame captured situation takes place. The comparison examined the transmission power efficiency given the location information and verified whether parallel transmission is viable when the transmission range is controlled. In addition, the evaluation also considered the impact of battery life and the new backoff values used by the new MAC and tested the robustness of the protocol by considering random positions of the nodes with different traffic type including CBR, TCP with FTP traffic and Exponential traffic.

All simulations in this chapter are carried out with the network parameters listed in Table 3.1 and antenna parameters described in chapter 3. During the test, some additional network parameters are considered in addition to the network parameters listed in Table 3.1. In the analysis, all the participating nodes are always in an active mode and no node goes to sleep mode. During the simulation, each node is charged with 1000 Joules as initial energy

and simulation is carried out for 1000 second and resultant value is an average of 100 rounds of simulations for all the cases.

7.2.1. Energy Utilisation

Given that LBT-NA with Optimised-EIFS MAC is a power control communication mechanism, when the communicating nodes are closer than the maximum transmission distance, its benefits are significant in higher density areas, with lower distances between communicating nodes. For measuring the energy usage during transmission and the amount of remaining energy level, an initial set of experiments used two communicating nodes positioned at a distance between 20m and 250m. Each simulation last for 1000 seconds, initially the distance of communication is 20m and repeats the simulation by initializing the node's energy to 1000J and increase the distance of communication by 10m until the distance of communication is 250m. The transmission power of a node for LBT-NA Cross Layer MAC and LBT-NA with Optimised-EIFS MAC is adjusted as per the location of the destination node, in contrast with the standard IEEE 802.11b that uses the standard fixed transmission power of 0.28183815W. The energy used by the source node and the next hop receiving node is studied in the next subsection.

7.2.1.1. Energy Utilisation at Source Node

As shown in Figure 7.1, as the distance of communication between the source and the destination node increases, the energy usage of the source for both the location based power controlled MAC LBT-NA Cross Layer MAC and LBT-NA with Optimised-EIFS MAC consumes low energy when the communicating pair is closer. The power consumption increases as the distance of communication increases unlike IEEE 802.11b, where the power usage remains high and constant irrespective of the distance. A constant amount of 240J of

energy out of 1000 J is used when the node sends data for 1000 seconds when IEEE 802.11b is considered due to use of fixed transmission power. Until the transmission range between the communicating nodes reaches 100m, the amount of energy used in transmission by the source node in LBT-NA Cross Layer MAC and LBT-NA with Optimised-EIFS MAC is less than 10J. The increase in the energy usage as the distance increases is due to the fact that the signal strength weakens by an order of distance d^4 , so the transmission power has to be increased as the communicating distance increases to compensate the loss of the attenuated signal. Thus, location based power control MAC is very efficient for low distance communication and, in the worst case scenario, is as good as the standard IEEE 802.11b in terms of energy utilisation. In this network with two nodes, despite using a small backoff value during contention, the throughput is improved but not significant (it's approximately 1-2% only).

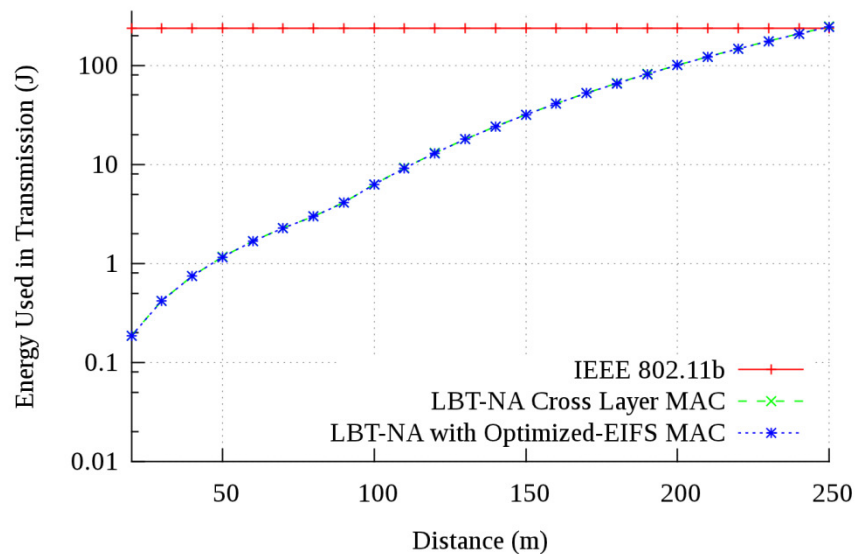


Figure 7.1: Energy used by the Source in Transmission.

During contention for accessing channel, an active node defers its access using a random backoff value to avoid collision; a node in such state is considered to be in an idle

mode. The amount of energy used in idle mode by a source node using IEEE 802.11b is approximately 2.6 times the energy used by LBT-NA Cross Layer MAC and LBT-NA with Optimised-EIFS MAC when the distance of communication is short i.e (20m) or when the distance of the communicating node is far i.e. 250m. Comparing to the energy used by IEEE 802.11b, both the power controlled MAC which uses the backoff values based on the contention levels saves approximately 60% of energy from the idle state. It means that the source mode is less idle in case of LBT-NA Cross Layer MAC and LBT-NA with Optimised-EIFS MAC compared to IEEE 802.11b due to use of small backoff value when contention level is low.

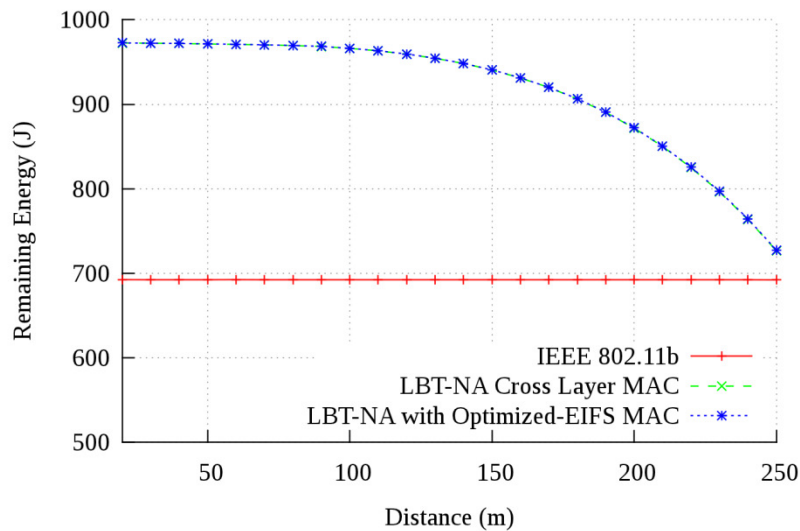


Figure 7.2: Remaining Energy at the Source Node.

Any participating node spends energy either in sleep mode, or transmission mode or contention mode or sensing mode or idle mode or receiving mode. Figure 7.2 shows the amount of energy saved or the remaining energy of source node when the distance of communication increases. The total amount of the remaining energy is very high in case of LBT-NA Cross Layer MAC and LBT-NA with Optimised-EIFS MAC compared to IEEE 802.11b. When the communicating distance is below 100m, the total amount of energy spent by the source in LBT-NA Cross Layer MAC and LBT-NA with Optimised-EIFS MAC is

approximately only 5% of the battery life. Comparatively, in case of IEEE 802.11b, irrespective of the distance, the source node uses 30% of the battery life due to the use of a fixed high transmission range irrespective of the distance of communication between the communicating pair. As a result, in a short distance communication the power controlled MAC uses only 1/6 of the amount of energy used by IEEE 802.11b, which is a huge advantage in enhancing the durability of the battery life. Even when the communicating distance is 250m, LBT-NA Cross Layer MAC and LBT-NA with Optimised-EIFS MAC saves approximately 4% of energy compared to IEEE 802.11b because of using small backoff value which corresponds to use of less energy during idle time as described by (6.6) of chapter 6 when the contention level is low.

7.2.1.2. Energy Utilisation at the Receiving Node

The destination node generally spends less energy comparing to the source node as shown in Figure 7.3, since it is in a receiving mode most of the time, except in responding with short CTS and ACK control frames. In the case of IEEE 802.11b, irrespective of the distance, approximately 25J of energy i.e. 2.5% of the initially battery life is used by the destination node in replying to the source with a CTS frame and an ACK control frame. In the case of LBT-NA Cross Layer MAC and LBT-NA with Optimised-EIFS MAC, the energy usage by the destination node varies based on the distance of communication between the source and the destination pair. LBT-NA Cross Layer MAC and LBT-NA with Optimised-EIFS MAC uses approximately 0.5% and 3.0% of the initial battery life when the distance of communication is less than 150m and 250m respectively. When a pair of nodes communicate, LBT-NA Cross Layer MAC and LBT-NA with Optimised-EIFS MAC yields an end-to-end performance gain of approximately 1-2% over IEEE 802.11b, which means that more CTS and ACK frames were generated by the destination, so more energy is used when maximum transmission range of 250m is used compared to IEEE 802.11b as shown in

Figure 7.3, but the overall use of energy in the power controlled MAC is less, depending on the distance of communication.

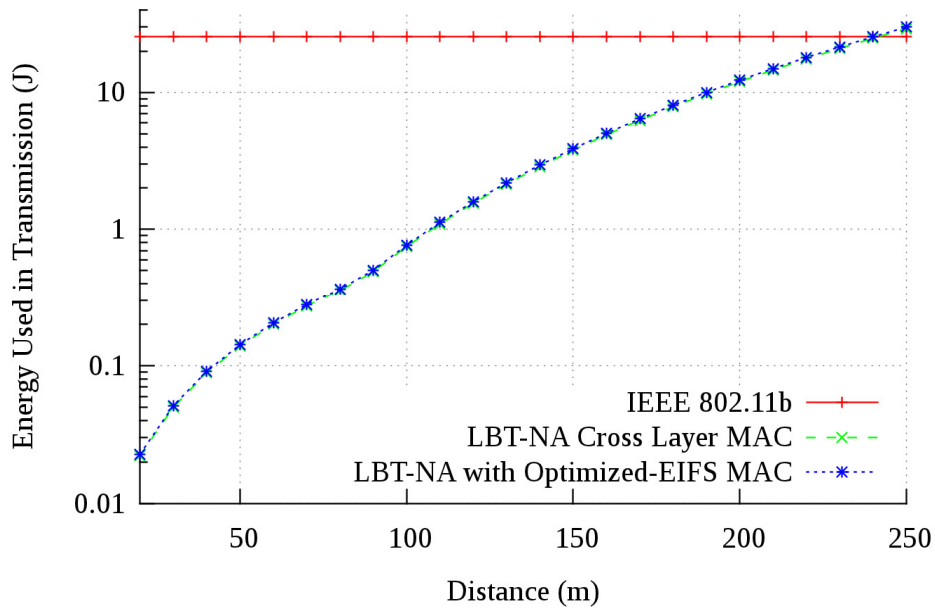


Figure 7.3: Use of Energy by Receiver while Responding to Source.

The amount of energy used by the destination node in an idle state is similar to that of the source node. The IEEE 802.11b MAC uses 2.6 times the energy used by LBT-NA Cross Layer MAC and LBT-NA with Optimised-EIFS MAC irrespective of the distance between the communicating nodes. As a result, the destination node saves approximately 60% of the energy during an idle mode in case of LBT-NA Cross Layer MAC, LBT-NA with Optimised-EIFS as compared to the energy used by IEEE 802.11b MAC.

The amount of energy used by a destination node is lesser to that of a data generating source. It is mainly because of the fact that the source generating RTS as well as a data frame has an overall longer period of transmission activity compared to the next hop destination which replies with a CTS and ACK frames. When one data frame of 1000 byte is successfully delivered to a next hop destination, the amount of data exchanged from a source is 1000 byte (data) + 52 byte (RTS frame). On the other hand, the amount of information

exchanged by the next hop destination in response to the source is 56 byte (CTS frame) + 38 byte (ACK frame) only. Thus, the per-frame busy state in transmission mode by a destination node is only approximately 9% in comparison to the total transmission time of the source. Thus, the source spent more energy in a transmission mode compared to the next hop destination.

In a short distance communication of less than 100m, in terms of remaining energy, out of the initial 1000J, after the node actively engaged in reception and sending data for 1000 seconds the destination node using LBT-NA Cross Layer MAC and LBT-NA with Optimised-EIFS uses less than 3% of the battery life, so the destination node is still equipped with approximately 97% of the battery life. In case of IEEE 802.11b, the destination node uses approximately 10% of the initial energy after the destination node is active for 1000 seconds. As shown in Figure 7.4, the amount of remaining energy reduces as the distance of communication increases and when the distance of communication is 250m, LBT-NA Cross Layer MAC and LBT-NA with Optimised-EIFS MAC uses approximately 6% and IEEE 802.11b still uses 10% because of using a fixed maximum transmission power. When the distance of communication is short (up to 100m), IEEE 802.11b uses 3.3 times the energy used by LBT-NA Cross Layer MAC and LBT-NA with Optimised-EIFS MAC. When the distance of communication is long (250m), then the IEEE 802.11b uses approximately 1.7 times the energy used in LBT-NA Cross Layer MAC and LBT-NA with Optimised-EIFS MAC.

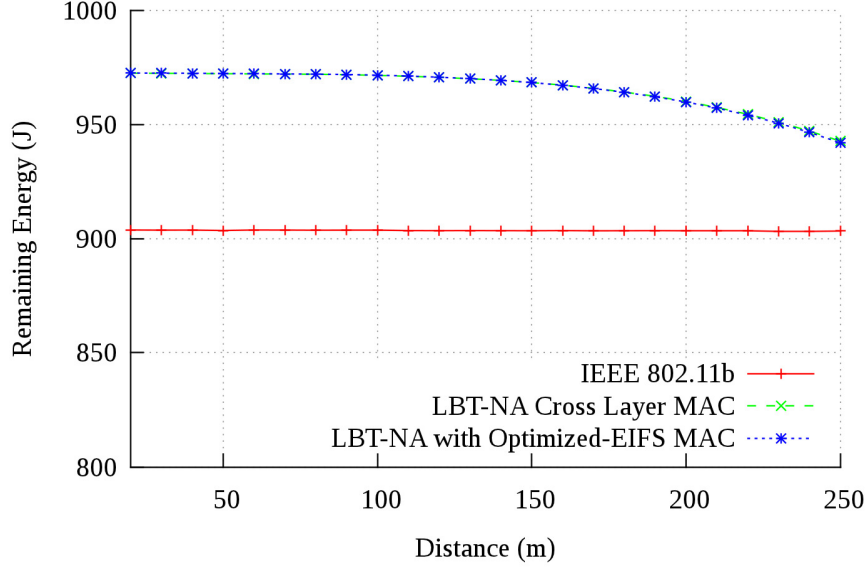


Figure 7.4: Remaining Energy at Destination Node.

7.2.2. Partial Hidden Node Issue

Consider the topology of Figure 7.5, where two different pairs of communication take place, node K sends to node M and node N sends to node J. In this topology arrangement of Figure 7.5, $d_{KM} = 50\text{m}$, $d_{NJ} = 100\text{m}$, $d_{KN} = 75$ and $d_{JM} = 75\text{m}$. So, when LBT-NA Cross Layer MAC, which uses a minimum transmission power to cover the Euclidian distance between the communicating nodes, node N and J are not aware of the existence of node K and node M respectively, but node K and M are both within the transmission range of node N and J. When the transmission power of the neighbour nodes are considered as in LBT-NA with Optimised-EIFS MAC, node M increases its transmission power to cover node J and node K also increases its transmission power to reach node N. Thus, in LBT-NA with Optimised-EIFS MAC, node N and J are aware of the activity of node K and M. Thus, in LBT-NA Cross Layer MAC, node K and M are communicated with a transmission power to cover only 50m. Likewise, node N and node J communicates with a transmission power to cover 100m. But in case of LBT-NA with Optimised-EIFS MAC, node K and node M

increases their transmission power to cover a radial distance of 75m to cover its transmission power to reach node N and node J.

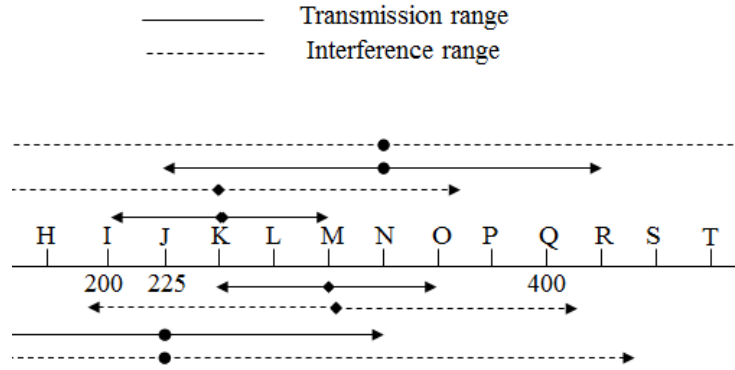


Figure 7.5: Partial Hidden Node Issue.

The fairness index of the partial hidden node issue of the network topology of Figure 7.5 is shown in Figure 7.6. As the offered load of the network increases, using LBT-NA Cross Layer MAC, one flow gradually overtakes the other and, at around 1500kb/s, the flow from node K to node M completely captures the channel. The fairness index is measured using the Jain's fairness index described in (3.1) of chapter 3. In this method of measuring fairness index, 50% fairness indicates that one flow has completely captured the channel, if there are only two flows in the network, 50% fairness means that the scenario is fully unfair for one of the two nodes. The degree of unfairness beyond 1500kb/s in LBT-NA Cross Layer MAC is due to two reasons. Firstly, use of minimum transmission power and secondly, use of fixed EIFS ($SIFS_{time} + DIFS_{time} + Tx_Time_{ack}$) for deferring by node N, assuming that the erroneous data frame arriving at node N from source node K as an ACK, which is not a correct amount of estimated time to defer because the overheard frame at the interfering region could be a data frame or RTS frame or CTS frame or ACK frame depending on the

role of the node as a sender or a receiver. But here in this case being a source, the hidden node K would generate data frames or an RTS frame.

In case of LBT-NA with Optimised-EIFS MAC, the optimal distance of an active neighbour is considered, which eliminates the impact of the hidden nodes, so the fairness of the flows is maximum. Regardless of the offered load in the network, LBT-NA with Optimised-EIFS MAC maintains fair access to all the flows. At network saturation, the LBT-NA with Optimised-EIFS is 99.97% fair compared to 50% fairness in IEEE 802.11b and 99.86% fair in LBT-NA Cross Layer MAC respectively. Even in terms of network throughput, there is a performance gain of at least 1-2% in an end-to-end performance in both the LBT-NA Cross Layer and LBT-NA with Optimised-EIFS MAC over IEEE 802.11b. The fairness obtained in IEEE 802.11b is due to the large fixed transmission range where the participating nodes are within the transmission range of each other.

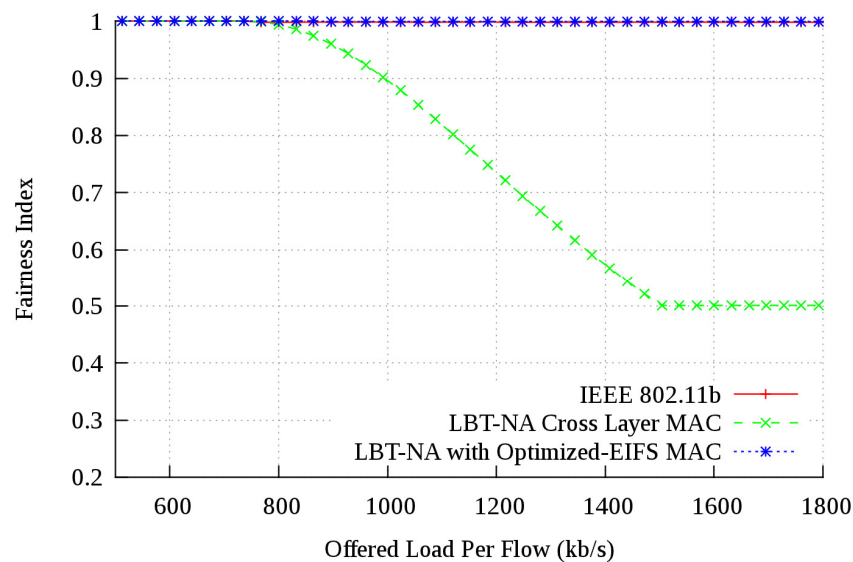


Figure 7.6: Fairness Index of Partial Hidden Node Issue.

7.2.3. Complete Hidden Node Issue

In order to test the impact and performance of the network when source nodes are hidden from one another, the network topology of Figure 7.7 is considered where pairs of nodes are communicating without the knowledge of another pair, but are within the interference range of each other i.e. in the network topology of Figure 7.7, Node L and node S sends data to node H and node W respectively. The distance between the source nodes L and S is 175m, and the distance between node L and node H is 100m, likewise the distance between the other source node S and its destination node W is also 100m. In such a scenario, activity of one node affects the other node without knowing the exact time to defer when the other node is busy, since the intercepted frame falls within an interference range and are erroneous in nature. In standard IEEE 802.11b, a fixed amount of $EIFS = SIFS_{time} + DIFS_{time} + Tx_Time_{ack}$ is deferred by a node when it senses erroneous data within an interfering/sensing range. When source node L is active, the other source node S does not know long to defer, because node S falls within the interference range and arriving frames are erroneous, when location based power controlled MAC is used.

The main disadvantage in such a scenario is that one node may keep deferring, and the other keeps accessing the channel or both sources may hibernate while deferring. As mentioned, IEEE 802.11b uses a fixed EIFS deferring time, when erroneous packets are overheard. Likewise, a power controlled LBT-NA Cross Layer, also uses a fixed deferring EIFS time. Deferring for a fixed time is not favourable, because the erroneous packets received within the sensing/interfering range may be a RTS, CTS, data, or an ACK frame. In the case of LBT-NA with Optimised-EIFS MAC, when active node receives an erroneous frame, then based on the length of the frame, the type of the erroneous frame is decoded, then

the node accurately defers with an Optimised EIFS values as presented in Table 6.6 and Table 6.7 of chapter 6.

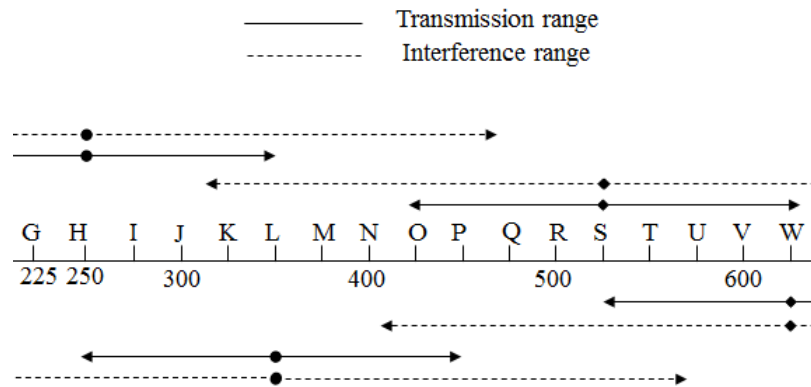


Figure 7.7: Completely Hidden Node Issue.

The fairness index of the network performance of the network topology of Figure 7.7 is shown in a graph of Figure 7.8, and is tested with an increasing offered load to the network. The flows of power controlled location based LBT-NA Cross Layer MAC is fair only up-to the offered network load of 1500kb/s, but after network saturation point the flows are not fair at all. Jain's fairness index shows that the fairness at network saturation for LBT-NA Cross Layer MAC is only 50%, suggesting that one flow completely overtakes the other, which is due to the fact that, when erroneous frames are received by an active node, the node defers for a fixed EIFS time and decreases the chances of deferring accurately for the next attempt of channel access. But in case of LBT-NA with Optimised-EIFS, the flows are completely fair to a degree of 99.99% due to the use of an optimised EIFS where deferring of an active node receiving an erroneous frames is done based on the type of the receiving erroneous frame rather than using an inaccurate fixed EIFS deferring time. In the case of IEEE 802.11b, a maximum fixed power transmission is used, so sources L and S are within the transmission range of each other since they are separated by only 175m, thus the flows

are expected to be fair. In case of power controlled LBT-NA Cross Layer MAC and LBT-NA Cross Layer MAC, there is a small improvement in terms of performance gain compared to IEEE 802.11b, but the gain is insignificant (approximately 1-2%) and this gain is due to use of less deferring time during contention when active neighbours are few.

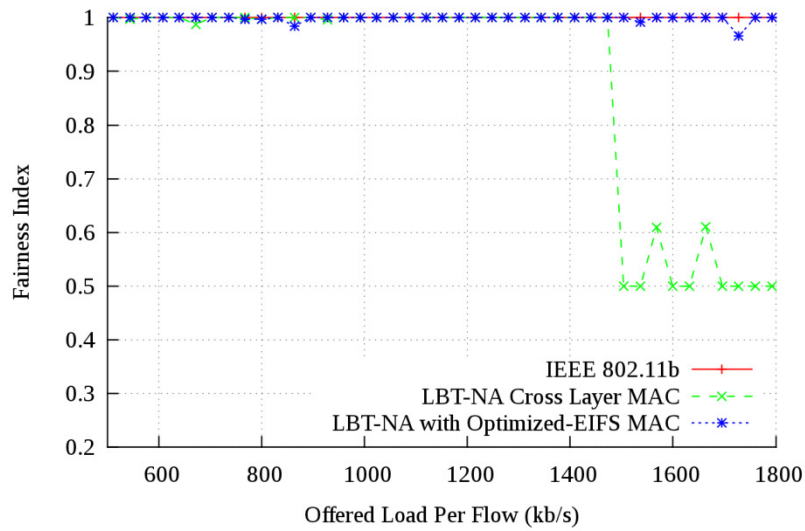


Figure 7.8: Fairness Index of Completely Hidden Node Issue.

7.2.4. Random Topology

In order to validate the robustness of the proposed technique and to confirm that the results are not an artefact of artificially arranged networks, a more realistic random topology with a defined space boundary is considered as shown in Figure 3.11 of chapter 3 and simulated by using the network parameters listed in Table 3.1 of chapter 3. The random topology is tested using different types of traffic like CBR, TCP with FTP traffic and Exponential. Nodes from Area-B and Area-C are used as sources and transmit to random nodes selected from Area-A and Area-D as destinations. Nodes are deployed in random in all the four sections of the defined space. Any node deployed in Area-B can communicate with any node of Area-A using a single hop communication. Likewise, any random node of Area-C can communicate with any random node of Area-D with one hop. The maximum allowable

transmission range is 250m. The space between Area-B and Area-C is separated by a space called Area-G and the length of Area-G is between [0;550]. The test is conducted by increasing the length of Area-G by 10m to study the probability of concurrent transmission as the distance between the sources are increased. The overall network performance is analysed using a UDP connection with CBR application as well as TCP with FTP traffic and Exponential traffic with same packet sizes of 1000 bytes. The per-flow data rate offered in the network is 2000kb/s in case of CBR and Exponential traffic. In this analysis, same burst-time and idle-time of 0.5 seconds are considered for the Exponential traffic.

7.2.4.1. Random Topology with CBR traffic

The network performance of CBR traffic using the network topology arranged in Figure 3.11 of chapter 3 is shown in Figure 7.9. As the distance between the sources increases, the resulting network performance of the proposed protocol LBT-NA with Optimised-EIFS MAC and LBT-NA Cross Layer MAC increases rapidly as the sources generate CBR traffic unlike IEEE 802.11b MAC, which uses a fixed maximum transmission range. Due to the increase in distance between the sources and the transmission power being controlled by the location of destination, the probability of parallel transmission of the exposed sources increases rapidly. In the case of fixed transmission power mechanism, such as IEEE 802.11b, the probability of parallel transmission in the network topology arrangement of Figure 3.11 is possible only when the length of Area-G is at least 300m due to high interference range. During network saturation, when the exposed sources could transmit concurrently with full bandwidth, location based power controlled MAC, LBT-NA with Optimised-EIFS MAC and LBT-NA Cross Layer MAC gains an additional 80kb/s i.e. approximately 3.0% over a fixed maximum transmission power like IEEE802.11b. Even when the sources are separated by a small distance there is at least a performance gain of approximately 3.0% in the proposed power controlled MAC over IEEE 802.11b. The

additional performance gain in the proposed power controlled MAC is due to use of backoff values based on the degree of contention and here in this test the degree of contention is low, so a small deferring time during contention is considered which leads to an overall higher data transmission rate over a given time.

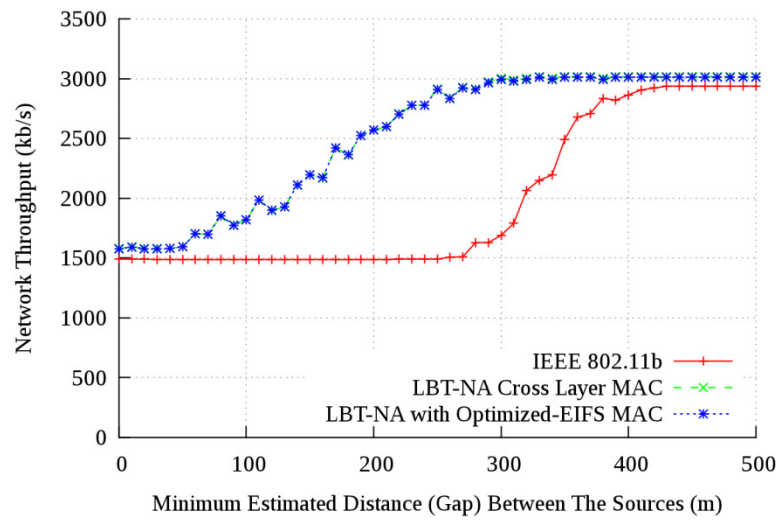


Figure 7.9: Network Performance of random sources and destinations using CBR traffic

The probability of parallel transmission increases as the distance between the sources increases as shown in Figure 3.11. Due to location based transmission, in LBT-NA with Optimised-EIFS MAC and LBT-NA Cross Layer MAC the probability of parallel transmission is fully achieved only when the length of Area-G is 300m and above, unlike IEEE 802.11b where parallel transmission is fully achieved only after the length of Area-G is at least 400m due higher interfering area since fixed maximum transmission power is used. In Figure 3.11, when the length of Area-G is 200m, the performance gain of location based power controlled MAC, LBT-NA with Optimised-EIFS and LBT-NA Cross Layer is approximately 70% over a IEEE 802.11b MAC which uses a fixed maximum power transmission power, is due to use of low transmission power based on the location of the

nodes, the probability of parallel transmission without interference is high. Thus, the probability of parallel transmission is directly proportional to the length of Area-G which defines the distance between the sources. Therefore, using a location based power controlled MAC enhances the overall network performance over a fixed transmission power method like IEEE 802.11b.

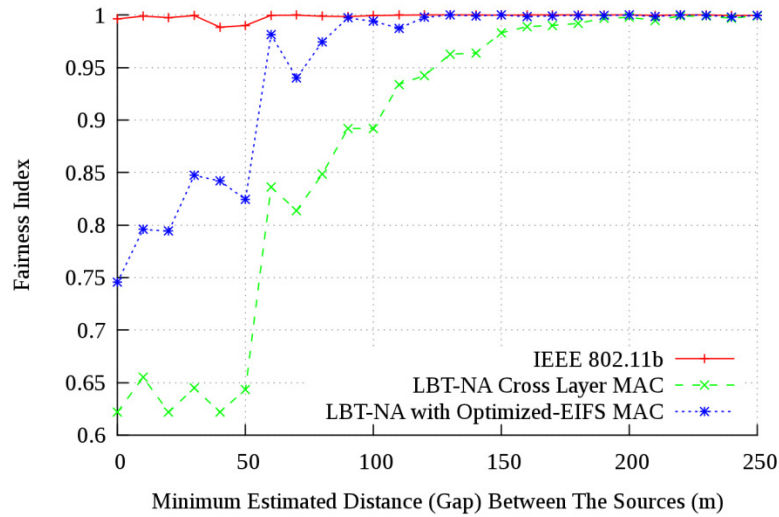


Figure 7.10: Fairness Index of random sources and destinations using CBR traffic

The fairness index of the CBR traffic for the random topology scenario is shown in Figure 7.10. The fairness index of the traffic flows, generated using random sources from Area-B and Area-C, shows that LBT-NA with Optimised-EIFS outperforms the minimum power MAC like LBT-NA Cross Layer MAC. When the transmission range is high and sources are within the transmission range of each other, the contending active nodes access the shared channel fairer than the situation where the nodes are not discoverable. As a result, the probability of a node being hidden is higher in the power controlled MAC due to small transmission range, which is a disadvantage of power controlled MAC. But, due to use of high fixed transmission power, IEEE 802.11b is fairer in accessing the shared channel. Thus, the traffic flows of IEEE 802.11b is fair throughout compared to power controlled MAC. The

degree of fairness of the traffic flow increases in as LBT-NA Cross Layer MAC as well as LBT-NA with Optimised-EIFS MAC as the length of Area-G increases. When the distance introduced by Area-G is reduced, the minimum degree of fairness in LBT-NA Cross Layer MAC is approximately 62% and that of the LBT-NA with Optimised-EIFS MAC is 75%. The reason LBT-NA with Optimised-EIFS MAC performs better to LBT-NA Cross Layer MAC, it is due to two factors: firstly, in LBT-NA with Optimised-EIFS MAC, an active node i increases its transmission range when the neighbour transmission power is higher to avoid hidden node issue and secondly, when an active node receives an erroneous frame then based on the length of the received frame, its type is interpreted and defers the access using optimised EIFS with perfect accuracy for the next attempt of accessing the channel and provides fairer chances for the contending nodes to access the channel. This is the reason, why LBT-NA with Optimised-EIFS MAC attends the degree of fairness with high degree of 95% only when the length of Area-G which separates the sources is only 50m, unlike LBT-NA Cross Layer MAC, which has the same degree of fairness only when the length of Area-G is approximately 125m.

7.2.4.2. Random Topology with Exponential Traffic

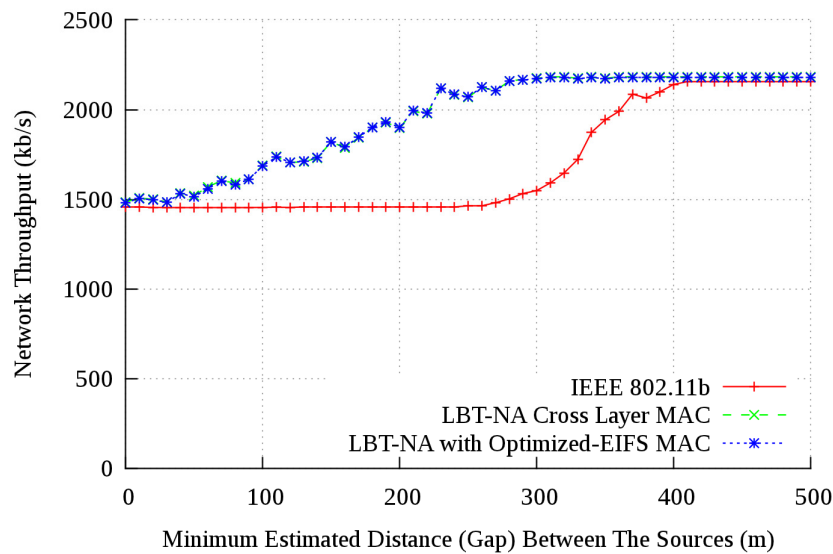


Figure 7.11: Network Performance of random sources and destinations using Exponential traffic

The random network topology of Figure 3.11 is considered for evaluating the Exponential traffic as well. The offered load considered is 2000kb/s per flow, same as the data rate considered by the CBR traffic to saturate the network. In terms of overall network performance, CBR traffic gains higher throughput since data is generated at a constant rate in CBR traffic, unlike Exponential traffic where the sources generate traffic during burst-time and goes silent during idle-time. During parallel communication, when the per flow data rate is 2000kb/s, the overall network gain using CBR traffic in this random scenario is approximately 27% over Exponential traffic when the burst-time and idle-time are considered to be 0.5 seconds. When the channel is shared (sources are close to each other) or during parallel communication (sources are out of the interference range of each other), the power controlled MAC gains approximately 30kb/s i.e. 1.5% of overall network throughput over IEEE 802.11b. This gain is due to the use of dynamic backoff values based on the number of active neighbours instead of using a fixed large contention window as in IEEE 802.11b. As shown in Figure 7.11, the network performance increases in power controlled MAC, as the length of Area-G increases; it is due to exhibiting parallel communication in the shared channel environment among the contending sources. The location based power control LBT-NA Cross Layer MAC and LBT-NA with Optimised-EIFS MAC outperforms the traditional IEEE 802.11b. When the Area-G length is 200m, there is an overall network performance gain of approximately 30% in case of LBT-NA Cross Layer MAC and LBT-NA with Optimised-EIFS MAC over IEEE 802.11b due to power control transmission.

The fairness index of the Exponential traffic using the random topology arrangement of Figure 3.11 is given Figure 7.12. The degree of fairness among the flows of the location based power control MAC of LBT-NA Cross Layer MAC and LBT-NA with Optimised-EIFS MAC are similar, with a slight increase of the fairness index for LBT-NA with

Optimised-EIFS MAC over LBT-NA Cross Layer MAC, especially when the distance introduced by Area-G is smaller, due to adjusting the transmission power of an active node i , based on the neighbour's transmission power and use of optimised EIFS based on the frame type. The lowest fairness index value of LBT-NA Cross Layer MAC is approximately 96% and that of LBT-NA with Optimised-EIFS MAC is approximately 98%. Since the transmission power of IEEE 802.11b is high and fixed, the degree of fairness among the contending source nodes are fair even in this case.

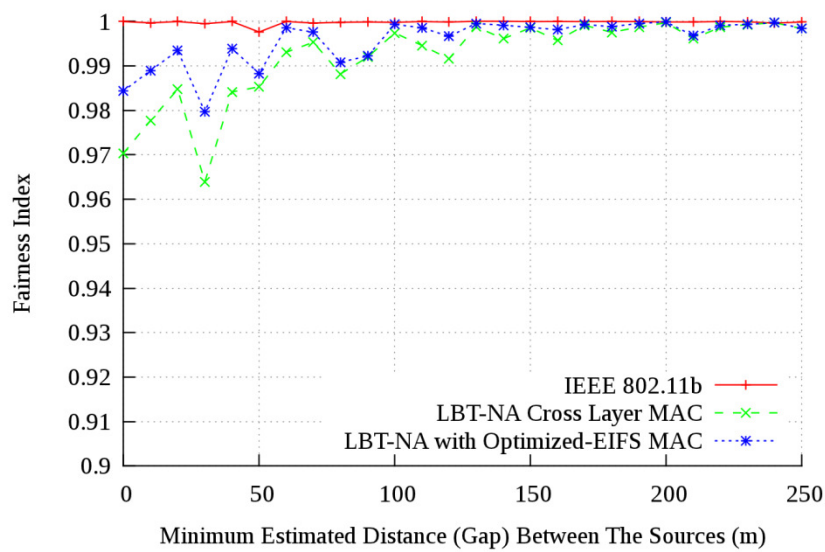


Figure 7.12: Fairness Index of random sources and destinations using exponential traffic

7.2.4.3. Random Topology with TCP Traffic

The random topology of Figure 3.11 was also tested using TCP with FTP traffic and the results of the network performance when the length of Area-G increases is presented in Figure 7.13. The resulting performance of LBT-NA Cross Layer and LBT-NA with Optimised-EIFS MAC increases as the length of Area-G increases, because the probability of parallel communication increases as the transmission power is controlled. When Area-G length is 200m, the network performance gain in the location based power control LBT-NA Cross Layer and LBT-NA with Optimised-EIFS MAC is approximately 63% over the fixed

maximum transmission power MAC like IEEE 802.11b. In a fixed power transmission like IEEE 802.11b, the sources of Area-B and Area-C could exhibit parallel communication only when the length of Area-G is at least 300m.

In the saturated region, the TCP with FTP traffic running with IEEE802.11b performs slightly better, with a network performance gain of 20kb/s i.e. less than 1.0% to that of the location based transmission power control LBT-NA Cross Layer MAC and LBT-NA with Optimised-EIFS MAC. This is due to the introduction of small contention window ranges for low contention, but it gives a probability of higher frame collision and if frame collision or error thus occurs, TCP shrinks its sliding window by misjudging it as a situation of congestion when frame loss occurs.

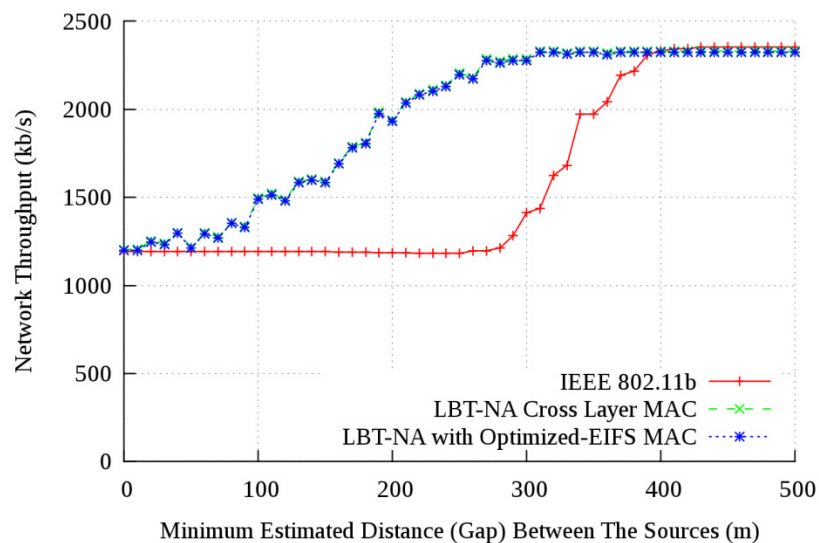


Figure 7.13: Network Performance of random sources and destinations using TCP with FTP traffic

The Fairness of the TCP with FTP traffic flows of the random topology network using random sources and random destinations of Figure 3.11 are relatively equally fair in both the fixed transmission power like IEEE 802.11b as well as power controlled MAC like LBT-NA Cross Layer MAC and LBT-NA with Optimised-EIFS MAC. It is due to the fact that, in TCP, frames are sent based on the congestion window. The lowest degree of fairness of the

traffic flows in the network using LBT-NA Cross Layer MAC is 96% that of LBT-NA with Optimised-EIFS MAC is 98% and that of fixed transmission power i.e. IEEE 802.11b MAC is 97.5%. Unlike CBR and Exponential traffic the degree of fairness among the traffic flows using TCP with FTP traffic are fairer in both the power controlled MAC as well as the fixed transmission power MAC like the standard IEEE 802.11b.

7.3. Evaluation and Discussion of Dynamic NA-PMAC

The proposed dynamic power controlled cross layer MAC is tested in different scenarios and benchmarked against the standard MAC and variants of Dynamic NA-PMAC as listed below:

1. IEEE802.11b: a standard MAC which uses a fixed maximum power (P_{max}) of transmission between the source and the next hop destination.
2. MaxRC-MinDA NA-PMAC: Variant of the Dynamic NA-PMAC protocol, where the RTS and the CTS packets are always transmitted using a maximum power (P_{max}). The Data packets as well as the ACK are sent using the estimated minimum transmission power (P_{est}).
3. Min NA – PMAC: Variant of the Dynamic NA-PMAC protocol, where any communicating pair transmits using only a minimum required transmission power between the two communicating nodes i.e. P_{min} .

The following sections thoroughly investigated the energy utilisation of the active nodes as sender and receiver against the distance of communication between the communicating pair. The fairness issue is also addressed and analysed when multiple flows generated from multiple sources are considered. The effectiveness of the robustness of the protocol is also tested by considering random topologies with different traffic type traffic namely CBR, TCP with FTP and Exponential.

7.3.1. Energy Usage

Since, Min NA-PMAC, MaxRC-MinDA NA-PMAC and Dynamic NA-PMAC are power control communication mechanisms, when the communicating nodes are closer. The amount of energy usage is less compared to the situation when the communicating nodes are of greater distance. As the distance between the communicating nodes increases, the energy

utilisation increases rapidly. For measuring the energy usage during transmission and the amount of remaining energy level, two communicating nodes i as source and j as destination are considered with an increasing distance of communication between them from 20m to 250m. The transmission power of an active node for Min NA-PMAC, MaxRC-MinDA NA-PMAC and Dynamic NA-PMAC power controlled protocol are estimated as per the distance between the source and the destination node, but for the standard IEEE 802.11b, a fixed transmission power of 0.28183815W (covers a transmission range of 250m) is considered. The energy utilisation of actively engaging nodes is studied in detail in the next sub-section.

7.3.1.1. Energy Utilisation at the Source Node

The source sends only RTS and Data packets, so this section analyses the energy utilisation of a source node while transmitting RTS and Data for duration of 1000 seconds of 100 rounds. As shown in Figure 7.14, as the distance of communication between the source and the destination node increases, the energy usage of the source node increases while using Min NA-PMAC, MaxRC-MinDA NA-PMAC and Dynamic NA-PMAC power control MACs. In the case of fixed transmission power like IEEE 802.11b, the power usage is constant irrespective of the distance between the communicating nodes. A constant amount of approximately 240J of energy is used by the source in the transmission mode in case of IEEE 802.11b for a simulation period of 1000 seconds. In the case of the power controlled MAC like MaxRC-MinDA NA-PMAC, the source power usage is much higher when the distance of communication is shorter, compared to Min NA-PMAC and Dynamic NA-PMAC, because the RTS and the CTS control frames are exchanged with a maximum transmission power and the Data and ACK are sent using a minimum transmission power. The power usage of Min NA-PMAC and Dynamic NA-PMAC are similar, because there are no additional active nodes communicating with other nodes with a higher transmission power, so both the mechanism uses transmission power to cover $d + \Delta$, where d the distance between

the source and the destination. When the distance of communication between the source and the destination is up to 100m, the amount of energy consumption by a source node is less than 5J for simulation duration of 1000seconds in case of the power controlled MAC like Min NA-PMAC and Dynamic NA-PMAC, but the power controlled MAC like MaxRC-MinDA NA-PMAC usages energy ranges from 20J to 25J for the same duration of the activity of the source. The energy consumption increases as the distance of communication increases, the energy consumption for a distance of communication from 100m to 150m for MaxRC-MinDA NA-PMAC ranges from 25J to 50J and for Min NA-PMAC and Dynamic NA -PMAC, the energy usage ranges from 5J to 30J for the same duration of sending for 1000 seconds. As the distance of communication increases to 250m (the maximum transmission range), the total amount of energy usage for all the power controlled MAC like Min NA-PMAC, MaxRC-MinDA NA-PMAC and Dynamic NA -PMAC are the same as that of a fixed and a maximum transmission range mechanism like IEEE 802.11b. When only two communicating nodes are considered, there is a small performance gain of approximately 1-2% in case of Min NA-PMAC, MaxRC-MinDA NA-PMAC and Dynamic NA -PMAC, it is due to the use of dynamic backoff values, where no active neighbours is considered to be in low contention and takes low backoff values while deferring for access. Due to carrying the transmission power value in the RTS and the CTS frames, additional overhead of energy utilisation is visible, though very small.

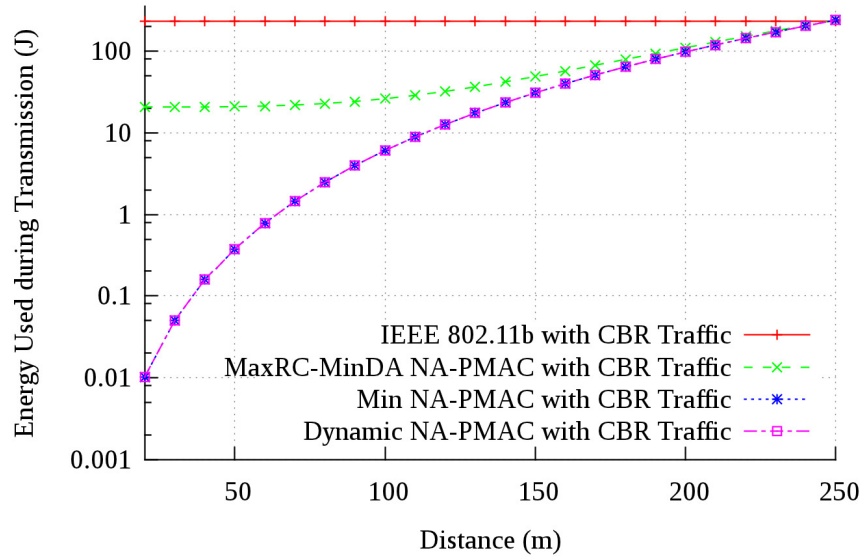


Figure 7.14: Energy used by the Source in Transmission.

When the node defers accessing the channel, it is considered to be in an idle mode. In such an idle mode, during a simulation of 1000s and a communicating distance of 20m, the amount of energy used while deferring is 67.4J, 25.7J, 25.7J, and 25.7J for IEEE 802.11b, MaxRC-MinDA NA-PMAC, Min NA-PMAC, and Dynamic NA –PMAC protocols respectively. When the communicating distance between the source and the next hop destination is 250m apart, the source node uses approximately 67.7J, 26.2J, 26.3J, and 26.2J in IEEE 802.11b, MaxRC-MinDA NA-PMAC, Min NA-PMAC, and Dynamic NA –PMAC protocols respectively, while deferring i.e. during the carrier sensing periods. The power controlled MaxRC-MinDA NA-PMAC, Min NA-PMAC, and Dynamic NA –PMAC medium access control protocols uses very less energy while deferring, it is due to the fact that when the number of active nodes are low then a small backoff values are chosen (so less deferring time), unlike the IEEE802.11b where a fixed range of backoff values are considered irrespective of the degree of contention.

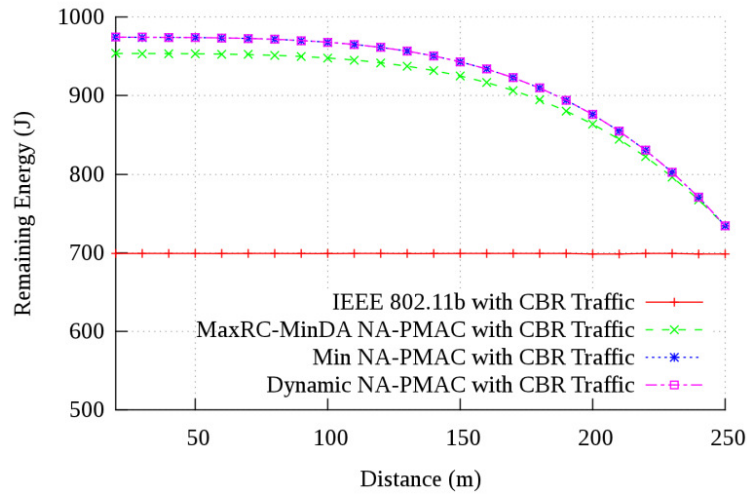


Figure 7.15: Total Remaining Energy of the Source.

When a node is not in a power switched OFF mode, it uses energy be it in sleep mode or transmission mode or contention mode or sensing mode or idle mode or in a receiving mode. The graph of Figure 7.15, shows the total amount of remaining energy in a node when the communicating distance between the source and the destination increases when the initial energy is 1000J each and simulation is carried out for 1000 seconds. When a fixed transmission power mechanism like IEEE 802.11b is considered then it consumes approximately 301J irrespective of the distance of communication between the source and the destination. In MaxRC-MinDA NA-PMAC mechanism the overall power consumption when the distance of communication is short is much higher to that of the power controlled MAC protocols Min NA-PMAC, and Dynamic NA –PMAC, because in such protocol the RTS and the CTS control frames are sent with highest transmission power. When the distance of communication is 20m, then the power consumption is 46.4J, 25.7J, 25.7J for MaxRC-MinDA NA-PMAC, Min NA-PMAC, and Dynamic NA –PMAC respectively. So, when the communicating distance is approximately 100m then there is an energy gain of approximately 44% in Min NA-PMAC and Dynamic NA –PMAC over MaxRC-MinDA NA-PMAC. When the distance of communication converge toward the maximum transmission range of 250m

then the overall power consumption of all the power controlled MAC are same (approximately 265J) because Min NA-PMAC and Dynamic NA –PMAC also uses the maximum transmission power as the distance of communication increases. Thus, communicating with a fixed transmission range for all form of transmission and using a maximum transmission power for RTS and CTS control frames while communicating consumes higher power compared to the power control MAC where all communication takes place with a minimum + Δ power or dynamic power controlled. All the considered power controlled MAC uses 12% less energy compared to IEEE 802.11b even when the communication takes place with a maximum distance of 250m, it is due to the new backoff mechanism where small backoff value is chosen when the number of active neighbours is less.

7.3.1.2. Energy Utilisation at the Receiving Node

The destination node is expected to spend less energy than the source node, since it spends most of the time receiving Data and responding to the source node with short control frames like CTS and ACK, as shown in Figure 7.16. In the case of IEEE 802.11b, irrespective of the distance, approximately 29.8J of energy is used by the destination node in transmitting the CTS and ACK frames. But in the case of power controlled MAC, the energy utilisation is based on the distance of communication. Since the CTS is generated with a fixed maximum transmission power in MaxRC-MinDA NA-PMAC the amount of energy used is relatively more than Min NA-PMAC and Dynamic NA –PMAC, but less than IEEE 802.11b MAC, as the ACK is sent with minimum power. When the communicating distance is less than 150m, the protocols Min NA-PMAC and Dynamic NA –PMAC consumes less than 5J of energy as a destination node for a simulation period of 1000 seconds, whereas MaxRC-MinDA NA-PMAC uses 20J to 25J of energy for the same duration. The energy utilisation of Min NA-PMAC and Dynamic NA –PMAC are same because there are no other active

neighbours other than the communicating source and the destination pair, so Dynamic NA – PMAC also sends with the same power as that of Min NA-PMAC. The energy utilisation of the MaxRC-MinDA NA-PMAC, Min NA-PMAC and Dynamic NA-PMAC are higher when the transmission range is 250m, because the destination node transmits with a maximum transmission power as that of IEEE 802.11b and the RTS and CTS frames are larger due to carrying additional information i.e. transmission power.

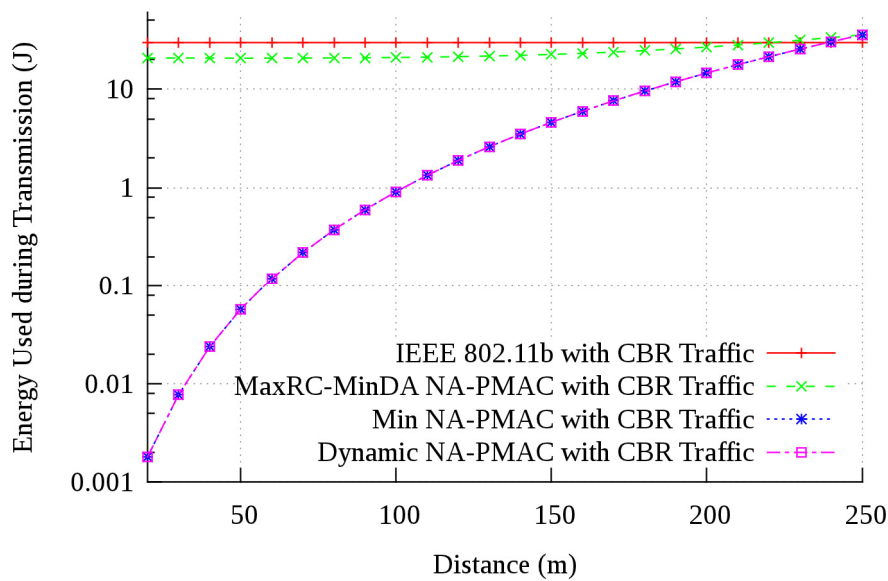


Figure 7.16: Energy of Destination while Responding.

When the channel is busy, then the other active nodes defer the channel access and waits for a random amount of time based on the values chosen from the backoff range. When the distance of communication between the source and the destination is only 20m, the amount of energy used while sensing (idle/deferring) is 67.4J when the simulation last for 1000seconds when IEEE 802.11b MAC protocol is considered. In the similar situation, the amount of energy used in idle state in case of MaxRC-MinDA NA-PMAC, Min NA-PMAC and Dynamic NA –PMAC protocols are 25.7J, 25.7J, and 25.7J respectively. When the distance of communication is higher (say) 250m, then the amount of energy usage in IEEE

802.11b, MaxRC-MinDA NA-PMAC, Min NA-PMAC and Dynamic NA –PMAC are 67.7J, 26.2J, 26.3J, and 26.2J respectively. So, comparing to the fixed transmission power controlled IEEE 802.11b MAC which uses a fixed random backoff values irrespective of the congestion and the activity of the neighbours, the power controlled MACs i.e. MaxRC-MinDA NA-PMAC, Min NA-PMAC and Dynamic NA –PMAC, which uses the new backoff values which depends on the number of active neighbour nodes saves approximately 61% when only two communicating nodes are considered.

Activity at the destination node is limited because it responds to the source node with a small control frames like CTS and ACK, so the energy usage is less in this scenario where there are only two communicating nodes. Each node is initially equipped with energy of 1000J each and Figure 7.17 shows how much energy remains in an active node when it is a destination node or how much of energy is utilised out of the initial energy, when the communication takes place for duration of 1000seconds. When a fixed transmission power like IEEE 802.11b is considered, the total remaining energy of the node is approximately 90.20% of the initial energy when the distance of communication is 250m, so the amount of energy used for a communication of 1000seconds is 9.75%. In the same situation, the destination node uses approximately 6.20% of the total energy in the power controlled MACs like MaxRC-MinDA NA-PMAC, Min NA-PMAC and Dynamic NA–PMAC. Due to the new backoff mechanism considered for the power controlled MACs, where small backoff values are chosen when the number of active nodes is low, the power controlled MACs i.e. MaxRC-MinDA NA-PMAC, Min NA-PMAC and Dynamic NA–PMAC uses 35.6J less overall energy compared to the IEEE 802.11b even when the distance of communication is 250m. When the nodes are in close proximity (at or below) 20m, the total remaining energy for IEEE 802.11b is 90.20% of the initial energy, and the destination node uses 9.72% (97.20J) of the initial total energy. Since, MaxRC-MinDA NA-PMAC sends RTS and CTS control

frames using a maximum transmission power and the rest of the communication using a minimum transmission power, the total amount of energy used when communicating 20m is 4.63% (46.3J) and is lower than the energy used by IEEE 802.11b. But the amount of energy used as a destination node in case of MaxRC-MinDA NA-PMAC is higher to that of Min NA-PMAC and Dynamic NA –PMAC power controlled MACs. Min NA-PMAC and Dynamic NA –PMAC uses only 2.57% (25.7J) of the total initial energy for communicating for duration of 1000seconds. So, when the distance of communication is closer, then the total remaining energy is highest in the ascending order of IEEE 802.11b, MaxRC-MinDA NA-PMAC, Min NA-PMAC and Dynamic NA –PMAC.

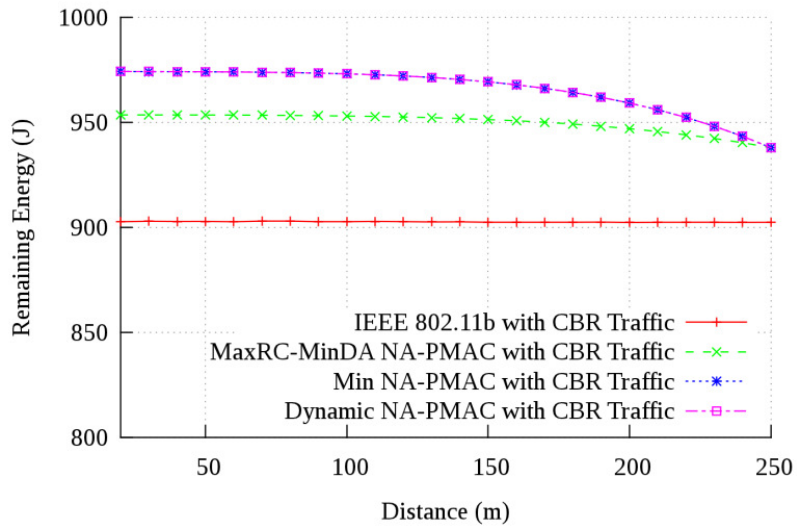


Figure 7.17: Remaining Energy as Destination.

7.3.2. Partial Hidden Nodes

When the transmission power is controlled, a node i may communicate with node j using a transmission power $P_{\min}^{i \rightarrow j}$ and a neighbour node k may communicate with another node l with a power $P_{\min}^{k \rightarrow l}$, where $P_{\min}^{i \rightarrow j} \gg P_{\min}^{k \rightarrow l}$; in such a situation, the node sending with higher power may disturb other nodes communicating with lower power, but may not be

aware about their existence since they communicate with low transmission power. The topology of Figure 7.18 depicts such a partially hidden node issue, where two different pairs of communicating nodes are considered; node K sends Data to node M and node N sends Data to node J. So, when power is controlled, and if neighbours activity is ignored, then node K sends to node M with a power to cover the distance of $d + \Delta$ i.e. 51m by considering $\Delta = 1m$. When node N sends to node J, then the transmission power is estimated to cover 101m with same value of Δ . Thus, the generation of RTS and Data packets from node N and CTS and ACK from node J are overheard by both the nodes K and M, but unfortunately the RTS and Data generated by node K is not received by node N since node N is out of the transmission range. In this scenario, the activity of node K cause interference with the activity of node N. Likewise, the CTS and ACK generated by node M for node K cannot be received by node J, but interfere with the activity of node J. Since, RTS and CTS are used; node K and M are within the transmission range of node J and N, but as discussed the activity of node K and node M are hidden to node N and node J respectively, even if the data of node M and node K can be received by node N and node J respectively. In order to make the activity of node K and node M receive by node N and J respectively, node K estimates a new optimal transmission power i.e. $Overheard_Max_{p_t}$ to cover the furthest active neighbour node (1 to n) from an active node i , $Max_i^{1\ to\ n}\{P_{i \rightarrow 1}, P_{i \rightarrow 2}, \dots, P_{i \rightarrow n}\}$, where $P_{i \rightarrow 1}$ is the power to reach node 1 from an active node i .

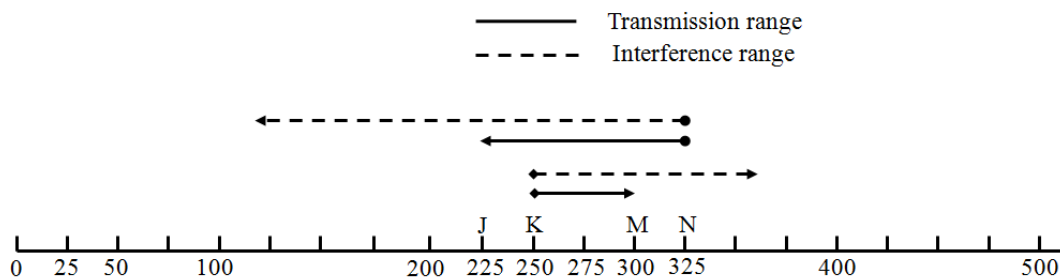


Figure 7.18: Partial Hidden Node Issue.

As shown in graph of Figure 7.19, as the offered load in the network increases, the power controlled Dynamic NA-PMAC is equally fair along with the fixed transmission power IEEE 802.11b MAC unlike MaxRC-MinDA NA-PMAC and Min NA-PMAC power controlled MAC where the degree of fairness drops after the per flow offered load is beyond 700kb/s. The fairness index is measured using (3.1) Jain's fairness index. In Dynamic NA – PMAC and IEEE 802.11b, the degree of fairness is 99.999%, and 99.90%, which is an ideal state of fairness. MaxRC-MinDA NA-PMAC and Min NA-PMAC power controlled MAC are perfectly fair until the per flow offered load is below 700kb/s and after 800kb/s per flow offered load the fairness index is 96.50%

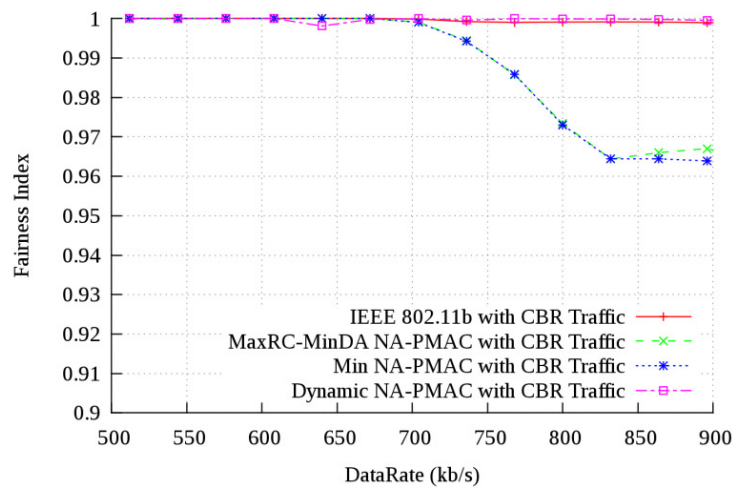


Figure 7.19: Fairness Index of Partial Hidden Node Issue.

The overall network performance of MaxRC-MinDA NA-PMAC and Min NA-PMAC power controlled MAC are compatible as that of the fixed transmission power IEEE 802.11b with a network throughput close to 1400kb/s as shown in Figure 7.20. The performance of MaxRC-MinDA NA-PMAC and Min NA-PMAC power controlled MAC has an overall higher network performance to that of Dynamic NA –PMAC during network

saturation, but Figure 7.19 proves that the channel was shared perfectly among the contending neighbour nodes in case of Dynamic NA –PMAC power controlled access mechanism when offered loads are high due to the fact that the active nodes uses optimal estimated transmission power by considering the neighbour’s transmission powers. While each active exposed nodes attempts to share loads during contention results in slightly decreasing the overall network performance in Dynamic NA –PMAC.

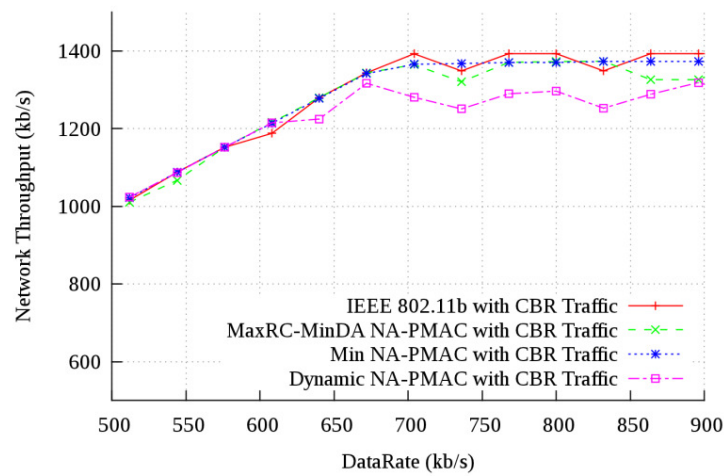


Figure 7.20: Network Performance of Partial Hidden Node Issue.

7.3.3. Random Topology

This is the section where the main test is conducted to validate the protocols. The proposed powered control MAC Dynamic NA –PMAC is tested with its variant power controlled MACs i.e. MaxRC-MinDA NA-PMAC and Min NA-PMAC; and also benchmarked the performance with a fixed transmission power IEEE 802.11b too. The network parameters listed in Table 3.1 is considered for the more realistic random topologies as arranged in Figure 3.11 with a defined space boundary in order to validate the robustness of the proposed techniques. The random topology is tested using different kinds of traffic like CBR, TCP with FTP and Exponential.

In the topology arrangement of Figure 3.11, any node deployed in section Area-B can communicate any nodes of section Area-A and any nodes deployed in section Area-C can reach any nodes of section Area-D with a one hop communication using a transmission range of $d + \Delta$, where d is the distance between the communicating nodes and $0m < d \leq 250m$. The Area-G which separates the areal sections Area-B and Area-C is increased by a factor of 25m and analysed the overall network performance using a UDP connection with CBR application, TCP with FTP traffic and Exponential traffic with same packet sizes of 1000 bytes. The per flow data rate offered in the network is 2000 kb/s in case of CBR and Exponential traffic. The exponential traffic uses equal burst-time and idle-time of 0.5 seconds.

7.3.3.1. Random Topology Using CBR Traffic

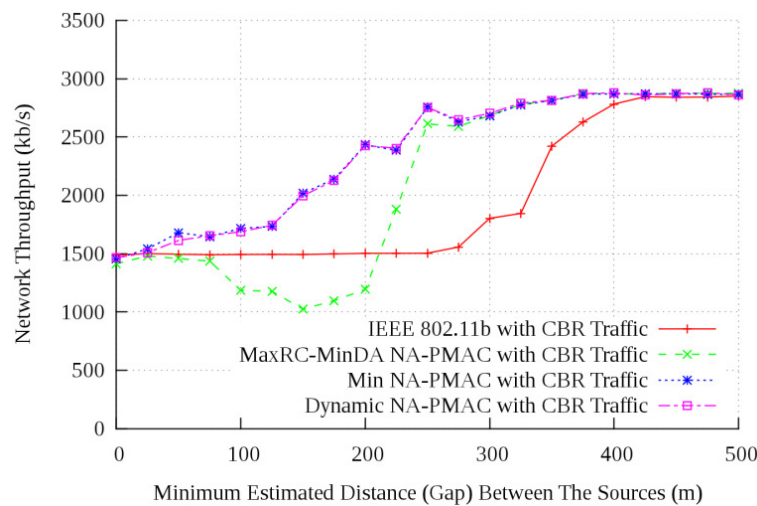


Figure 7.21: Network Performance of random sources and destinations using CBR traffic.

The network performance of CBR traffic using the network topology set up in Figure 3.11 is shown in Figure 7.21, with the help of the network parameters listed in Table 3.1 and a packet size of 1000 byte. As the distance of separation between the sources areal sections B and C increases, the total network performance of the proposed protocol Dynamic NA –

PMAC and its variant Min NA-PMAC where transmission takes place with a transmission range to cover $d + \Delta$. Both Dynamic NA –PMAC and Min NA-PMAC increases the overall network performance as the distance between the sources increases because, the probability of the parallel transmission increases, unlike MaxRC-MinDA NA-PMAC. In MaxRC-MinDA NA-PMAC power controlled MAC, where the RTS and CTS are sent using a maximum transmission range and Data and ACK sent with minimum power, the overall network performance is same as that of IEEE 802.11b MAC until the minimum areal separation between the sources is 75m. The network performance of MaxRC-MinDA NA-PMAC decreases below IEEE 802.11b MAC when the distance between the sources is 75m to 200m; it is due to the conflicting transmission ranges of the RTS and CTS which were sent using maximum transmission power with the Data and ACK which were generated using a minimum transmission power. In MaxRC-MinDA NA-PMAC power controlled MAC, in average parallel communication is possible only after the areal separation of the sources are 225m. In case of an IEEE 802.11b, the probability of parallel transmission of the sources is possible only when the areal separation between the sources is at least 275m. As the areal distance of separation between the sources increases, the probability of parallel communication increases tremendously for Dynamic NA –PMAC and Min NA-PMAC from the situation when the distance of separation of Area-G is 25m. When the length of Area-G is 200m, MaxRC-MinDA NA-PMAC power controlled MAC performs 20% less than the fixed transmission power IEEE 802.11b and Dynamic NA –PMAC and Min NA-PMAC performs 63% better than IEEE 802.11b when the sources are separated for a minimum of 200m.

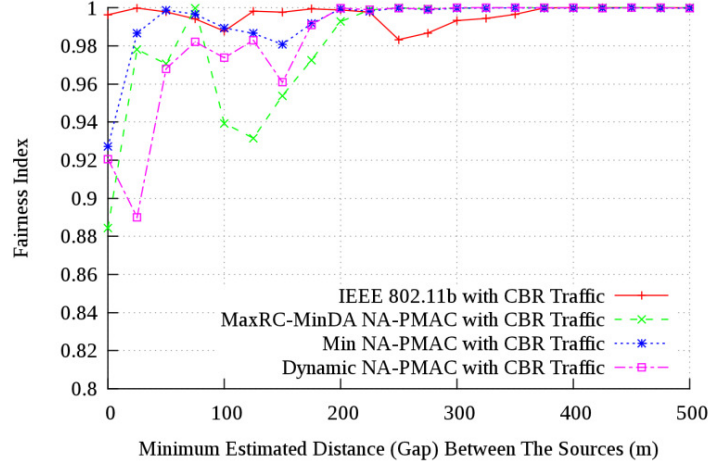


Figure 7.22: Fairness Index of random sources and destinations using CBR traffic.

The fairness index of the real time CBR traffic of the random topology setup is shown in Figure 7.22. The fairness degree among the flows in the power controlled MACs i.e. MaxRC-MinDA NA-PMAC, Min NA-PMAC and Dynamic NA-PMAC are all above 88% and the fairness index increases as the distance of separation between the sources increases. When the distance of separation between the sources is small (say 25m) then MaxRC-MinDA NA-PMAC and Min NA-PMAC are fairer. The degree of fairness of MaxRC-MinDA NA-PMAC is lower to that of Min NA-PMAC and Dynamic NA-PMAC when the distance between the sources is approximately 100m to 200m. After the areal distance of Area-G is 25m, the degree of fairness of NA-PMAC and Dynamic NA-PMAC is always above 96%. The fairness degree among the multiple flows is 99.999% for MaxRC-MinDA NA-PMAC, Min NA-PMAC and Dynamic NA-PMAC when the minimum distance between the sources is 200m (length of Area-G). The degree of fairness drops by 1-2% for IEEE 802.11b when the minimum sources' distance is 250-300m.

7.3.3.2. Random Topology Using Exponential Traffic

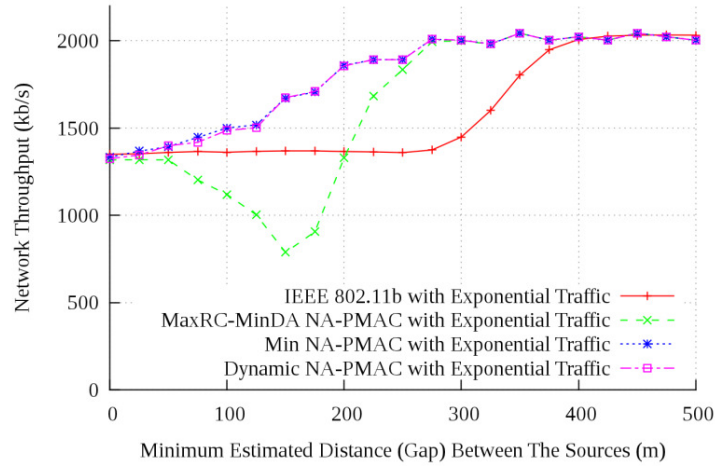


Figure 7.23: Network Performance of random sources and destinations using exponential traffic

The random network topology described in Figure 3.11 is considered for evaluating the performance of Exponential traffic using the power controlled MACs and the IEEE802.11b MAC. The source node generates Data with a rate of 2000kb/s per flow. In terms of overall network performance, generating a CBR traffic gains higher end-to-end throughput, since Data is generated at a constant rate throughout the duration of the communication, but in case of an Exponential traffic, the source generates traffic at the given rate for t second as burst time and goes for t' second as an idle time. In analysis the burst time and the idle time are considered to be equal and the source burst Data for 0.5 seconds and then goes on silent mode for the same amount of time as the burst time. As shown in Figure 7.23, Min NA-PMAC and Dynamic NA –PMAC power controlled MAC performs with higher throughput as the minimum distance between the sources increases unlike MaxRC-MinDA NA-PMAC and IEEE 802.11b MAC. Despite controlling the power of Data transmission, the RTS and CTS are sent using a maximum power in MaxRC-MinDA NA-PMAC, so the chances of parallel of parallel transmission reduces and it is seen possible only after the minimum distance between the sources is 200m or greater. When Area-G length is below 150m, the overall network performance of MaxRC-MinDA NA-PMAC degrades as low as 750kb/s when IEEE 802.11b stands above 1300kb/s and Min NA-PMAC and Dynamic NA–PMAC have an

overall performance as high as approximately 1700kb/s. When the areal distance of Area-G is 200m apart, the performance of IEEE 802.11b and MaxRC-MinDA NA-PMAC are similar, but the performance of Min NA-PMAC and Dynamic NA –PMAC is very high and gains at least 35% compared to IEEE 802.11b and MaxRC-MinDA NA-PMAC. In case of IEEE 802.11b MAC, the probability of parallel transmission is viable only when the distance of separation between the sources is 275m or greater. Beyond a minimum distance between the sources of at least 400m, the probability of parallel transmission of any all the power controlled and fixed power transmission IEEE 802.11b MAC is 100%.

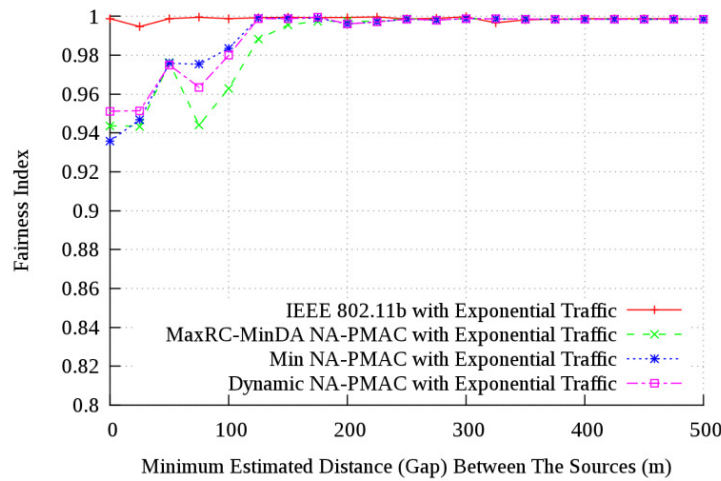


Figure 7.24: Fairness Index of random sources and destinations using exponential traffic

The degree of fairness for multiple flows generating Exponential traffic using the random topology set up of Figure 3.11 is shown in Figure 7.24. The degree of fairness of the traffic flows is high even when the distance of separation between the sources is small and is exposed to each other. The minimum degree of fairness of the flows in the power controlled MACs i.e. MaxRC-MinDA NA-PMAC, Min NA-PMAC and Dynamic NA–PMAC is approximately 94%. The degree of fairness increases as the length of Area-G increases. At a distance between sources of at least 125m, the degree of fairness of Min NA-PMAC and Dynamic NA –PMAC is 99.99% and the degree of fairness using MaxRC-MinDA NA-

PMAC is 99.99%, only after the minimum areal distance between the sources is 175m. Among the power controlled MAC, the overall degree of fairness is better in case of Min NA-PMAC and Dynamic NA –PMAC comparing to MaxRC-MinDA NA-PMAC, where the RTS and CTS are sent with maximum transmission power, but Data and ACK are sent with minimum required power. In case of IEEE 802.11b, if a node is within the transmission range of neighbour nodes then the neighbour also lies within the transmission range of that node, since all the nodes used the same maximum transmission range, therefore the degree of fairness is very high irrespective of the distance between the sources. In case of power controlled MACs, one source may communicate with high power and the neighbour may be communicating with less power and remain hidden, but falls under an interference range, so degree of fairness of powered controlled MAC is lower compared to fixed maximum transmission power controlled MAC when the sources are closer to each other. In the random topology using the Figure 3.11 setup, the degree of fairness of exponential traffic is better to that of CBR traffic.

7.3.3.3. Random Topology Using TCP Traffic

Lastly, the random topology of Figure 3.11 is tested with TCP with FTP traffic and the network performance as the offered load of the per flow increases is shown in Figure 7.25. The overall network performance of a fixed maximum transmission power controlled MAC like IEEE 802.11b ranges from 1000kb/s to 1100kb/s when the minimum distance between the sources is below 275m, thereafter the probability of sending in parallel develops and the performance increases until it saturates when the length of Area-G is above 400m. The performance of IEEE 802.11b slows down from 1100kb/s to 1000kb/s when the sources are separated by a minimum distance of 175m to 275m. In case of a power controlled MAC like MaxRC-MinDA NA-PMAC, the overall performance of the network is below the performance of IEEE 802.11b and the probability of parallel transmission occurs only after

the minimum distance between the sources is at least 175m, and in fact the performance gain increases as the distance between the sources increases. In a power controlled MAC like MaxRC-MinDA NA-PMAC the performance gain is slow, but steady. In case of a power controlled MAC like Min NA-PMAC and Dynamic NA –PMAC the performance gain over 80% and 63% compared to IEEE 802.11b and MaxRC-MinDA NA-PMAC respectively when the distance of communication among the sources are 200m apart.

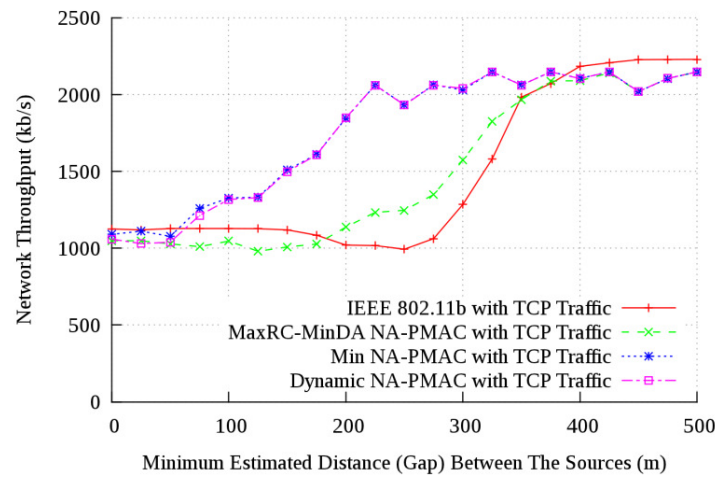


Figure 7.25: Network Performance of random sources and destinations using TCP with FTP traffic.

The degree of fairness of the Data flows using TCP with FTP traffic performs better than CBR and Exponential traffic as shown in Figure 7.26. The minimum degree of fairness in a power controlled MACs like MaxRC-MinDA NA-PMAC, Min NA-PMAC and Dynamic NA –PMAC is 97% and the fairness index increases as the distance between the sources increases and the fairness index goes up to 99.99%. The degree of fairness of the traffic fluctuates for a fixed transmission power like IEEE 802.11b and a partially power controlled MAC like MaxRC-MinDA NA-PMAC unlike Min NA-PMAC and Dynamic NA –PMAC, where the degree of fairness is increased as the areal distance of Area-G increases. The degree of fairness of IEEE 802.11b drops by 1-2% when the minimum distance between the sources is 200m to 300m. When the minimum distance between the sources i.e. Area-G is beyond 50m, the fairness index of Min NA-PMAC and Dynamic NA –PMAC is above 99%.

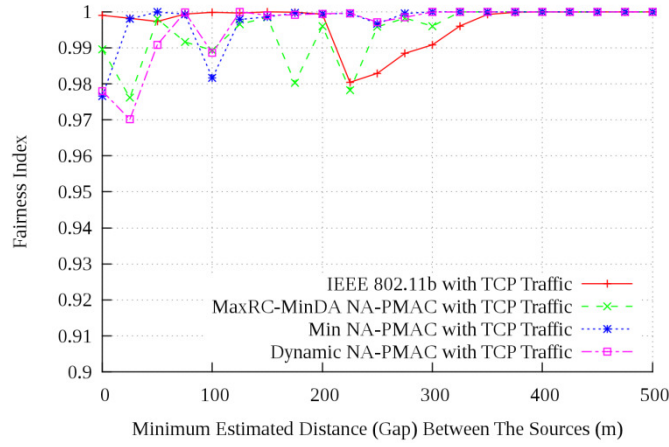


Figure 7.26: Fairness Index of random sources and destinations using TCP with FTP traffic

7.4. Conclusion

This chapter proposed a new MAC called LBT-NA with Optimised-EIFS, which controls transmission power based on the location and the optimal distance of the active one hop neighbour. This cross-layer protocol uses a dynamic EIFS based on the type of the frame when frame error occurs mainly due to reception within an interference range of other active node or when a frame with a stronger signal is captured. Unlike LBT-NA cross-layer MAC, which use a minimum power transmission based on the location of the communicating node, LBT-NA with Optimised-EIFS MAC uses an optimal transmission power by actively listening to the activity and the transmission power of the neighbour nodes to avoid a situation where node i is within the transmission range of node j , but not the other way round, due to difference in transmission power. Such a situation where a node can receive data from other nodes, but not the other way round is an inherent issue of using power control. Thus, to avoid hidden node issues, the active node transmit with a transmission power to reach the farthest one hop active neighbour. Due to the use of optimised EIFS based on the overheard frame type, the degree of fairness of the flows improves and starvation of hidden active node is avoided. The introduced random backoff values, based on the number of the active

neighbours around the node, enhance the performance of the network for fewer active neighbour nodes as the node sets a small backoff value. Due to the power controlled mechanism, the performance of the network in terms of utilisation and reuse of bandwidth increases in comparison with the standard IEEE 802.11b. The proposed power controlled method increases the probability of parallel communication by reducing the transmission and the interference range. LBT-NA with Optimised-EIFS MAC is better than the power controlled LBT-NA Cross Layer MAC, which uses the minimum power transmission. In a random topology with a random source and destination with two sources that are separated by a minimum distance of 200m, the performance gain of power controlled MAC over IEEE 802.11b ranges from 30% to 70% depending on the type of traffic in the network.

Considering location information is not feasible unless GPS or reference points are used, so a new power controlled MAC called Dynamic Neighbour Aware – Power controlled MAC (Dynamic NA -PMAC) based on power estimation is designed and bench marked with variant of Dynamic NA -PMAC. The degree of energy utilisation while transmitting as a source or destination node in the order efficiency is: IEEE 802.11b, MaxRC-MinDA NA-PMAC, Min NA-PMAC and Dynamic NA-PMAC. Due to the new backoff mechanism which defers channel access based directly on the number of the active neighbours, the amount of energy used up during the defer state is less if the number of active neighbours is low, but the performance gain is not significant. Unlike Min NA-PMAC mechanism which uses a minimum transmission power, considering an optimal transmission power like Dynamic NA -PMAC to reach the farthest active neighbour increases the degree of fairness among the contending nodes. The probability of parallel transmission of multiple sources in a random topology in the increasing order of efficiency is: IEEE 802.11b, MaxRC-MinDA NA-PMAC, Min NA-PMAC and Dynamic NA-PMAC. Among the power controlled MAC, Min NA-PMAC and Dynamic NA -PMAC outperformed the MaxRC-MinDA NA-PMAC.

Instead of using a minimum power transmission to cover a distance d considering a $d + \Delta$ coverage while transmitting enforced link stability when node mobility is taken into account. When the network traffic is CBR, Exponential and TCP with FTP traffic the degree of fairness of the flows is 99.999% for Dynamic NA –PMAC when the minimum distance of separation between the random sources is for a minimum of 200m, 125m and 125m respectively. The proposed power controlled MAC viz. Min NA-PMAC and Dynamic NA –PMAC provides the best overall network performance compared to MaxRC-MinDA NA-PMAC and IEEE 802.11b when random topology with different traffic types are considered. The thesis ends with a conclusion in the following chapter.

Chapter 8. Conclusion and Future Work

8.1. Key Contributions of the Thesis

The main contributions of the thesis are summarised and highlighted as follows:

- ✓ The hop based dynamic fair scheduler described in Chapter 4 provides equal chances of accessing the channel based on the hop count of the arriving packets to maintain fairness among different traffic transiting different hops. The degree of fairness among the multiple flows originating from different sources using the new scheduler is increased by at least 10% over a FIFO queue. Moreover, even during network saturation, it guarantees route establishment, because the routing packets are buffered in a special queue and are given the highest probability to schedule.
- ✓ An access mechanism is proposed in Chapter 5, called Dynamic Queue Utilisation Based (DQUB) MAC, which adjusts the contention window range (backoff value) based on the current utilisation of the queue, so a node with higher queue utilisation is prioritised over a node whose queue is less utilised. The proposed DQUB MAC demonstrated a performance gain of up to 35% over IEEE 802.11b when CBR traffic is considered for a 6-hop path. The performance gain of DQUB MAC is robust with respect to path length, packet size, topologies and DQUB MAC also works well with exponential traffic applications with a performance gain of over 16% when a burst time is greater than or equal to the idle time. Even when the burst time of the packets at the source is less than the idle time, the end-to-end throughput of DQUB MAC outperforms IEEE 802.11b. There is a high degree of stability and consistency in DQUB-MAC even with random topologies.

✓ In order to incorporate the importance of hop count as described in Chapter 4, DQUB MAC is enhanced and renamed Queue Utilisation with Hop based Enhanced Arbitrary Inter Frame Spacing (QU-EAIFS). QU-EAIFS leads to two main benefits when compared to DQUB MAC in terms of reducing collision and prioritising packets with higher hop count. QU-EAIFS reduces collision rate since it uses exponential backoff values when the retransmission attempt increases unlike DQUB MAC which increases its backoff value linearly. QU-EAIFS also provides higher access probability for packets transiting with higher hop count since packets with higher hop count wait the least Inter Frame Spacing unlike DQUB MAC which uses a fixed DIFS. Experiments with a 6-hop topology demonstrate a performance gain of 40% in QU-EAIFS over IEEE 802.11b, 87% over IEEE 802.11e (Lowest Priority), and 160% over IEEE 802.11e (Highest priority).

✓ In order to control the interference range, in chapter 6, transmission range is controlled based on the distance of communication. Controlling the power of transmission not only reduces interference, but it saves battery life, enhances the probability of areal reuse and increases the probability of parallel transmission. Thus, a power control MAC called LBT-NA with Optimised-EIFS is designed and active node transmit based on the distance of the next hop destination. In a random topology with a random source and destination, when the two sources are separated by a minimum distance of 200m, the performance gain of LBT-NA with Optimised-EIFS over IEEE 802.11b ranges from 30% to 70% depending on the type of traffic in the network (CBR or Exponential Traffic)

✓ A dynamic deferring time is used when packet error or collision or capture occurs instead of using a fixed EIFS to maintain fair channel access by removing hidden node issues.

- ✓ Using location information for controlling the transmission power is expensive, so a variant of power controlled MAC called Dynamic Neighbour Aware – Power controlled MAC (Dynamic NA -PMAC) is designed which estimates the distance of communication based on the received signal strength. In this approach, a power to reach more than distance d is considered to counter signal fading effect.
- ✓ A dynamic random backoff values depending on the level of congestion are used in the proposed power controlled MAC instead of using a fixed initial backoff value.

Thus, the overall aim of optimising and providing QoS in the resource constrained Ad Hoc networks is achieved by designing a dynamic scheduler based on hop count to provide fairness. In order to reduce packet lost and enhance the end-to-end performance of the network, MACs based on utilisation of the active queues are considered. Moreover, in order to further enhance the overall network performance, power controlled transmission is used either by using location information or by measuring the received signal strength. Hidden node issues which arise due to power control transmission are avoided by considering a dynamic EIFS instead of using a fixed EIFS based the length of the busy state of the channel. Finally, the deferring time is optimised by using backoff values based on the degree of contention within a neighbourhood.

8.2. Limitations of the Thesis

The assumptions and the testing environment considered in the thesis leads to some limitations in real life implementation.

- The node deployment is considered to be on a flat surface, but in reality node deployment are in a 3-dimension model.

- A perfect channel is considered, but in real life scenarios *obstruction, reflection, refraction, and scattering effects* may degrade the performance of the wireless network.
- Mobility of nodes is restricted in the study, but in reality unless it is a sensor networks, node mobility is inevitable.
- Location information is considered to be provided by GPS, but in reality providing location information requires additional subscription to an internet or cellular network.
- The transmission and the sensing ranges are considered to be circular, but the nature of signal distribution will totally be based on the environment in which the nodes are deployed.
- The topologies considered in the study are mainly linear and random, but in reality the shape of the network topologies can be anything.
- The traffic types tested in the study are CBR, Exponential and TCP, but in real applications types of traffic could be voice, video etc.

Lastly, all the testing is conducted in a simulated environment using NS2, so test results for a real life environment is not covered in the study.

8.3. Conclusions

In a multi hop Ad Hoc network, as the number of hops increases the end-to-end throughput decreases due to interference and limited shared bandwidth. In fact, it is found that at network saturation, the throughput between ends of a chain Ad Hoc network is inversely proportional to the number of hops. Packets which have travelled more hops experience lower forwarding rate compared to additional flows encountered along the path. Therefore, along the same path, when fresh flows are introduced along the path of older flows, the fresh flows tends to capture the channel and the old flow arriving passing through the fresh flow suffers starvation. A self-bottleneck is created along a high hop path length

when a source generates a high traffic and resultant in heavy loss of packets along the path and affects the end-to-end throughput. Since, the distance of communication among the active nodes vary, it is better to transmit based on the distance rather than using a fixed transmission power to exhibit parallel transmission and deliver high network performance. It is also better to use a dynamic backoff values based on the number of active nodes rather than using a fixed initial backoff value.

8.4. Future Work

Future work will be based on integrating independent Ad Hoc networks into a MESH network with good QoS support in the following areas:

- Designing a hop based multiple queue schedulers which will prioritize based on the type of traffic since UDP traffic like voice is more sensitive to delay and jitter then TCP traffic like FTP. Also designing a MAC based on the utilisation of each queue based on the hop and traffic types.
- Incorporate an Ad Hoc network into a MESH network and optimise to support end-to-end QoS support for real time traffic like voice.
- In power controlled data transmission, when different transmission ranges are experienced by a node and the number of hidden or exposed nodes vary when power is adapted based on the activity of neighbour nodes.
- Focus shall also be given to investigate the importance of Ad Hoc networks in creating smart machine to machine communication (Internet of Things).
- Actual voice or video traffic will be considered, instead of using UDP with CBR traffic or Exponential traffic.

- An erroneous channel state would be considered by taking into account the effect of *obstruction, reflection, refraction, and scattering effects* during simulation.
- Lastly, study would be conducted and tested in a real life scenarios and compare the result with simulation work.

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Appendices

In total, five papers are published; one peer-reviewed journal and four peer-reviewed conferences and an additional two journal papers are under review. The programming codes are too long to include in this thesis, if required, then it can be made available on request through email (jimsmarchang@gmail.com). Due to copyright, the published articles are not included in this thesis, but DOI/ISBN/links are provided.

1	<p>Hop-Based Dynamic Fair Scheduler for Wireless Ad-Hoc Networks <i>Marchang J, Ghita BV, Lancaster D</i> Proceedings of 7th IEEE International Conference on Advanced Networks and Telecommunications Systems (ANTS), 15-18 December 2013, Chennai, India, ISBN: 978-1-4799-1477-7, pp1-6, 2013. DOI: 10.1109/ANTS.2013.6802873</p>
2	<p>Dynamic Queue Utilization Based MAC for Multi-Hop Ad Hoc Networks <i>Marchang J, Ghita BV, Lancaster D</i> European Wireless 2015 - 21th European Wireless Conference, 20-22 May, Budapest, Hungary, ISBN 978-3-8007-3976-9, ISSN 2198-3909, pp362-367, 2015. Print ISBN: 978-3-8007-3976-9</p>
3	<p>Queue Utilization with Hop Based Enhanced Arbitrary Inter Frame Spacing MAC for Saturated Ad Hoc Networks <i>Marchang J, Ghita BV, Lancaster D</i> Med-Hoc-Net 2015, The 14th IFIP Annual Mediterranean Ad Hoc Networking Workshop, June 17-18, Vilamoura, Algarve, Portugal, ISBN 978-1-4673-7306-7, 2015. DOI: 10.1109/MedHocNet.2015.7173170</p>
4	<p>Dynamic Queue Utilization Based MAC for Multi-Hop Ad Hoc Networks <i>Marchang J, Ghita BV, Lancaster D</i> Infocommunications Journal - A Scientific Association for Infocommunications (HTE), Volume VII Number 3 ISSN 2061-2079, pages: 25-32, 2015. http://www.infocommunications.hu/documents/169298/1598142/InfocomJ_2015_3_5_Marchang.pdf</p>
5	<p>Location Based Transmission Using a Neighbour Aware-Cross Layer MAC for Ad Hoc Networks <i>Marchang J, Ghita BV, Lancaster D</i></p>

	Wired/Wireless Internet Communications (WWIC), 14th IFIP WG 6.2 International Conference, Thessaloniki, Greece, May 25-27, Volume 9674 of the series Lecture Notes in Computer Science pp 15-27, Springer, ISBN: 978-3-319-33935-1, 2016. DOI 10.1007/978-3-319-33936-8_2
6	Location Based Transmission Using a Neighbour Aware-Cross Layer MAC for Ad Hoc Networks [Full version] <i>Submitted at Journal of Ad Hoc – Elsevier (Under review)</i>
7	Dynamic Neighbour Aware Power Controlled MAC for Ad Hoc Networks <i>Submitted at Journal of Ad Hoc - Elsevier (Under review)</i>