Interface Diversity for Enhanced Quality of Experience in Home Networks

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Abstract

Most of the modern home-networking devices have multiple interfaces, e.g., WiFi, PLC, Ethernet, for connection. These devices constitute an in home heterogeneous mesh network. Channel aggregation and routing between these mesh-nodes are critical challenges that have potential to improve application quality. In order to aggregate the channels and find a best route, variety of parameters, such as interference, link quality and access technology must be considered.

In this work, we propose to use multiple interfaces as an apparatus of diversity to enhance the Quality of Experience of video streaming users. The proposed method, Interface Diversity, provides full-redundancy, and thus, not only decreases the packet loss, and average delay but also increases the saturation throughput. We formulated a multi-radio mesh network considering Interface Diversity. Centralized solutions are obtained for different network scenarios. Then, the distributed end-to-end routing using the Interface Diversity method and AODV is implemented by modifying a wellknown multi-radio routing method available in the literature. The performance of our interface diversity method and the proposed routing method are validated by extensive simulations in OPNET.

Ev Ağlarında Deneyim Kalitesini Arttırmak İçin Kullanılan Arayüz Çeşitlemesi

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Özet

Çoğu ev ağı cihazları Ethernet, Wifi,PLC gibi birden fazla arayüze sahiptirler. Bu cihazlar birlikte çokgen bağlantılı ağ yapısı oluşturmaktadırlar. Bu çokgen bağlantılı ağ cihazları arasındaki kanal birleştirmesi ve rotalama problemlerinin çözülmesi uygulama kalitesini arttırma potansiyeli taşımaktadır. Kanal birleştirme ve rotalamanın uygulanabilmesi için girişim, kanal kalitesi ve erişim teknolojisi gibi birçok parametrenin göz önünde bulundurulması gerekmektedir.

Bu çalışmada, birden fazla arayüzün çeşitleme metodu ile beraber kullanılması sağlanarak video tecrübe kalitesinin arttırılması önerilmiştir. Önerilen Arayüz Çeşitlemesi metodu tam yedeklilik sağlamaktadır. Böylece paket kayıpları ve ortalama paket gecikme süresi azaltılmakta ve üretilen doygunluk iş miktarı arttırılmaktadır. Birden fazla radyo tipinin bulunduğu çokgen bağlantılı ağ yapısını arayüz çeşitleme metodunu da gözönünde bulundurarak matematiksel olarak formulledik. Farklı senaryolarda merkezi çözümler elde ettik. Sonra, dağıtılmış ve uçtan uca rotalamayı AODV algoritmasını ve literatürde var olan MIC metriğini kullanarak ve arayüz çeşitlemesini de kullanarak elde ettik. Kullandığımız rotalama ve Arayüz Çeşitlemesi metodlarının yararlarını OPNET programını kullanarak gösterdik.

To my family…

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Chapter 1

Introduction

Since the introduction of internet, data communication devices, such as smartphones, computers and smart TVs, penetrate into the home environment. These devices use different access technologies involving variety of MAC and PHY protocols. Inter-operation of such devices as a mesh network would enhance the QoE of many applications[3] including video applications.

Improving the online video applications' quality has a huge demand. Both the number of users and data demand per user are increasing. Therefore, the amount of traffic generated by on-line video platforms is huge and growing rapidly. For example, the global consumer video internet traffic is expected to be 80 percent of all consumer Internet traffic in 2019 up from 64 percent in 2014 [4]. The quality of a video streaming content is a function of both compression/streaming process and transmission conditions[5]. Therefore, increasing the video streaming quality depends on the improvements of both compression/streaming process and transmission conditions. Transmission conditions involve bandwidth, delay, jitter and loss[6]. In this thesis, we try to optimize the transmission conditions in order to obtain a better QoE for video streaming applications.

Mesh network is a promising technology for many applications[7]. In a mesh network, each node operates as a source, destination and router. Using some intermediate nodes as routers, a source node may communicate with a destination node even if it is not in the transmission range [8]. Also, transmission conditions may be developed using such intermediate nodes. Mesh networks may benefit from heterogeneous interfaces[9]. Considering physical and upper layer characteristics of different access technologies is a necessity, in order to solve such heterogeneous mesh network problems.

In this thesis, we consider the channel aggregation and routing problem of home networks that have the topology of heterogeneous mesh networks involving PLC and Wifi devices. Our ultimate goal is to develop the video transmission quality between mesh network nodes. In order to be competible with both PLC and Wifi devices, our approach do not change MAC layer and PHY layer characteristics significantly. We consider an Abstract Layer solution that is in between Data Link Layer and Network Layer. A new Interface Diversity method is proposed between neighbor devices. Interface Diversity involves the transmission of the same packets from both interfaces and control of the re-transmissions using MAC layer acknowledgements. Interface Diversity method provides full-redundancy, and thus, not only decreases the packet loss, and average delay but also increases the saturation throughput. Also, Interface Diversity provides more resistance to the link breaks. Considering the interface diversity method, a centralized problem formulation is obtained. The centralized problem formulation provides the effectiveness of Interface Diversity in heterogeneous mesh networks under ideal conditions. Then we propose a distributed routing using AODV protocol. In a distributed routing, the nodes do not have every knowledge in the network; but they have the knowledge that is given by AODV packets. Finally, we simulate our distributed routing algorithm with different network scenarios using OPNET simulator. OPNET considers both physical and network layer characteristics of the devices, therefore provides a realistic estimation for the scenarios created.

1.1 Contributions

The contributions of this thesis are as follows:

- A new link aggregation method, Interface Diversity, is introduced. Interface Diversity provides full-redundancy, and thus, not only decreases the packet loss, and average delay but also increases the saturation throughput. Also, Interface Diversity provides more resistance to the link breaks.
- A problem formulation involving Interface Diversity, interference and link capacities is defined.
- A wellknown multi-radio routing method available in the literature is developed further.
- End-to-end routing considering Interface Diversity is proposed.

1.2 Thesis Organization

The rest of this thesis is organized as follows. Chapter 2 provides the background and the previous work related to this thesis. Chapter 3 represents the system model and network model that is considered. Protocol interference model, AODV routing protocol and routing metrics are discussed in this chapter. Chapter 4 provides the problem formulation that would define the system and network model explained in Chapter 3. The problem formulation considers link capacities, multi-flows, multi-radios, Interface Diversity and interferences. Since the problem formulation is complex, the effects of link capacities, multi-flows, multi-radios, Interface Diversity and interferences are reflected step by step. Chapter 5 proposes Interface Diversity algorithms for both a transmitter and a receiver. Then, implementation of Interface Diversity in a multi-hop network is explained considering flow priorities, Metric of Interference and Channel Switching, abstract nodes and variable link costs. Chapter 6 provides both centralized and distributed network simulations. The centralized simulation is obtained using fmincon function of MATLAB. The distributed solution to the same problem is analyzed using OPNET. Finally, Chapter 7 overviews the work and concludes the thesis.

Chapter 2

Background and Related Work

2.1 Background

This section provides the sufficient knowledge for the topics that are used in the rest of this thesis. Section 2.1.1 explains wireless mesh networks and Section 2.1.2 explains powerline communication protocol. Both Section 2.1.1 and Section 2.1.2 provide necessary knowledge in order to understand our network topology, since our focus is heterogeneous mesh networks involving powerline communication and wifi devices. Section 2.1.3 discusses the diversity method, which provides a preliminary knowledge for our diversity implementation given in Chapter 5. Section 2.1.4 investigates the interference models and types which are used in both Chapter 4 and Chapter 5. Section 2.1.5 explains traffic prioritization, which is used in Chapter 5.

2.1.1 Wireless Mesh Networks

A wireless mesh network (WMN) is a flourishing technology to provide open access to the Internet with high bandwidth and low cost while covering a wide area. Compared to ad-hoc networks, WMNs can be considered as a generalized technology for fulfilling the actual user requirements such as low up-front cost, easy network maintenance, robustness and reliable service coverage[1]. Therefore, WMNs are one of the most promising candidates for developing the Future Internet technology. WMNs consist of mesh clients, which are not capable of forwarding data, mesh routers, which may forward data as an intermediate node and gateways which are connected to the internet. In a WMN, intermediate nodes may pass data in order to improve the performance and the coverage of the network. Figure 2.1 pictures a typical WMN.

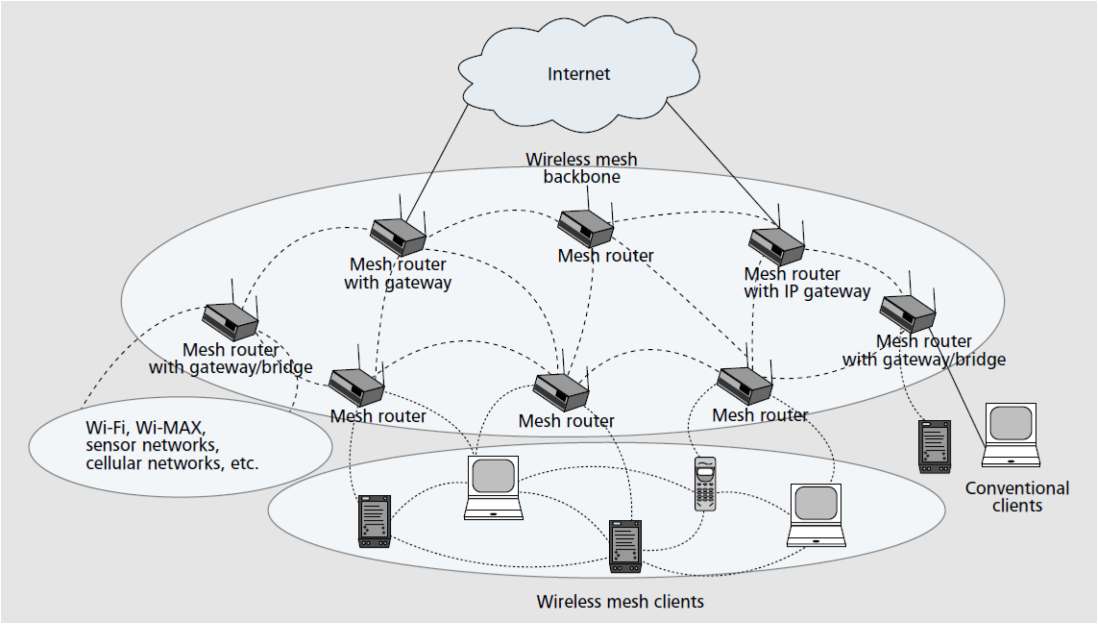

Figure 2.1: Wireless Mesh Network [1]

2.1.2 Powerline Communication

Powerline Communication(PLC) is a communication protocol that uses the existing electrical infrastructure as the physical medium. Since PLC does not require additional infrastructure like the other wired communication technologies, such as ethernet, it offers a practical use with satisfactory QoS. PLC promises variety of implementations such as home networking, in-vehicle networking and broadband communication. IEEE published the standard for PLC technology, IEEE 1901[10] in 2010. There are various home networking specifications of PLC, such as Homeplug AV[11], Homeplug AV 2[12] and Homeplug Green[13] published by Homeplug Alliance.

2.1.3 Diversity

Diversity refers to the use of independent signal paths in order to develop the quality of transmission. Diversity is a commonly used method in physical layer. The independent signal paths have a low probability to experience deep fades simultaneously. Therefore, using these paths and selecting the strongest received signal provides some reduction of the fading of the resultant signal[14][15]. There are different implementations of diversity including time diversity, frequency diversity and multiuser diversity. Time diversity refers to the transmission of the same signal at different times. Time diversity decrases the data rate since it consumes some of the time for retransmissions[14][15]. Multiuser diversity allows the best conditioned channel to be active at a given time. Therefore, each transmitter would have an opportunity to transmit, if their channel is the best conditioned. Therefore overall system capacity may be improved[14][15]. However, a centralized knowledge of the channels is required. Frequency diversity is the transmission of the same narrowband signal at different carrier frequencies. In other words, frequency diversity refers to the use of orthogonal frequency channels for improving the reliability of a message[14][15]. Our diversity implementation involves a similar approach with frequency diversity.

Frequency diversity is commonly used by many areas of telecommunication. For example, Watteyne et. al. propose to send subsequent packets over different frequency channels[16]. They decrease the number of expected transmission count and increase stability of wireless sensor networks. [17] uses frequency diversity to effectively reduce the variation in received signal strength values. In this way, some decrease of location determination error is achieved. However, to the best of our knowledge, this is the first work that uses diversity above MAC layer on heterogeneous mesh networks with a better QoE purpose for video applications.

2.1.4 Interference

If two signals with the same frequency and in the same medium superpose, the resultant signal may be corrupted and unrecoverable. This phenomenon is named interference. In order to model the effect of interference, Protocol Interference Model and Physical Interference Model are widely used in the literature[18].

Protocol Interference Model: In one channel, a transmission is successful, only if the following conditions are satisfied:

- $d_{ij} \leq R_i$
- Any node n_k, such that $d_{kj} \leq R'_k$ is not transmitting

where d_{ij} denotes the distance between node i and node j, R_i denotes the communication range and R'_k denotes the interference range of node i.

Physical Interference Model: In one channel, a transmission is successful, only if the following condition is satisfied:

- $SNR_{ij} \geq SNR_{threshold}$

where SNR_{ij} is the signal-to-noise ratio observed on node n_j for the transmission of node n_i. $SNR_{threshold}$ denotes a predefined threshold signal-to-noise ratio level.

The inter-flow interference and intra-flow interference terms are frequently used in this thesis. Intra-flow interference refers to the interference between the nodes carrying the same flow. Figure 2.2 shows a simple example of the effect of intra-flow interference on the path selection. The use of different interfaces for the consecutive links, provides less interference.

Inter-flow interference refers to the interference between the nodes carrying different flows. Figure 2.3 shows a simple example of the effect of inter-flow interference on the path selection. Since C and E nodes interfere, it is better to use $A \rightarrow B \rightarrow D$ path rather than $A \rightarrow C \rightarrow D$ path.

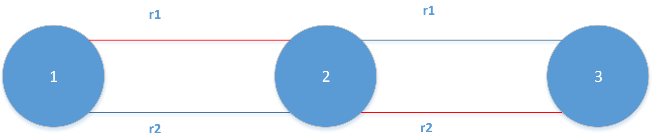

FIGURE 2.2: Intra-flow Interference

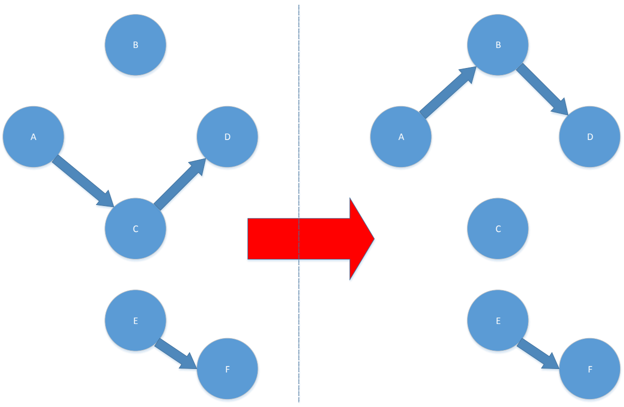

FIGURE 2.3: Inter-flow Interference

2.1.5 Flow Priority

The priority mechanism in MAC protocols provide better access to higher prioritized nodes. In this way, more resource can be deployed to more important flows. Both PLC and Wifi protocols support priority mechanizms[10][19][20]. In [19], the prioritization is handled by different channel window and Arbitrary Interframe Space Number (AIFSN) assignments. AIFSN refers to the number of slots that would a transmitter wait, before transmitting its next frame. A smaller AIFSN yields shorter waiting time that provides higher priority compare to a greater AIFSN. Contention window refers to the number of slots that would a transmitter wait after the end of AIFS. Contention window may change between the minimum and the maximum value, depending on the traffic. Both AIFS and contention window are waiting periods, therefore they decrease the saturation throughput and increase average delay. There are four predefined priority levels that are called access categories(ACs) in EDCA. Table 2.1 shows the EDCA ACs and their parameter settings. Figure 2.4 shows the AIFS and backoffs for AC_VI. Short Interframe Space(SIFS) is used before AIFS for every ACs. If no

AC	**CWmin**	**CWmax**	**AIFSN**
AC_BK	aCWmin	aCWmax	7
AC_BE	aCWmin	aCWmax	3
AC_VI	(aCWmin+1)/2-1	aCWmin	2
AC_VO	(aCWmin+1)/4-1	(aCWmin+1)/2-1	2

Table 2.1: Default EDCA Parameter Set

transmission is detected during the waiting periods, the user earns Transmission Opportunity(TXOP) which is a predetermined time for packet transmissions.

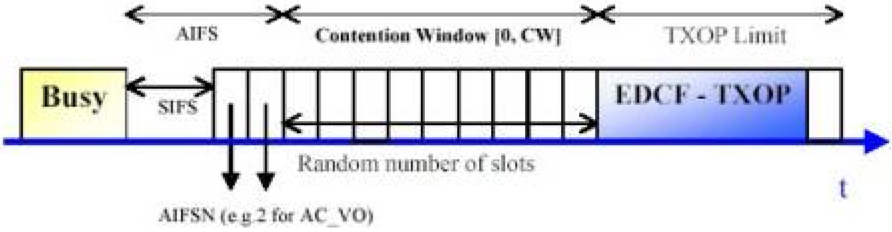

Figure 2.4: EDCA Channel Access [2]

2.2 Related Work

The increase in the channel count provides less co-channel interference, therefore more concurrent transmissions may become possible. [21] investigates the the joint routing and scheduling optimization in a multi radio multi hop network. In this paper, the objective is to minimize the system activation time considering end to end rate demand, interference and the network conditions. Also, [22] considers a distributed scheduling for video streaming over multi-channel multi-radio multi-hop networks. This work aims to achieve minimum video distortion by jointly considering media-aware distribution and network resource allocation. However, these studies do not consider interface aggregation, which may provide further gain.

Heterogeneous interfaces aggregation problem is widely studied before[3][23][24][25]. Multi-path aggregation may be achieved in different layers of OSI model. Kaspar explains multi-path aggregation in different layers from the link layer to the application layer[3].

Channel aggregation in link layer is mostly called bonding, trunking or bundling in the literature[3]. Bonding driver [26] of Linux OS is used by many researchers in order to accomplish link layer interfaces aggregation[24][27]. In order to prevent frame re-ordering, most of the link layer aggregation methods aggregate multiple physical channels of equal technology.

Network layer path aggregation is refered as multi-path routing in the literature. [28] provides network layer multi-path routing by assigning two IP addresses to a user. Also, Liu et.al. propose a heterogeneous mesh network architecture involving WiMax and Wifi[29]. They design a protocol to combine the resources.

Multipath TCP (MP-TCP)[30] is another way of heterogeneous interfaces aggregation and much research has been done about it before [25]. MP-TCP creates an MP-TCP layer above the TCP layer and controls more than one TCP connections from this layer.

[31] provides an application layer interface aggregation, by implementing additional sequence numbers to ensure correct assembly at the receiver.

The network layer, transport layer and application layer aggregation methods are upper layer solutions compare to our solution. We propose an abstraction layer solution, which is in between link layer and the network layer. Therefore, different IP adresses are not assigned to each radio in our system. The abstraction layer is standardized in IEEE Standard for a Convergent Digital Home Network for Heterogeneous Technologies(IEEE 1905 [32]). Rather than link layer bonding, abstraction layer solutions may achieve aggregation of different physical channel technologies.

Since IEEE 1905 is introduced recently(in 2013), there are a few works about abstraction layer channel aggregation. [33] studies the abstraction layer aggregation of PLC and Wifi devices. [33] focuses on estimating the PLC channel capacity by using a few probe packets and distributing the data packets among PLC and Wifi links proportional to their channel capacities. In this way, throughput is increased. However, we propose a solution to optimize the video applications' quality by decreasing delay and jitter of the network.

Chapter 3

System and Network Model

3.1 System Model

We consider a heterogeneous home network involving fixed nodes with PLC and Wifi interfaces. Figure 3.1 shows a typical heterogeneous home network. A node may have only one interface. Also, a node may be a hybrid node involving both of the interfaces. We consider that all of the nodes in the network cooperate in the distribution of data. In other words, the intermediate nodes in the network have the ability to relay data. Therefore, the system is a mesh network.

The nodes using the same interfaces simultaneously may interfere. Protocol interference model is considered in this thesis. It is explained in Section 2.1.4.

3.2 Routing

We use Adhoc On-Demand Distance Vector Routing protocol[34] in order to find the best path. Every node in a network keep routing tables in order to establish the paths. The routing tables are created on demand using Route Request(RREQ) and Route Reply(RREP) messages. The routing tables contain next node, destination node, cost and sequence number fields for every entry. Therefore, the

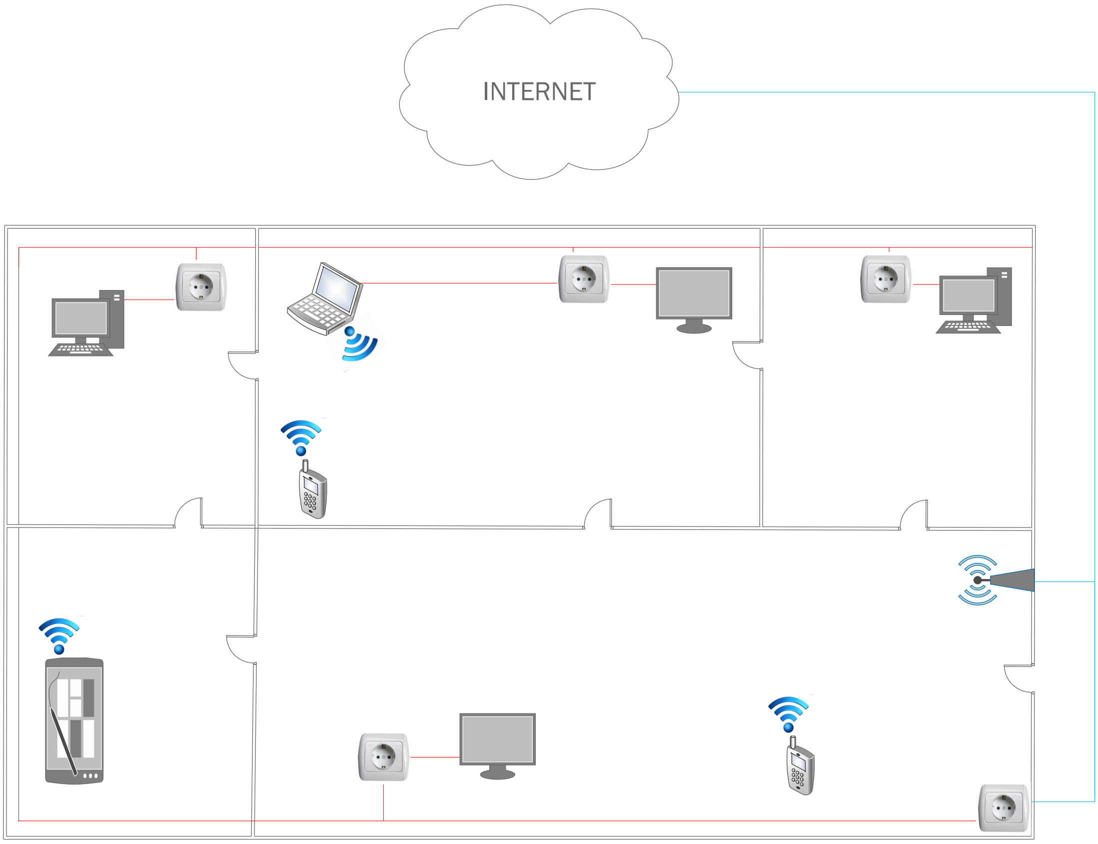

Figure 3.1: Heterogeneous Home Mesh Network

next node information of a packet is available for a node, if the destination node is obtained. Sequence number is held in order to keep the table updated. Only new RREQ and RREP messages that have higher sequence number or lower cost are eligible to change routing tables. RREQ and RREP messages contain source node, destination node, cost and sequence number fields. RREQ messages are broadcasted while RREP messages are unicasted through a specific destination. If a node has packets for transmission, the routing table is checked for the desired destination node. If there is not any entry for the destination, a RREQ message is broadcasted. Every intermediate node that receive the RREQ message, refresh their routing tables. If any change on an intermediate node's routing table occur, a new RREQ message is broadcasted. When a RREQ message arrives to the destination node, the destination node refreshes its routing table and unicasts a RREP message to the previous node on the path. Using the routing tables, every intermediate node unicast the RREP message to the one previous node on the path. When the RREP message arrives to the source node, the data packets' transmission starts through the established path.

Routing Metrics

AODV protocol generates a best path using link costs. The link costs are routing metrics that are designed to optimize the resultant path of the protocol. There are many routing metrics for different purposes[35][36][37][38]. A good fit for the routing problem provides more efficient results. Hop count is the traditional metric that is used by many routing protocols. Expected Transmission Count(ETC) is used to capture MAC retransmission effects on the network[35]. However, both hop count and ETC do not consider any kind of interference. Weighted Cumulative Expected Transmission Time(WCETT) proposed in [36], considers intra-flow interference, which is the interference the interference between the nodes carrying the same flow, by giving more penalty to the congested paths. However, WCETT do not consider inter-flow interference, which is the interference between the nodes carrying different flows. Therefore, WCETT performs inefficient, if the network includes more than one flow. Metric of Interference and Channel Switching(MIC) proposed in [37] and Interference Aware Routing Metric(iAWARE) proposed in [38] are considering both inter-flow and intra-flow interferences. iAWARE considers physical interference model while MIC considers protocol interference model.

In this paper, we implement AODV using MIC metric. Our implementation is explained in Chapter 5

Chapter 4

Problem Formulation

In this chapter, we present our problem formulation (PF) with the constraints imposed by interference, interface diversity, multi-radios and multi-flows in a multi-hop wireless network. A similar but simpler problem formulation is presented in [39]. Jain et. al. consider a multi-hop wireless network with interference and one flow. Also, they suggest the ways to extend the work for multi-radio and multi-flow problems. In section 4.1, the PF that Jain et.al. introduced is explained. In section 4.2, multi-flow extension is applied. In section 4.3, multi-radio extension is applied. In section 4.4, interface diversity extension is applied. In section 4.5, interference extension is applied and the final version of the problem formulation is presented.

4.1 Mesh Network Problem Formulation

Given a wireless network with N nodes, Jain et. al. derive a connectivity graph C as follows[39]. The vertices of C correspond to the wireless nodes (N_C) and the edges correspond to the wireless links (L_C) between the nodes. There is a directed link l_{ij} from node n_i to n_j if $d_{ij} \leq R_i$ and $i \neq j$. The PF is given in (4.1).

$$
\begin{aligned}
&\mathbf{max} \sum\nolimits_{l_{si} \in L_c} f_{si} \\
&\mathbf{Subject\ To:} \\
&\qquad \sum\nolimits_{l_{ij} \in L_c} f_{ij} = \sum\nolimits_{l_{ji} \in L_c} f_{ji} \quad , n_i \in N_c \setminus \{n_s, n_d\} \\
&\qquad \sum\nolimits_{l_{is} \in L_c} f_{is} = 0 \\
&\qquad \sum\nolimits_{l_{di} \in L_c} f_{di} = 0 \\
&\qquad f_{ij} \leq C_{ij} \qquad\qquad , \quad \forall_{ij} \mid l_{ij} \in L_c \\
&\qquad f_{ij} \geq 0 \qquad\qquad , \quad \forall_{ij} \mid l_{ij} \in L_c
\end{aligned}
\tag{4.1}
$$

In (4.1), f_{ij} denotes the amount of flow on link l_{ij} ,C_{ij} denote the capacity of link l_{ij}, and L_C is a set of all links in the connectivity graph. The objective function forces the source's outgoing flow to be maximized. The first constraint restricts the intermediate nodes. With this restriction, the incoming flow and the outgoing flow of an intermediate node are provided to be equal. The second constraint restricts the source node. There should not be any flow incoming to the source node. The third constraint restricts the destination node. There should not be any flow departing from the destination node. The forth and the fifth constraints provide that the flow amounts are between zero and the capacity.

4.2 Multi-flow Extension

The problem formulation given in (4.1) considers only one source and one sink nodes. A multi-commodity multi-hop network has more than one source-destination pair. To implement the multi-flow extension, we assigned a connection identifier, k, to each source-destination pair. The problem formulation considering multiple source-destination pairs is given in (4.2).

$$\begin{aligned}
&\mathbf{max} \sum\nolimits_{l_{si} \in L_c} f^k_{s_k i} \\
&\textbf{Subject To:} \\
&\qquad \sum\nolimits_{l_{ij} \in L_c} f^k_{ij} = \sum\nolimits_{l_{ji} \in L_c} f^k_{ji} && , n_i \in N_c \setminus \{n_{s_k}, n_{d_k}\} \\
&\qquad \sum\nolimits_{l_{is} \in L_c} f_{is_k} = 0 \\
&\qquad \sum\nolimits_{l_{di} \in L_c} f_{d_k i} = 0 \\
&\qquad \sum\nolimits_{allk} f^k_{ij} \leq C_{ij} && , \quad \forall_{ij} \mid l_{ij} \in L_c \\
&\qquad f^k_{ij} \geq 0 && , \quad \forall_{ij} \mid l_{ij} \in L_c
\end{aligned} \tag{4.2}$$

f^k_{ij} denotes the amount of flow on link l_{ij} for the k'th commodity. Source, sink and intermediate node assignments change for each k. Therefore, the first three constraints are applied considering the type of the nodes for each k. For example, the total incoming flow into a source node is zero only for the connections originating at that node.

4.3 Multi-radio Extension

A multi radio network has more than one radio and these radios do not interfere. To implement the multi radio extension, we assigned a radio identifier, r, to each radio. The problem formulation with this upgrade is given in (4.3).

$$\begin{aligned}
&\mathbf{max} \sum\nolimits_{l^r_{si} \in L_c} f^{kr}_{s_k i} \\
&\textbf{Subject To:} \\
&\qquad \sum\nolimits_{l^r_{ij} \in L_c} f^{kr}_{ij} = \sum\nolimits_{l^r_{ji} \in L_c} f^{kr}_{ji} && , n_i \in N_c \setminus \{n_{s_k}, n_{d_k}\} \\
&\qquad \sum\nolimits_{l^r_{is} \in L_c} f^r_{is_k} = 0 \\
&\qquad \sum\nolimits_{l^r_{di} \in L_c} f^r_{d_k i} = 0 \\
&\qquad \sum\nolimits_{allk} f^{k(r=1)}_{ij} \leq C^{(r=1)}_{ij} && , \quad \forall_{ij} \mid l_{ij} \in L_c \\
&\qquad \sum\nolimits_{allk} f^{k(r=2)}_{ij} \leq C^{(r=2)}_{ij} && , \quad \forall_{ij} \mid l_{ij} \in L_c \\
&\qquad f^{kr}_{ij} \geq 0 && , \quad \forall_{ij} \mid l_{ij} \in L_c
\end{aligned} \tag{4.3}$$

4.4 Interface Diversity Extension

(4.3) reflects a PF of a multi-radio multi-commodity multi-hop network. The radios are permitted to be used simultaneously. However, in our design, the resource sharing is atomic, in the sense that a demand cannot be split among resources [40]. In other words, a flow cannot be separated among different paths and bonded on the receiver side. The radios can be used simultaneously, only if they apply Interface Diversity, which is the transmission of the same signals between two consecutive nodes, in order to prevent packet losses. Therefore, it is necessary to apply atomic routing and Interface Diversity to the PF.

Consider a network with only a transmitter and a receiver. Also, consider that their physical transmission rates are equal, they are always in the same phase of packet transmission and they are always transmitting the same packets. Then, the successful flow density between the nodes is:

$$f_{ij} = C * p_{ij}^{(r=1)} + (1 - p_{ij}^{(r=1)}) * p_{ij}^{(r=2)}$$

C denotes the physical transmission rate and $p_{ij}^{(r=n)}$ denotes the probability of success of the l_{ij} of the n'th radio.

4.5 Interference Extension

We incorporate interference using the same method of [39]. We define a conflict graph, F. Vertices of F correspond to the links in the connectivity graph, C. There is an edge between the vertices of F, if the corresponding links in C may not be active simultaneously. The conflict graph is derived considering the protocol interference model. An independent set is a set of vertices such that any two of the vertices are not connected with an edge. A maximal independent set is an independent set with the most number of vertices possible. Let σ_1, $\sigma_2 ... \sigma_n$ denote the fraction of time allocated to each maximal independent set. (4.4) demonstrates the sufficient constraints to reflect the effects of interference.

$$\begin{aligned}
&\sum_{l=1}^{K}\sigma_l \leq 1\\
&f_{ij} \leq \sum_{l_l\in I_l}\sigma_l C_{ij}
\end{aligned}\tag{4.4}$$

By applying all extensions that are explained in the previous sections, we build the sufficient PF for our network. It is given in (4.5).

$$\begin{aligned}
&\mathbf{min}\sum_{k}\sum_{i,j}\left(\alpha_{ij}^{k}\right)^{-1}(1-\lambda_{ij})+\theta_{ij}^{k}\lambda_{ij}\\
&\textbf{Subject To:}\\
&\sum_{j,r} f_{s_kj}^{kr}=0\\
&\sum_{j,r} f_{d_kj}^{kr}=0\\
&\sum_{j}\alpha_{ij}^{k}(1-\lambda_{ij})+\beta_{ij}^{k}\lambda_{ij}=\sum_{j}\alpha_{ji}^{k}(1-\lambda_{ji})+\beta_{ji}^{k}\lambda_{ji}\\
&\sum_{j,r}\alpha_{s_kj}^{k}(1-\lambda_{s_kj})+\beta_{s_kj}^{k}\lambda_{ji}\geq\gamma^{k}\\
&\sum_{l=1}^{K}\sigma^{lr}\leq 1\\
&\sum_{k} f_{ij}^{kr}\leq\sigma^{lr}C_{ij}^{r}\\
&f_{ij}^{kr}\geq 0\\
&\mu_{ij},\lambda_{ij}\in 0,1
\end{aligned}\tag{4.5}$$

$$\begin{aligned}
\text{where}\quad \alpha_{ij}^{k}&=f_{ij}^{k(r=1)}P_{ij}^{(r=1)}\mu_{ij}+f_{ij}^{k(r=2)}P_{ij}^{(r=2)}(1-\mu_{ij})\\
\beta_{ij}^{k}&=f_{ij}^{k(r=1)}P_{ij}^{(r=1)}+f_{ij}^{k(r=2)}P_{ij}^{(r=2)}\left(1-\frac{f_{ij}^{k(r=1)}P_{ij}^{(r=1)}}{C_{ij}^{(r=1)}}\right)\\
\theta_{ij}^{k}&=f_{ij}^{k(r=1)}P_{ij}^{(r=1)}+f_{ij}^{k(r=2)}P_{ij}^{(r=2)}\left(1-\frac{f_{ij}^{k(r=1)}P_{ij}^{(r=1)}}{C_{ij}^{(r=1)}}\right)^{-1}
\end{aligned}$$

We modified the objective function such that it minimizes the total delay of the commodities. In this way unsaturated networks, that do not require extra throughput but require better delay, are optimized. The throughput demand of each application is reflected in fourth constraint. λ binary variable reflects the decision of interface diversity use in a link. If interface diversity is not used, then the connection is atomic. μ binary variable reflects the decision of interface selection. If a connection is atomic, only one interface can be active.

In Chapter 6, proportional fair maximization of two flows is also used. To implement proportional fairness, we canceled the fourth constraint of (4.5) and changed the objective function as in (4.6).

$$\mathbf{max} \sum_{k} log\left(\alpha^{k}_{i_k j}(1 - \lambda_{i_k j}) + \beta^{k}_{i_k j} \lambda_{i_k j} \right) \tag{4.6}$$

Chapter 5

Interface Diversity

In this chapter, the interface diversity method and its multihop implementation is explained. The interface diversity method aims to benefit from two radios by increasing reliability and throughput while decreasing the average delay. Figure 5.1 illustrates the layered structure of a heterogeneous node which involves two radios.

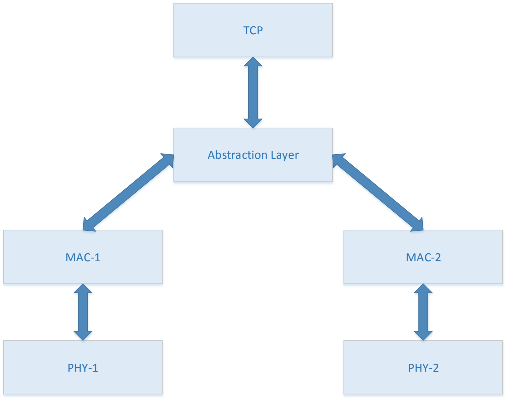

Figure 5.1: Hybrid Node OSI Layers

Interface Diversity algorithms run in the Abstraction Layer. Therefore, the MACs are unaware of interface diversity. However, the MACs are required to deliver the ACKs, that they have received, to the Abstraction Layer. This is the only change in MAC that the interface diversity algorithm requires.

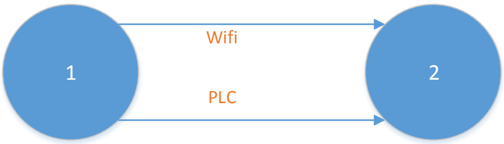

FIGURE 5.2: A Transmitter and a Receiver

5.1 Source and Destination Algorithms

Consider there is only one transmitter and one receiver in the network (Figure 5.2). The algorithm which runs on the transmitter side is given in Algorithm 1.

The packets, which are expected to be transmitted by the upper layers, are indexed in order. The goal of Algorithm 1 is to successfully transmit every packets that are delivered from the upper layers and prevent the transmission of the packets that are already ACKed. In order to achieve this goal, c1 and c2 counts the

```
Input: Data packets to be transmitted, $P_1, P_2....P_n$;
Append index number 1 to $P_1$'s header;
Send $P_1$ to interface 1;
Send $P_1$ to interface 2;
Set index number variables c1=1, c2=1 ;
while $n + 1 > c1$ && $n + 1 > c2$ do
    if interface 1 sends an ACK then
        c1=c1+1;
        if c1 > c2+1 then
            c2=c1-1;
        end
        Append c1 to $P_{c1}$'s header;
        Send $P_{c1}$ to interface 1;
    end
    if interface 2 sends an ACK then
        c2=c2+1;
        if c2>c1+1 then
            c1=c2-1;
        end
        Append c2 to $P_{c2}$'s header;
        Send $P_{c2}$ to interface 2;
    end
end
```

Algorithm 1: Transmitter

transmitted number of packets in the relevant radio. If one of the radio achieves more packet transmission than the other one, the difference between c1 and c2 becomes greater, which means the slower radio has some packets in its queue that is already ACKed. These ACKed packets are already received by the receiver, which means their further transmission is unnecessary. These packets are skipped and the relevant counter is increased. In this way, both of the goals are satisfied.

The algorithm which runs on the receiver side is given in Algorithm 2.

```
current index number, c=1;
if interface 1 sends a packet then
    Get the index number of the packet, set it to i;
    if $i>c$ then
        Send ACK to both interface 1 and interface 2;
        c=i;
    end
end
if interface 2 sends a packet then
    Get the index number of the packet, set it to i;
    if $i>c$ then
        Send ACK to both interface 1 and interface 2;
        c=i;
    end
end
```

Algorithm 2: Receiver

The goal of Algorithm 2 is to send the new arriving packets, that the same index numbered packets are not already received, to the upper layers. In order to achieve this goal, c records the last successfully received packet index. If the received packet contains lower or equal packet index, the packet is ignored. Because, it is already received before.

Algorithm 1 and Algorithm 2 are designed to achieve that the radios transmit the same packets. Therefore, if a packet transmission fails in a radio, the other radio backups immediately. If the difference between the transmitted packets are not balanced, the slower radio might not backup before the faster radio's retransmission, because it would be busy for the transmission of a packet that is already ACKed.

5.2 Multihop Implementation

We group the active links in the network as main links and auxillary links. Main links are the links that would still be active if the interface diversity method would not applied. Therefore, there is a main link between each consecutive node on the path. An auxillary link is the second active link between two consecutive nodes. Activation of an auxillary link makes possible to use interface diversity between two consecutive nodes. Auxillary links are the links that are activated to improve the main links' performance.

In a multihop scenario, the use of interface diversity as described in Section 5.1 may be inefficient. Auxillary links may consume the resources that might be beneficial for main links. This results some decrease on the quality of applications running in the network. Therefore, auxillary links should be activated when there are resources that are not preferred to be used by other flows.

5.2.1 Flow Priorities

The priority mechanism in MAC protocols provide better access to higher prioritized nodes. In this way, more resource can be deployed to more important flows. Both PLC and Wifi protocols support priority mechanisms[10][19][20]. In [19], the prioritization is handled by different channel window and AIFSN assignments. AIFSN refers to the number of slots that would a transmitter wait, before transmitting its next frame. A smaller AIFSN yields shorter waiting time that provides higher priority compare to a greater AIFSN. Contention window refers to the number of slots that would a transmitter wait after the end of AIFSNs. Contention window may change between the minimum and the maximum value, depending on the traffic. Both AIFSN and contention window are waiting periods, therefore they decrease the saturation throughput and increase average delay. There are four predefined priority levels that are called access categories(ACs) in EDCA. The predefined priority levels and their parameters are given in Table 2.1 of Section 2.1.5.

The main links may dominate the network by giving them higher priorities and the auxillary links may still be beneficial if the network is not overloaded. Since we are trying to optimize the video transmission quality, we preferred to use AC_VI(video) parameters for the main links. For the auxillary links, we prefer to modify the AIFSN value to assign lower priority. We do not change the backoff counter, because increasing backoff, increases average delay significantly. The ideal AIFSN value for the auxillary links is calculated as $AIFSN = 12$ by simulations that are discussed in Section 6.2.3.

5.2.2 MIC metric

We prefer to use MIC[37] as our AODV routing metric, because MIC considers the transmission rates and using Protocol Interference Model it considers intra-flow interference and inter-flow interference. MIC punishes extra interference by increasing the link cost(metric), therefore paths with less metric tend to provide less interference.

MIC metric is given in (5.1). It involves two components: Interference-aware Resource Usage(IRU) and Channel Switching Cost(CSC). IRU is designed to capture the transmission rates, packet losses and inter-flow interference. CSC is designed to capture the effect of intra-flow interference. α represents the tradeoff between two components. The formulas for IRU and CSC are given in (5.2) and (5.3).

$$MIC(p) = \alpha \sum_{link\, l \in p} IRU_l + \sum_{node\, i \in p} CSC_i \tag{5.1}$$

$$IRU_{ij}(c) = ETT_{ij}(c) \times |N_i(c) \cup N_j(c)| \tag{5.2}$$

In (5.2), $ETT_{ij}(c)$ refers to the expected transmission time of the transmission between node i and node j on channel c. ETT captures both transmission rate and loss ratio. $N_i(c)$ is the set of neighbors that node i interferes with when it transmits on channel c. $|N_i(c) \cup N_j(c)|$ is the total number of nodes that would interfere during the transmission. The overal physical meaning of $IRU_{ij}(c)$ is the total time spent by the network for the transmission of flow between node i and node j on channel c. Therefore, a minimum weight algorithm using MIC, would result in a path with higher transmission rates, lower loss ratios and less inter-flow interference.

$$CSC_x = \begin{cases} w1, & \text{if CH(prev(X))} \neq \text{CH(X).} \\ w2, & \text{if CH(prev(X))} = \text{CH(X).} \end{cases} \tag{5.3}$$

(5.3) shows the CSC component's formula. CSC component is designed to capture the intra-flow interference effect. If a node X and a previous node prev(x) use the same channel to transmit their flow to their next node, the flow experiences intra-flow interference. In other words, if two consecutive links use the same channel, intra-flow interference occurs. In order to avoid this, CSC implements two different costs, w1 and w2, depending on the occurrence of the intra-flow interference. $w2 > w1 \geq 0$ is a necessary condition in order to obtain less intra-flow interference.

[37] also proposes a routing protocol in order to make MIC isotonic. The isotonic property of a routing metric means that the metric must preserve the order of two different path's weight, while they are added by a third path's weight. Assume that for a path a, the weight function is represented by W(a). Also, concatenating two paths, a and b, is represented by $a \oplus b$. Therefore, W is an isotonic function if $W(a) \leq W(b)$,implies both $W(a \oplus c) \leq W(b \oplus c)$ and $W(d \oplus a) \leq W(d \oplus b)$ for all a,b,c,d. Isotonicity is a sufficient and necessary condition for Bellman-Ford and Dijkstra's algorithm to find minimum weight paths[37]. However, MIC metric is not isotonic because of the CSC component. Authors of [37] propose a routing algorithm, LIBRA, in order to make MIC isotonic. LIBRA creates abstract nodes for every combination of CSC. Therefore, routing between these abstract nodes become isotonic. We do not use LIBRA, but we develop AODV with a similar abstract node approach.

5.2.3 Abstract Nodes

Assume that only the consecutive links interfere and AODV routing is intended using CSC component of MIC metric. Therefore, w1 should be the price, if the links are different; w2 should be the price, if the links are the same. When an AODV-RREQ packet arrives to a node, the node should have the knowledge of the link that RREQ arrived, in order to distinguish the price. The abstract node method provides this knowledge. We represent a real node with 2 different abstract nodes. If the RREQ packet comes from interface 1, we assume that the packet arrives to the abstract node 1; if the RREQ packet comes from interface 2, we assume that the packet arrives to the abstract node 2. Therefore, each abstract node contains the knowledge of the previous link and uses the proper price: w1 or w2. Figure 5.3 shows the abstract nodes and the link prices of a network including three devices. The red lines represent the wifi connections and the green lines represent the PLC connections. The abstract nodes are represented inside the real nodes. Abstract nodes represent the previous link. w1 is the cost when there is no interference and w2 is the cost when there is an interference.

The abstract node method may be extended for more complex interference scenarios. Assume that a link interferes with not only the consecutive nodes but also their consecutive nodes(2 neighbors). In this case, a real node should be represented by 4 abstract nodes and three possible prices: w1,w2 or w3. Figure 5.4 shows the abstract nodes and the link prices of a network including four devices. Since 2 neighbor links interfere, all of the links interfere in Figure 5.4. The second node includes two abstract nodes, since there is only one link before it. These abstract nodes include only the previous link's knowledge. Node 3 and 4 include 4 abstract nodes. These abstract nodes include not only the previous link's knowledge, but also one more previous link's knowledge. w1 is the cost when there is no interference and w2 is the cost when two nodes interfere and w3 is the cost when three nodes interfere.

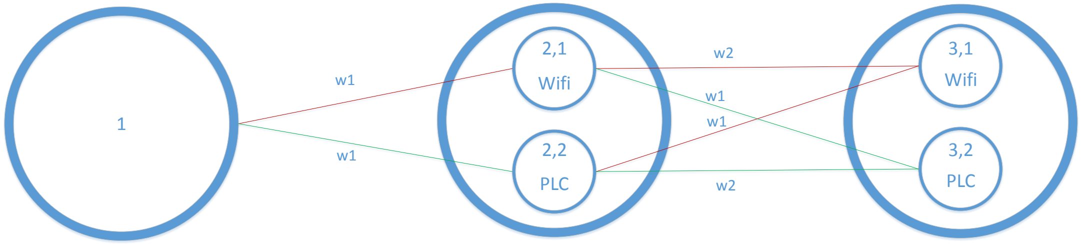

FIGURE 5.3: Abstract Node 1

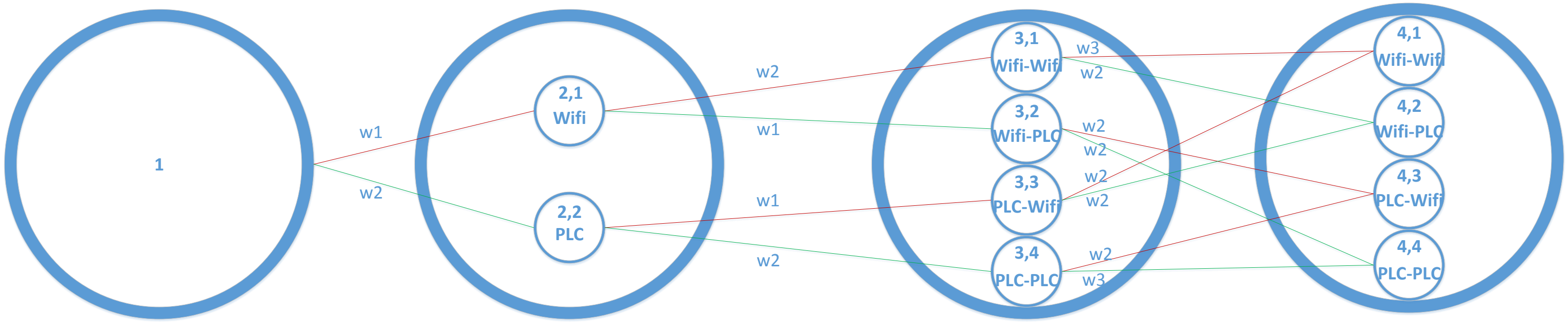

FIGURE 5.4: Abstract Node 2

5.2.4 Variable Link Costs

Abstract node method considers intra-flow interference using constant costs(w_i). However, the effect of interference is not the same for every flow. For example, a congested traffic creates huge interference, while a low traffic creates lower interference. Therefore, we do not use constant w_i as the price. Consider, we are trying to solve the problem given in Figure 5.5. The average delay between node 1 and node 2 is x, while the average delay between node 2 and node 3 is y. If these two links do not interfere, the average delay between node 1 and node 3 would be $x+y$. However, if these two links interfere, using Protocol Interference Model, the first link would be active $\alpha = x/(x+y)$ of total time, while the second link would be active $\beta = y/(x+y)$ of total time. Therefore, if these two links interfere, the average delay between node 1 and node 3 would be $2(x+y)$.It may be observed that the delay under interference is two times of the delay without interference. If the same example would be repeated for the interference of more than two links(n), the resultant end to end delay would be n times the delay without interference.

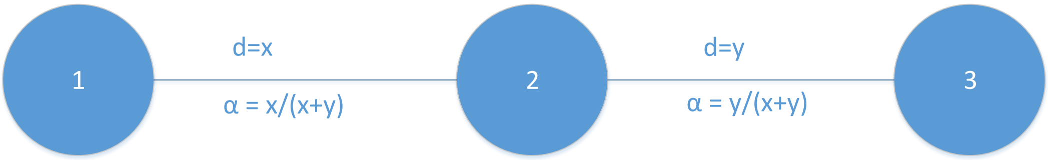

FIGURE 5.5: MIC

We assume that the number of inter-flow interferer and summation of the delay of these interferers are given. When an AODV-RREQ packet arrives, the time spent on the link would be this packet's delay, d_{link}. If there is no intra-flow interference, w1 in Figure 5.3 would be $(d_{link} + d_{inter-flow}) \times (numberofinterferer + 1)$. If there is an intra-flow interference, w2 in Figure 5.3 would be $(d_{link} + d_{inter-flow}) \times (numberofinterferer + 1) + d_{nextlink}$.

Interface Diversity works in the multihop scenario using priorities and AODV. Firstly, the route from source to destination is obtained by AODV. AODV seeks for an ideal route using MIC metric and abstract nodes. The resultant links are main links and higher priority level is assigned to these links. Finally, each node on the path decides, whether using the interface diversity or not by considering the average delay of their radios. If an auxillary link has an average delay which is lower than K times of its main link, interface diversity would be applied and the lowest priority level is assigned to the auxillary link. The K value is assigned considering the simulation results.

Chapter 6

Simulations

6.1 Centralized Solutions

In this section, different simulation scenarios are created. They are modeled using PF discussed in section 4.5 and solved using fmincon function of MATLAB. This is a centralized solution, since all of the knowledge in the network is assumed to be known. Also, packet loss ratio is assumed to be constant and each packet's loss is assumed to be independent; queuing and processing delays are neglected.

In this section, the scenarios are represented by Figures. An arrow between two nodes means that there exist both PLC and Wifi connection between the connected nodes. Figure 6.1 represents two nodes, a source and a destination node. Consider, the saturation throughput for both interfaces is 40Mbit/s and the success probability for both interfaces is $P_s = 0.7$. These inputs yield the saturation throughput of interface diversity to be equal to 36.4Mbit/s. Consider,the saturation throughput for Wifi and PLC interfaces are 40Mbit/s and 30Mbit/s respectively. The success probability for Wifi and PLC interfaces are $P_s = 0.9$ and $P_s = 0.7$ respectively.

Figure 6.1: A Transmitter and a Receiver

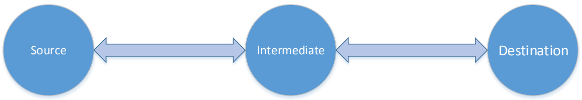

FIGURE 6.2: 3 Nodes Cascaded

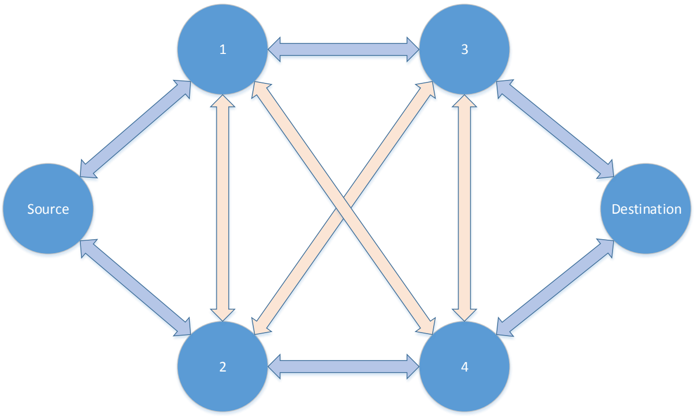

FIGURE 6.3: Network Model 1

These inputs yield the saturation throughput of interface diversity to be equal to 29.8Mbit/s.

Figure 6.2 represents three nodes, a source, an intermediate node and a destination node. Consider the Wifi links have 40Mbit/s saturation throughput separately with the same $P_s = 0.8$ and PLC links have 20Mbit/s saturation throughput separately with the same $P_s = 0.8$. Without interface diversity, the maximum throughput between source and destination nodes is 16Mbit/s while 17.6Mbit/s can be achieved by interface diversity.

Figure 6.3 represents a network involving 6 nodes. The blue arrows represent the existence of PLC and Wifi connections while the orange arrows represent the existence of weak PLC and Wifi connections. The connections represented by orange are so weak that a transmission is not possible, but they cause interference. Since we apply protocol interference model, their effect on interference is the same with the blue arrows. In other words, orange nodes are not used for data transfer, but they change the interference graph. In the rest of this chapter, the network in Figure 6.3 is named network model 1.

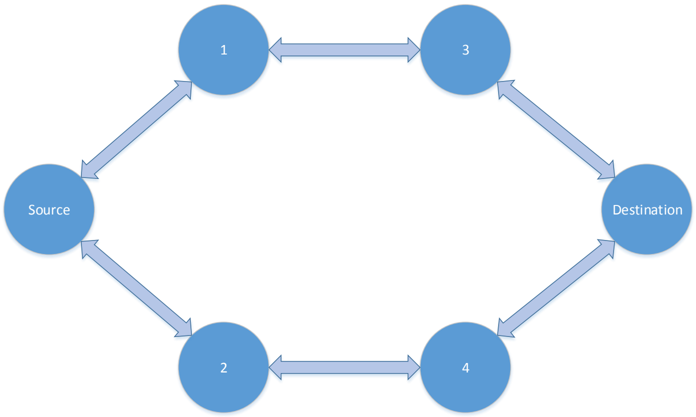

Figure 6.4: Network Model 2

Figure 6.4 represents a network involving 6 nodes. In the rest of this chapter, the network in Figure 6.4 is named network model 2. The main difference between network model 1 and network model 2 is interference. In network model 1, node 1 and node 4 may receive flows simultaneously. However, in network model 2, node 1 and node 4 may not receive flows simultaneously because of the weak connection represented by the orange arrow.

Consider there are two different flows going from node 1 to node 6 in Network Model 1. Every link has a packet loss probability, $p_l = 0.3$. The saturation throughput of every wifi link is 44 Mbit/s, while the saturation throughput of every PLC link is 38 Mbit/s. When the objective function is the proportional fairness of the two flows, the resultant throughput values are given in Figure 6.5. If the same scenario with the same objective function is applied, the resultant throughput values would be as in Figure 6.6. Black represents wifi flows, while red represents PLC flows.

Notice that in Network Model 1, interface diversity is not preferred to be used, while in Network Model 2 interface diversity is used. For the Network Model 2, if the Interface Diversity would not be used, the resultant throughput values would be similar to Figure 6.5, which provides less proportional fair maximal result. It may be concluded that as interference increases, the use of interface diversity becomes less profitable.

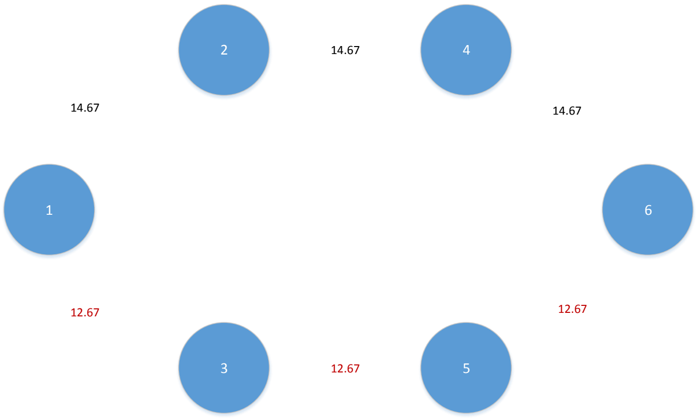

FIGURE 6.5: Network Model 1-Simulation Results for p=0.7

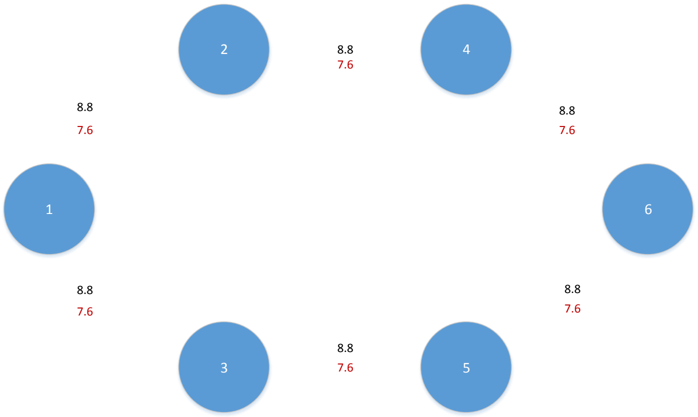

FIGURE 6.6: Network Model 2-Simulation Results for p=0.7

6.2 Distributed Solutions

Distributed solutions are calculated using OPNET simulator. OPNET is a fast discrete event simulation engine for analyzing and designing communication networks[41]. It provides a graphical interface to build models for various network entities from application processes to physical layer modulator. A Node Model is the definition of each network object. We developed a new Node Model(Figure 6.7), in order to define the characteristics of our hybrid devices.

In Figure 6.7, there are 11 process models. The process models store the main code of the model. Source model is used to generate and sink model is used to absorb traffic. Packet duplication, distribution and AODV are handled in Abstraction Layer. Wlan_mac_intf and wireless_lan_mac are used for MAC layer characteristics

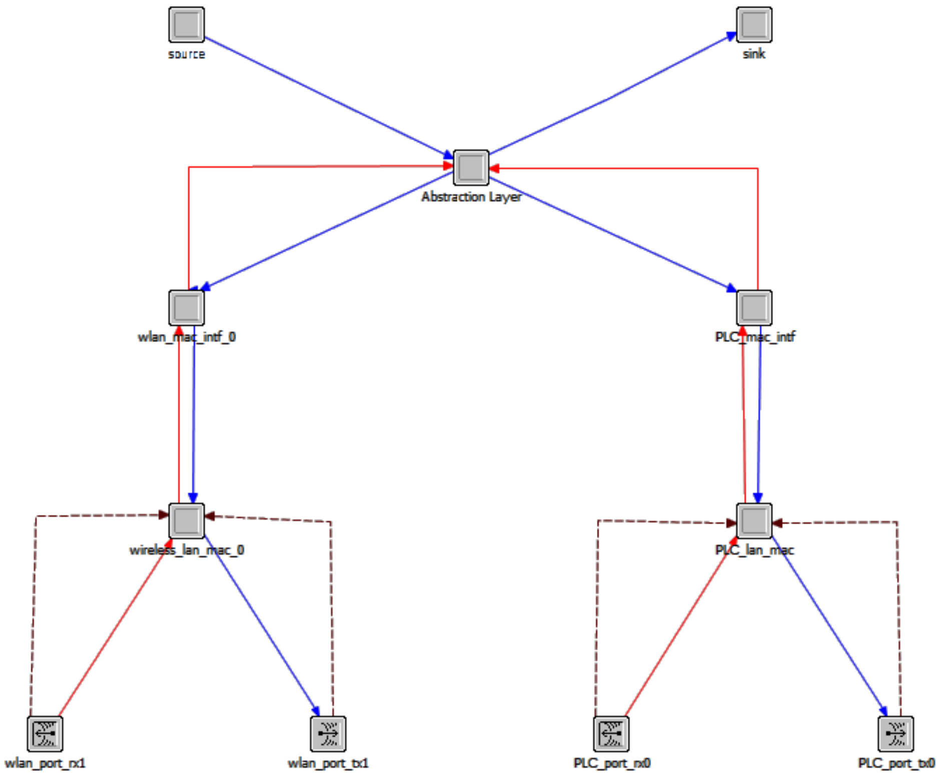

FIGURE 6.7: Hybrid Node Model

of wifi. PLC_mac_intf and PLC_lan_mac are used for MAC layer characteristics of PLC. Finally rx and tx process models are used for physical layer characteristics of the interfaces.

6.2.1 Channel Model

The wireless and PLC channels are modeled by pipeline stages which compute transmission delay, antenna gains, propagation delay, signal-to-noise ratio etc. As the path loss model, we implemented free space model which is:

$$PL = \frac{\lambda^2}{16\pi^2 d^2} \tag{6.1}$$

where λ is the wavelength in meters and d is the distance between the transmitter and the receiver. The received power is calculated as:

$$P_r = P_t \times txgain \times rxgain \times PL \tag{6.2}$$

where P_t represents transmit power, tx gain represents the gain of the transmitter antenna and rx gain represents the gain of the receiver antenna. However, this model do not consider fading. Therefore, we modified by implementing Rayleigh fading as the multi-path fading. The probability density function of received power is:

$$f(P_r, \bar{P}_r) = \frac{1}{\bar{P}_r} e^{\frac{P_r}{\bar{P}_r}} \tag{6.3}$$

where $\bar{P}_r$ is the average received power calculated in 6.2. OPNET considers both background and interference noises. The background noise is calculated as:

$$N = k \times T \times B \tag{6.4}$$

where k s the Boltzmann constant, T is the temperature and B is the channel bandwidth(Hz).

Signal to interference plus noise ratio(SINR) is calculated as:

$$SINR = \frac{P_r}{I + N} \tag{6.5}$$

where I represents the total interference power.

6.2.2 Simulation Parameters

Table 6.1 shows the parameters that we used in our simulations.

Table 6.1: Simulation Parameters

Packet Size	1500 byte
Traffic Type	Constant interarrivals
Wifi Data Rate	65Mbps(base)600Mbps(max)
PLC Data Rate	54Mbps
Wifi PHY	5.0GHz 802.11n
RTS CTS	Disabled
PCF	Disabled
40 MHz Operation	Disabled
Frame Aggregation	Disabled
Buffer Size	2.000.000.000 bits

6.2.3 EDCA Priority Settings

In chapter 5, the links on a path are classified as main links and the auxillary links. Also, in chapter 5, it is indicated that the auxillary links should be activated when there are resources that are not preferred to be used by the main links. This action is achieved using EDCA priorities which are explained in chapter 5. Assigning high priority to the main links and low priority to the auxillary links provides the specified purpose. In this section, we resolve the high priority and low priority parameters, using OPNET simulations.

Since we are trying to optimize the video transmission quality, we preferred to use AC_VI(video) parameters for the main links. There are two features an auxillary link should possess:

1. An auxillary link should not have a poor performance in order to improve its main link's performance
2. The activation of an auxillary link should not harm a main link's performance

Assigning AC_BK(background) or AC_BE(best efford) parameters on Table 2.1 to the auxillary links seems logical. However, because of the high contention window of AC_BK and AC_BE, auxillary links may perform poorly. Therefore, we created our own priority class for the auxillary links.

Figure 6.8: Test 1

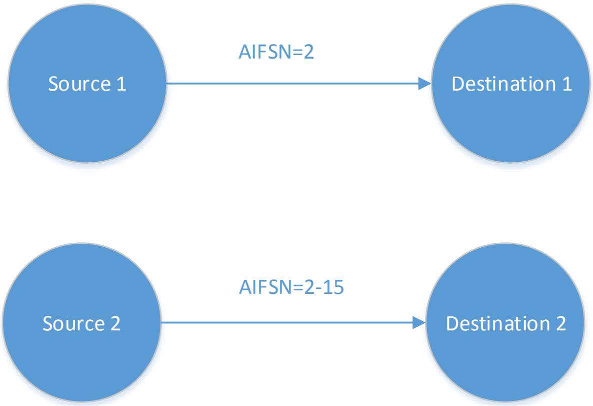

Figure 6.9: Test 2

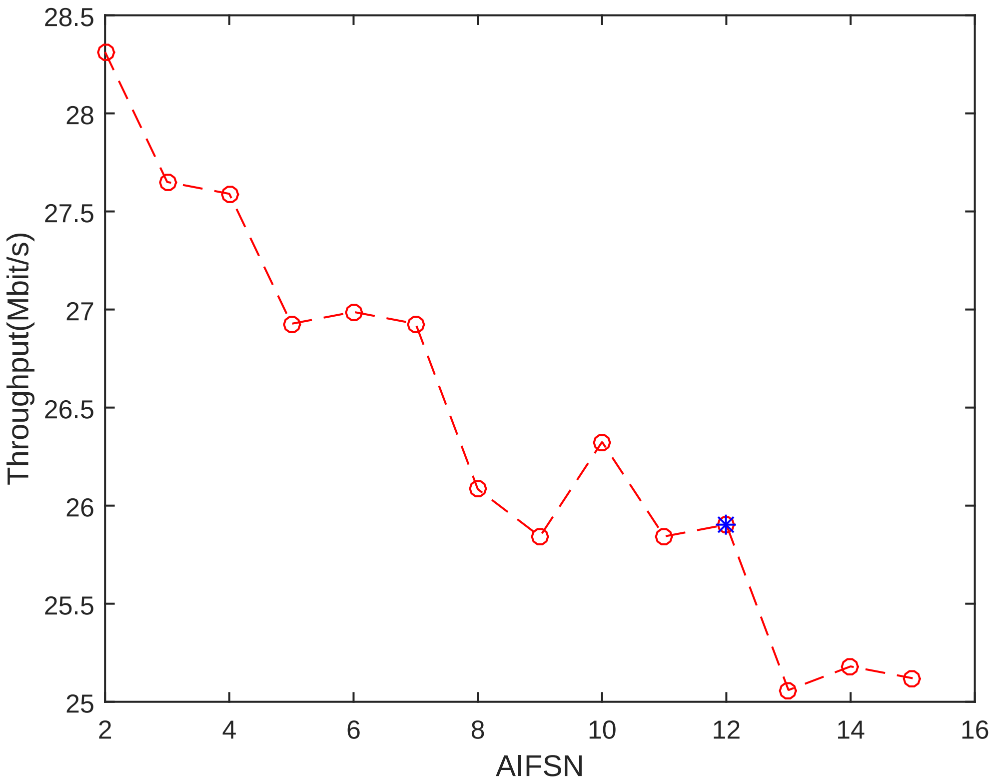

Figure 6.10: Throughput for Different AIFSN Assignments

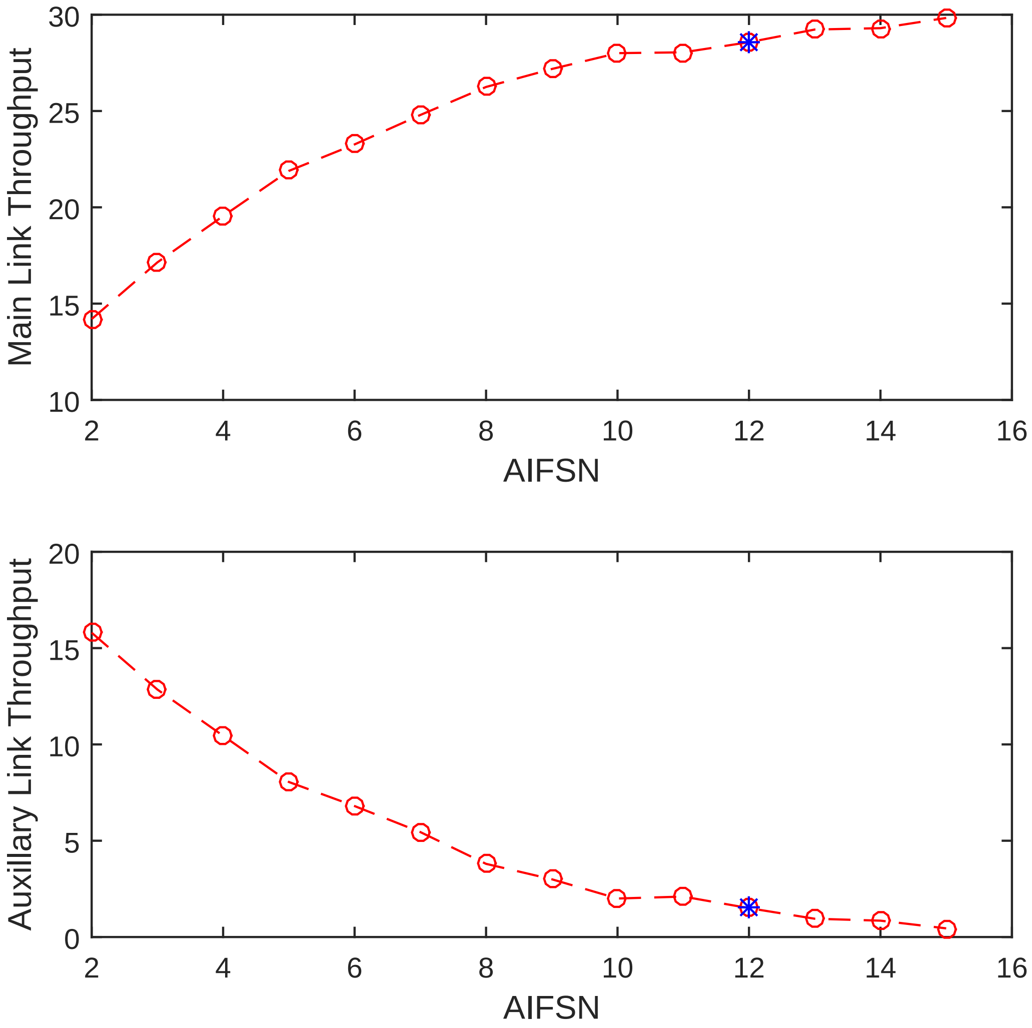

FIGURE 6.11: Effect of Auxillary Link on Main Link for Different AIFSN Assignments

For the auxillary links, we prefer to modify the AIFSN value to assign lower priority. We do not change the backoff counter, because increasing backoff, increases average delay significantly which is a violation of the first feature.

To decide the AIFSN value of the auxillary link, we created two tests. Figure 6.8 pictures the first test which includes only one link without any interferer. The saturation throughput for different AIFSN assignments is measured. Figure 6.8 pictures the second test which includes a link with $AIFSN = 2$ and an interferer link with varying $AIFSN$ assignments.

Figure 6.10 shows the saturation throughput for different AIFSN assignments of the first test. Figure 6.11 shows the saturation throughputs of Destination 1 and 2 in the second test for different $AIFSN$ assignments.

To satisfy two features that are given above, the AIFSN value should have a high throughput in Test 1 and the main link throughput in Test 2 should also be high. We decide to assign $AIFSN = 12$ to the auxillary links, since it has a throughput decrease lower than 9% (Test 1) and it harms the main links less than 5% (Test 2).

6.2.4 Activation of An Auxillary Link

In chapter 5, the activation of an auxillary link is conditioned by its average delay compare to its main link's average delay. We concluded that, an auxillary link would be active, if it has an average delay which is lower than K times of its main link. In this section, we decide the value of K by simulations.

$$K = \frac{d_{auxillary}}{d_{main}}$$

Figure 6.12 shows the change in gain by using interface diversity with different average delay ratios. Average Wifi delay is kept constant, but average PLC delay is increased for each sample. Therefore $PLC/Wifi$ ratio is also increasing for each sample. The gain represents to the advantage by using interface diversity instead of a better path among PLC and Wifi. The formula for gain is given below:

$$Gain = \frac{min(d_{wifi}, d_{PLC}) - d_{ID}}{min(d_{wifi}, d_{PLC})} \tag{6.6}$$

Considering, Figure 6.12 we decided to set $K = 1.5$, which conditions the interface diversity gain to be at least 25% . Therefore, an auxillary link would be activated only if $K < 1.5$

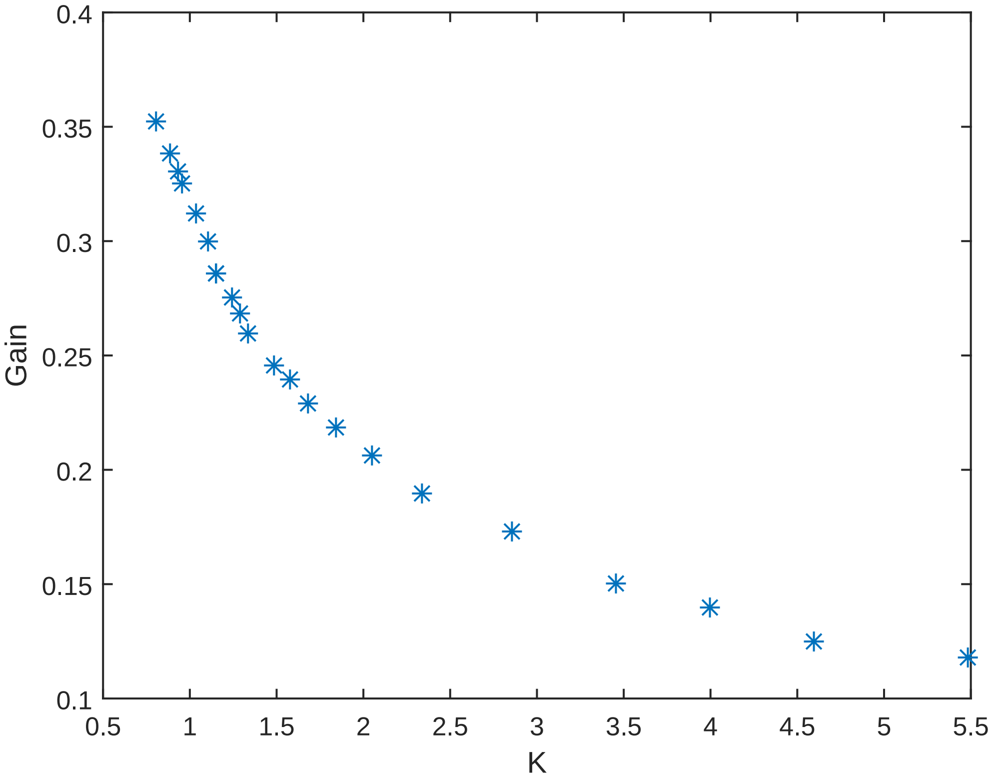

FIGURE 6.12: Gain vs. K

6.2.5 Scenarios

In this section, the advantages of interface diversity are demonstrated considering saturation throughput and delay under different scenarios. The simulations are performed using OPNET network simulator.

6.2.5.1 Simulations Involving Constant Interarrival Time Inputs

Two Node Scenario

Table 6.2 demonstrates the effect of interface diversity on the saturation throughput. In this scenario, the transmitter always has a packet on its queue to be transmitted. There is no interference. Rayleigh Fading is implemented. Since interface diversity has a backup link, it observes less retransmissions. Therefore, interface diversity provides higher saturation throughput. The network is sketched in Figure 6.13

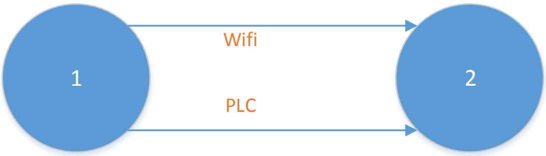

FIGURE 6.13: 1 Hop Scenario

	Throughput
Interface Diversity	32.1
Wifi	30.8
PLC	29.1

TABLE 6.2: Average Throughput(Mbit/s)

The throughput advantage may only be observed on the saturation, because retransmissions do not cause throughput decrease in the unsaturated scenarios. The advantage of interface diversity in the unsaturated scenarios may be observed on delay. Table 6.3 demonstrates the effect of interface diversity on delay in an unsaturated scenario. In this scenario, the throughput is 20 Mbit/s. There is no interference. Rayleigh Fading is implemented. The network is sketched in Figure 6.13. The complete statistics for the one hop scenario and the cumulative distribution functions of the delay results are given in Table 6.4 and Figure 6.14. The use of Interface Diversity creates some extra congestion. The duplicate packets which are already received by the receiver are deleted. The price of using Interface Diversity is these duplicate packets that are deleted. Table 6.5 gives the amount of deleted packets for the scenario. In other words, it gives the price of using Interface Diversity.

	Delay
Interface Diversity	307
Wifi	432
PLC	457

Table 6.3: Average Delay(microseconds)

Table 6.4: Link Statistics for Two Node Scenario

	Delay (10^{-6}s)	Loss (%) ($d > 0.002$)	Jitter (10^{-6}s)	Saturation Throughput (Mbit/s)
Wifi	432	0,807	186	30.8
PLC	457	0,861	161	29.1
I. Div.	307	0,003	100	32.1

Table 6.5: Interface Diversity Bandwidth Overhead

	PLC($Mbit/s$)	PLC(Ratio)	Wifi($Mbit/s$)	Wifi(Ratio)
Saturation	16.8	%63	9.0	%29
20 Mbit traffic	13.6	%70	5.7	%29

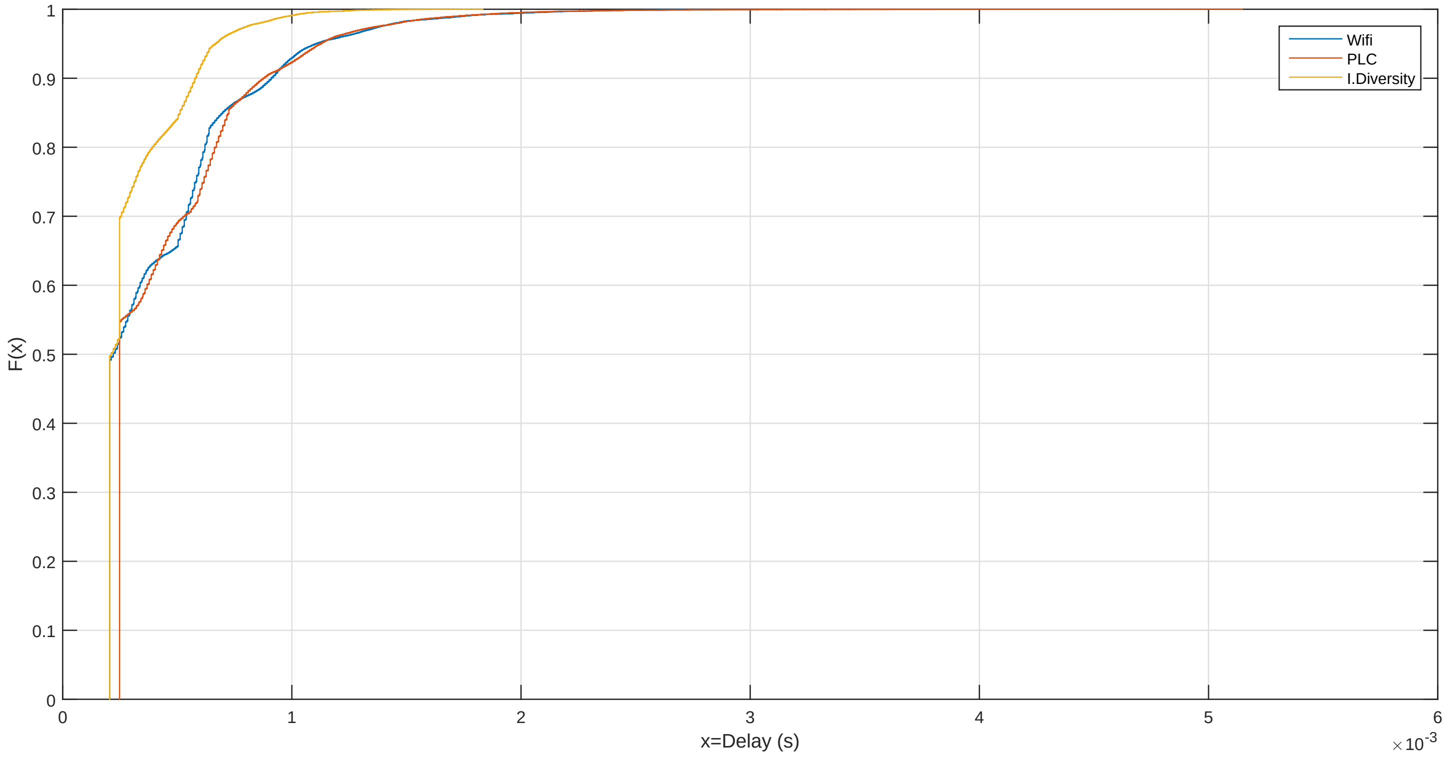

Figure 6.14: The Cumulative Distribution Functions for the 2 Node Scenario

Two Node Scenario with a High Priority Interferer

In this part, the effect of inter-flow interference on Interface Diversity is investigated. The goal of Interface Diversity is increasing the link's quality, while the channel is empty. An auxillary link may not harm a main link on the network, since the main links are necessary links for commodities.

Figure 6.16 illustrates the effect of inter-flow interference on Interface Diversity. The interferer contains a high priority video flow with constant packet sizes and interarrivals. While there is a 15 Mbit/s Interface Diversity link, the PLC interference is applied. In Figure 6.16 x axes represents the amount of traffic, which creates a high priority PLC interference. The network is sketched in Figure 6.15. The main link between Node 3 and Node 4, that is the reason of interference, is PLC. The main link between Node 1 and Node 2 is Wifi. Also there is an auxillary PLC link between Node 1 and Node 2. The gain formula that is used in Figure 6.16 is defined in 6.6.

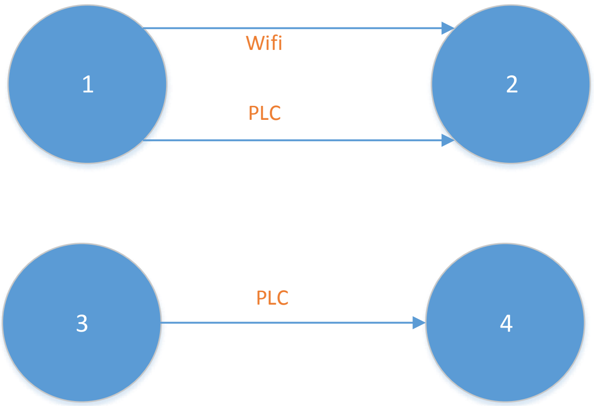

FIGURE 6.15: 1 Hop Scenario with Inter-flow Interference

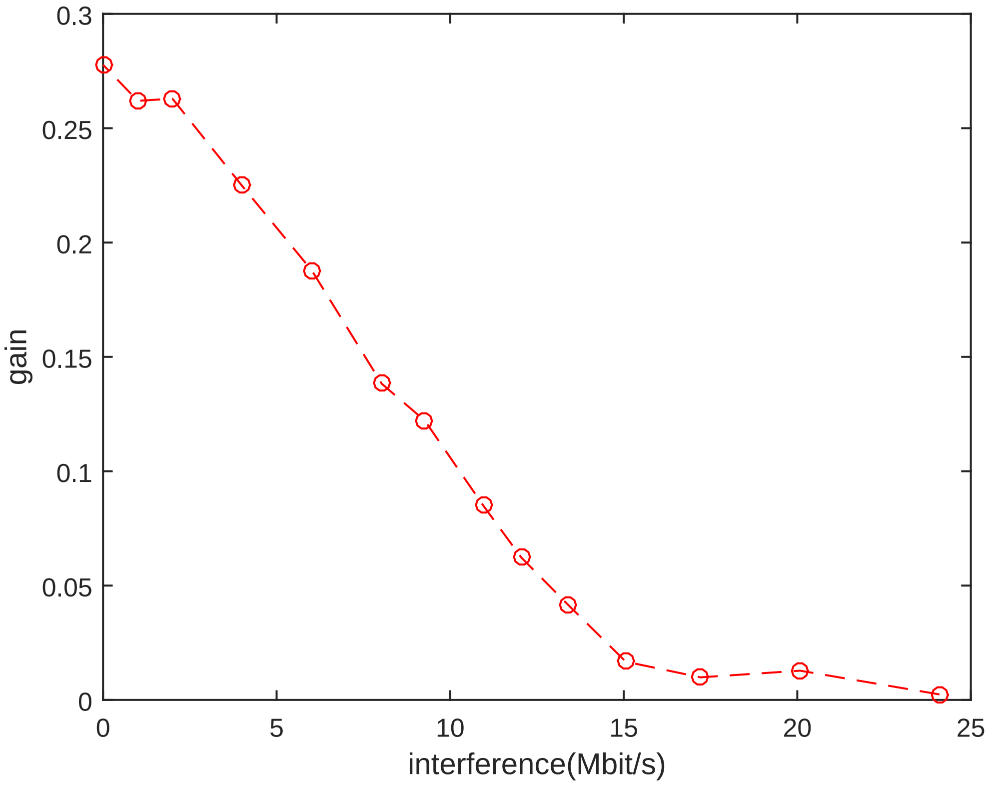

FIGURE 6.16: The Effect of Inter-flow Interference on Interface Diversity

15Mbit/s is the level when the PLC channel is saturated. The auxillary link becomes dominated by the main link interference. Therefore, after this level, Interface Diversity becomes inefficient. In other words, the auxillary link between Node 1 and Node 2 does not provide any profit, in order to not harm the main link between Node 3 and Node 4.

Two Node Scenario with a Data Flow Interferer

In the previous part, the effect of interflow interference is observed considering a video prioritized interferer with constant packet sizes and constant packet interarrivals. In this part, the effect of interflow interference is observed considering a best efford prioritized data flow interferer with exponential interarrivals and variable packet sizes. The size of an interferer packet is either 100 or 1024 bytes with equal distribution. The network is similar(Figure 6.15). The main link between Node 1 and Node 2 is Wifi. Also there is an auxillary PLC link between Node

1 and Node 2. The PLC link between Node 3 and Node 4 is a main link, but it is best efford prioritized, since it contains a data flow. Figure 6.17 illustrates the effect of the PLC link interference on the average delay of Interface Diversity link. The gain formula that is used in Figure 6.17 is defined in 6.6.

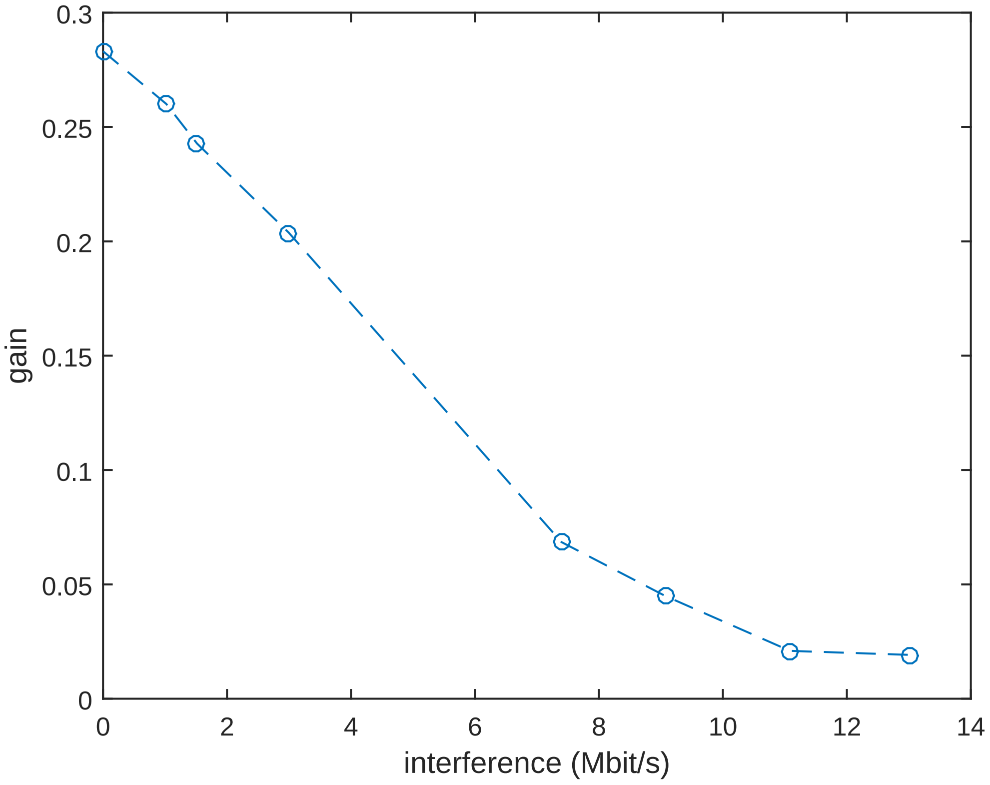

Figure 6.17: The Effect of Inter-flow Interference on Interface Diversity

The best efford priority constains $AIFSN = 3$(Table 2.1). Since the AIFSN value for the auxillary link is 12, the auxillary link becomes dominated by the data flow interference as it increases. The effect of data flow interference and the video flow interference vary on the saturation level. The best efford prioritized flows approach saturation with less throughput, since these flows spend some extra overhead time because of higher AIFSN value. Therefore, auxillary link becomes completely dominated by the data flow interferer with lower interference amount$(12\ Mbit/s)$ compare to the video flow interferer$(15\ Mbit/s)$.

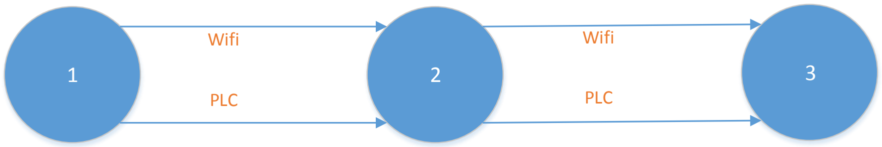

Figure 6.18: 3 Node Scenario

	Delay
Interface Diversity&MIC	625
MIC	673
Wifi	785
PLC	807

Table 6.6: Average Delay(microseconds)

Three Node Scenario

In figure 6.18, 7.5 Mbit/s traffic is transferred from source to destination via the intermediate node. The delay results are given in Table 6.6. Also, the cumulative distribution functions of the delay results are given in Figure 6.19. The average delay of using only Wifi interfaces and only PLC interfaces are higher. The use of MIC metric provides a heterogeneous path, which decreases the intra-flow interference. Therefore, a better average delay compare to the homogeneous paths is obtained. However, the best result is obtained by implementing both MIC and Interface Diversity. The complete network statistics for this scenario is given in Table 6.7. Also, the cost of Interface Diversity is given in Table 6.8.

Table 6.7: Link Statistics

	Delay (10^{-6}s)	Loss (%) ($d > 0.002$)	Jitter (10^{-6}s)	Saturation Throughput (Mbit/s)
Wifi	785	1,65	339	15,2
PLC	807	1,20	291	14,50
MIC	673	0,59	307	29,5
I. Diversity&MIC	625	0,06	163	25,0

Table 6.8: Interface Diversity Bandwidth Overhead for 3 Node Scenario

	PLC($Mbit/s$)	PLC(Ratio)	Wifi($Mbit/s$)	Wifi(Ratio)
Saturation	5.1	%17	3.5	%12
20 Mbit traffic	11.4	%77	3.6	%24

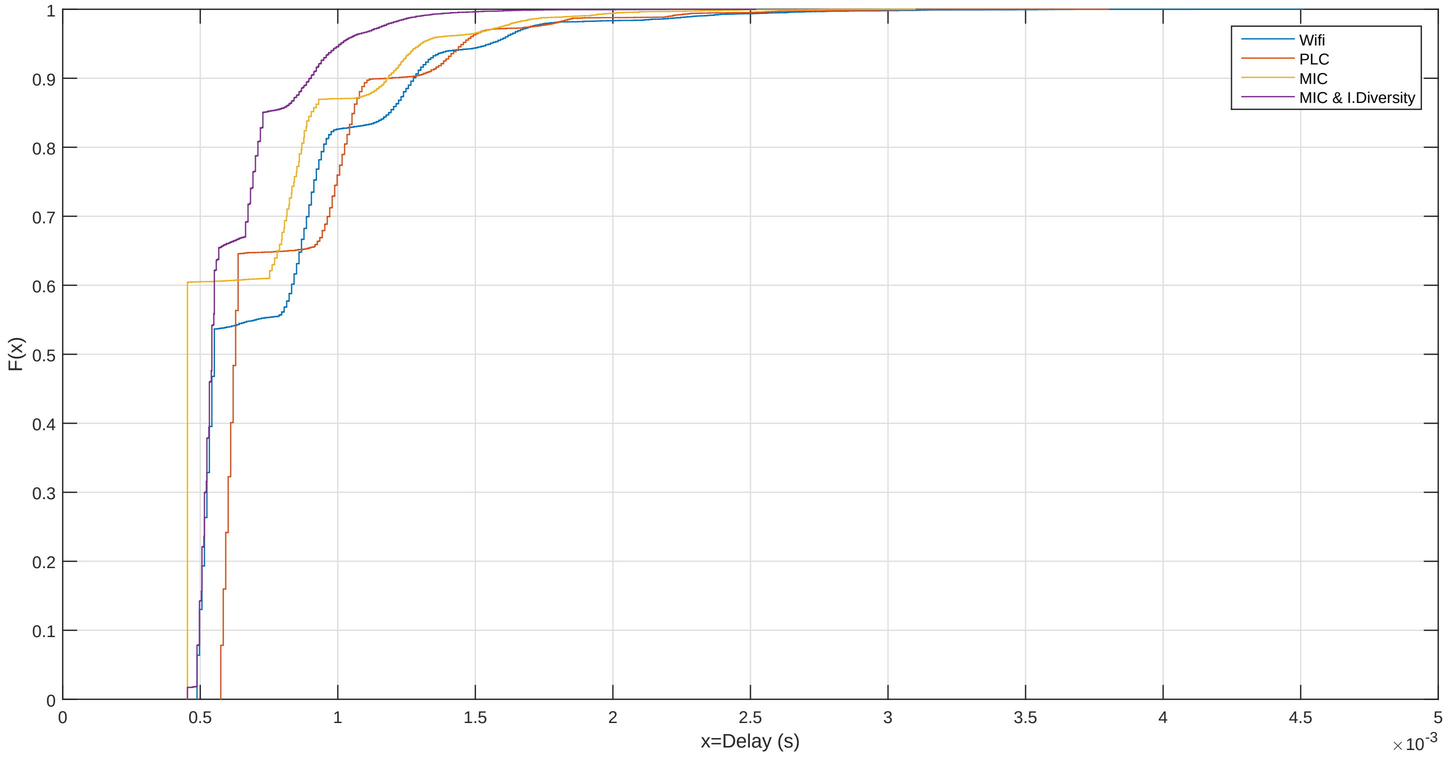

FIGURE 6.19: The Cumulative Distribution Functions for the 3 Node Scenario

Multihop Scenario with One Flow

In this part, a multi-hop scenario is simulated in OPNET. The network is in the form of Network Model 1 (Figure 6.3). Wifi channel capacity is 44 Mbit/s while the PLC channel capacity is 38 Mbit/s. The successful packet transmission probabilities for each link is given in Table 6.9 and Table 6.10. In this part, only one flow between the source and the destination nodes is considered. The resultant link statistics are given in Table 6.11. Also, the CDF graphs for this scenario is given in Figure 6.20.

Table 6.9: Wifi Probability of Success

	Source	Node 1	Node 2	Node 3	Node 4	Destination
Source	x	39.9/44	38.4/44	0	0	0
Node 1	39.9/44	x	35.8/44	34.0/44	0	0
Node 2	38.4/44	35.8/44	x	25.9/44	33.7/44	0
Node 3	0	34.0/44	25.9/44	x	35.3/44	38.0/44
Node 4	0	0	33.7/44	35.3/44	x	38.7/44
Destination	0	0	0	38.0/44	38.7/44	x

Table 6.10: PLC Probability of Success

	Source	Node 1	Node 2	Node 3	Node 4	Destination
Source	x	19.0/38	17.9/38	0	0	0
Node 1	19.0/38	x	17.0/38	11.0/38	5.5/38	0
Node 2	17.9/38	17.0/38	x	5.0/38	11.1/38	0
Node 3	0	11.0/38	5.0/38	x	16.8/38	18.0/38
Node 4	0	5.5/38	11.1/38	16.8/38	x	18.7/38
Destination	0	0	0	18.0/38	18.7/38	x

Table 6.11: Multihop Link Statistics

	Delay (10^{-6}s)	Loss (%) ($d > 0.002$)	Jitter (10^{-6}s)	Saturation Throughput (Mbit/s)
MIC	1000	1,81	337	17,6
I. Diversity&MIC	974	0,067	234	17,2

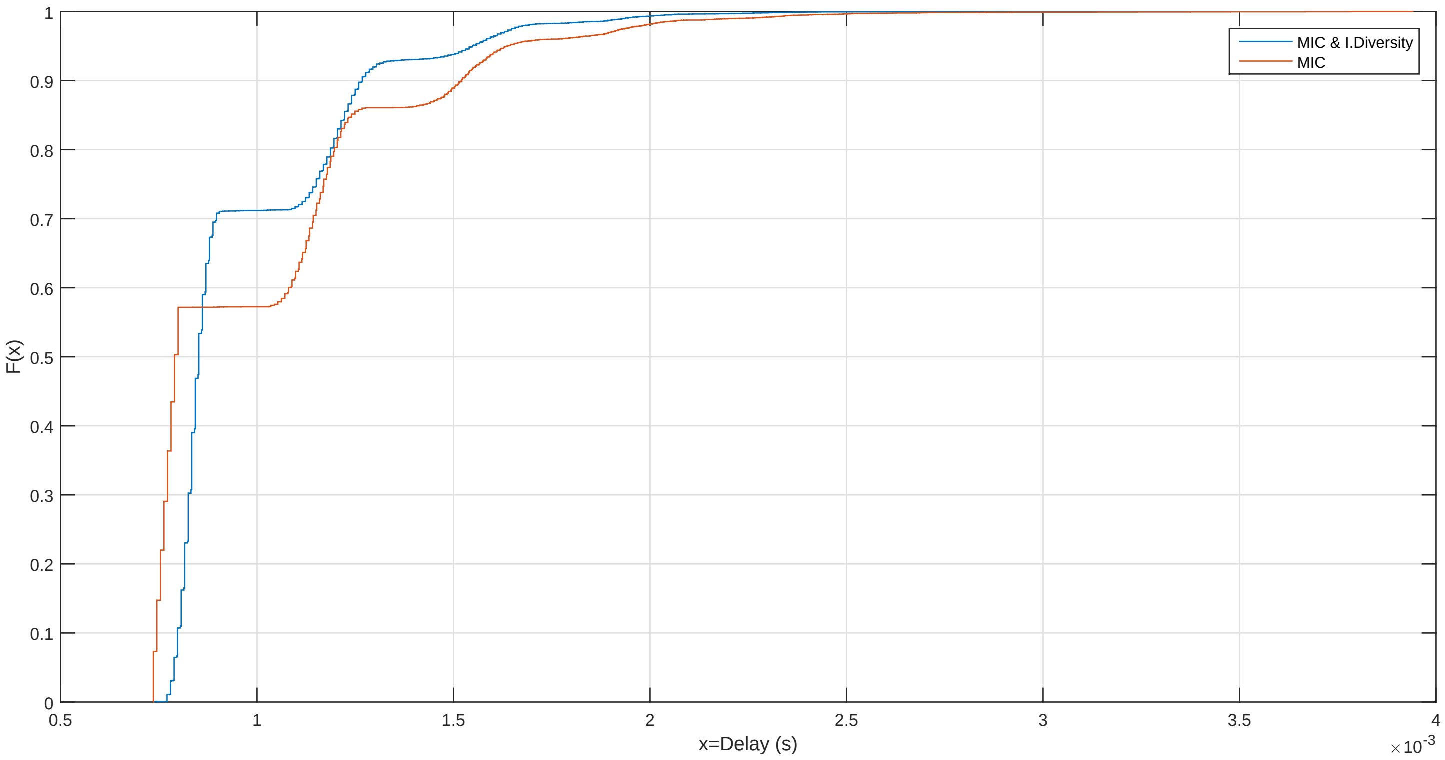

Figure 6.20: The Cumulative Distribution Functions of the One Flow Multinode Scenario

Multihop Scenario with Two Flows

In this section, a multi-hop scenario is simulated in OPNET and it is compared with the centralized solution obtained by Matlab. The network is in the form of Network Model 1 (Figure 6.3). Wifi channel capacity is 44 Mbit/s while the PLC channel capacity is 38 Mbit/s. The successful packet transmission probabilities for each link is given in Table 6.9 and Table 6.10.

Consider there are two independent flows going from source node to destination node. In Matlab, we solve the proportional fair maximization of these flows, while in OPNET we give saturated traffic to two different paths. The results are given in Table 6.12, Table 6.13 and Table 6.14.

	Throughput
First Flow	7.75
Second Flow	8.05

Table 6.12: OPNET Saturation Throughput(Mbit/s) Results without Interface Diversity

	Throughput
First Flow	8.1
Second Flow	8.6

Table 6.13: OPNET Saturation Throughput(Mbit/s) Results Considering Interface Diversity

	Throughput
First Flow	7.1
Second Flow	10.1

Table 6.14: Matlab Proportional Fairness Results Considering Interface Diversity

There are two important observations to highlight in these results. Firstly, Interface Diversity provides higher throughput. Table 6.13 contains higher results than Table 6.12. Secondly, the centralized Matlab solution gives a better result than the distributed MIC metric. Some of the reasons are given below:

- OPNET simulations consider Contention Window, which decreases the throughput. As the number of users increases, Contention Window tends to increase. The Matlab simulations ignore Contention Window.
- Interface Diversity is scheduled in Matlab with different ratios. However, in OPNET, Interface Diversity is implemented by auxillary links that have a lower priority in the network.
- Routing is handled considering Interface Diversity in Matlab. MIC metric, that is used in OPNET, does not consider Interface Diversity for routing.

The complete network statistics for the multinode scenario is given in Table 6.15 for the first flow and Table 6.16 for the second flow. Also, the cumulative distribution functions of the delay results are given in Table 6.21. Table 6.17 provides the deleted traffic.

In this scenario, using MIC without Interface Diversity provides better delay results. Because, the network contains a lot of intra-flow and inter-flow interferences. This network is not tolerant to Interface Diversity's bandwidth overhead. Similarly, on the centralized scenario, we observed that Interface Diversity is not used for highly interfered scenarios(Figure 6.5).

TABLE 6.15: Multihop Link Statistics for the First Flow

	Delay (10^{-6}s)	Loss (%) ($d > 0.003$)	Jitter (10^{-6}s)	Saturation Throughput (Mbit/s)
MIC	1239	0,36	492	7,79
I. Diversity&MIC	1501	1,23	563	8,10

TABLE 6.16: Multihop Link Statistics for the Second Flow

	Delay (10^{-6}s)	Loss (%) ($d > 0.003$)	Jitter (10^{-6}s)	Saturation Throughput (Mbit/s)
MIC	1261	0,64	517	8.05
I. Diversity&MIC	1514	1,51	562	8,60

TABLE 6.17: Interface Diversity Bandwidth Overhead for Multinode Scenario

	PLC($Mbit/s$)	PLC(Ratio)	Wifi($Mbit/s$)	Wifi(Ratio)
Saturation	11,2	% 40	1,1	% 3
5 Mbit traffic	4,1	% 27	5,9	% 21

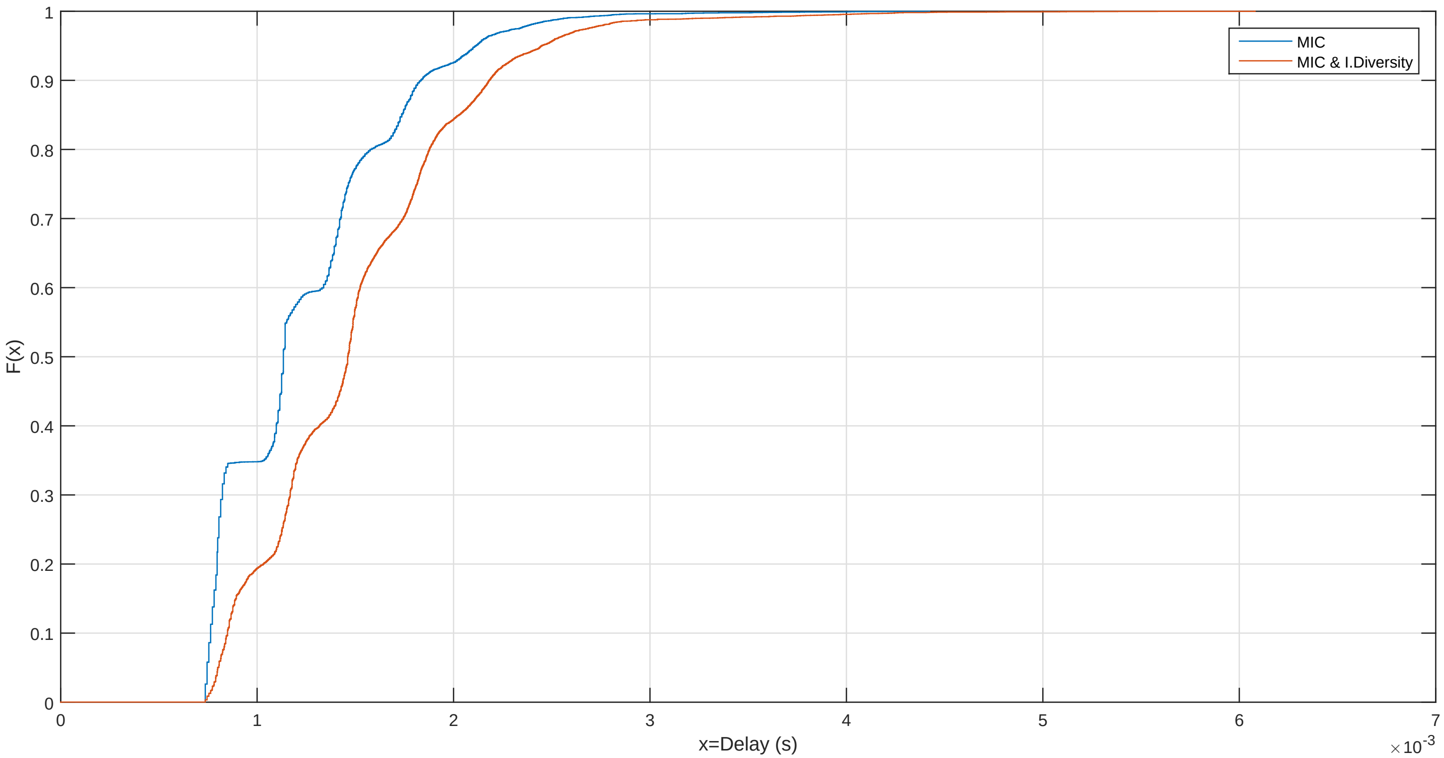

Figure 6.21: The Cumulative Distribution Functions for the First Flow of the Multinode Scenario

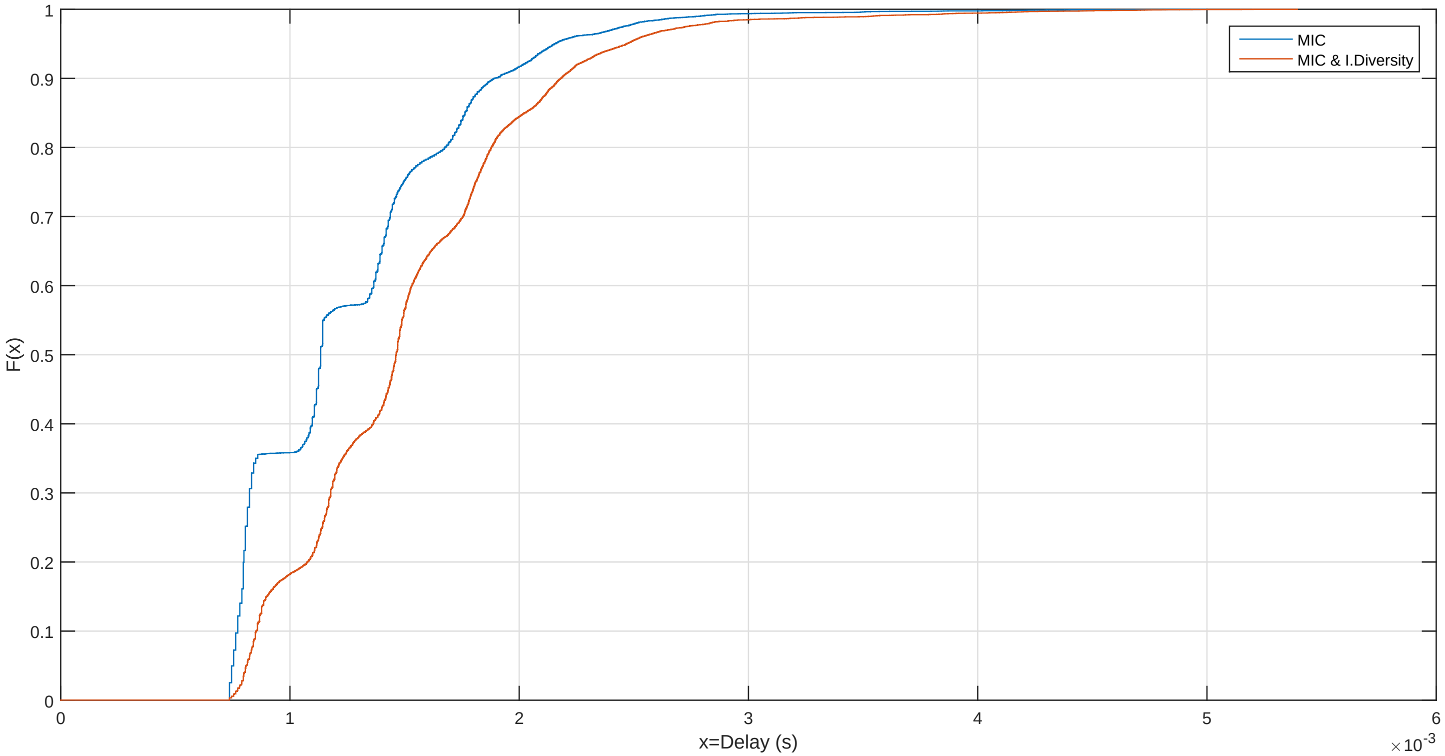

Figure 6.22: The Cumulative Distribution Functions for the Second Flow of the Multinode Scenario

6.2.5.2 Video Streaming Input

On the previous section, the traffic is generated using constant interarrival times. In a realistic scenario, the input rate of the video streaming applications is variable and dependent on the density of the action in the visual. In this section, we generated a realistic video input(Figure 6.23) and gathered the same network statistics for the aforementioned scenarios: 2 node, 3 node and multinode scenarios. The scenarios are similar to the ones in Section 6.2.5.1, except from the data input.

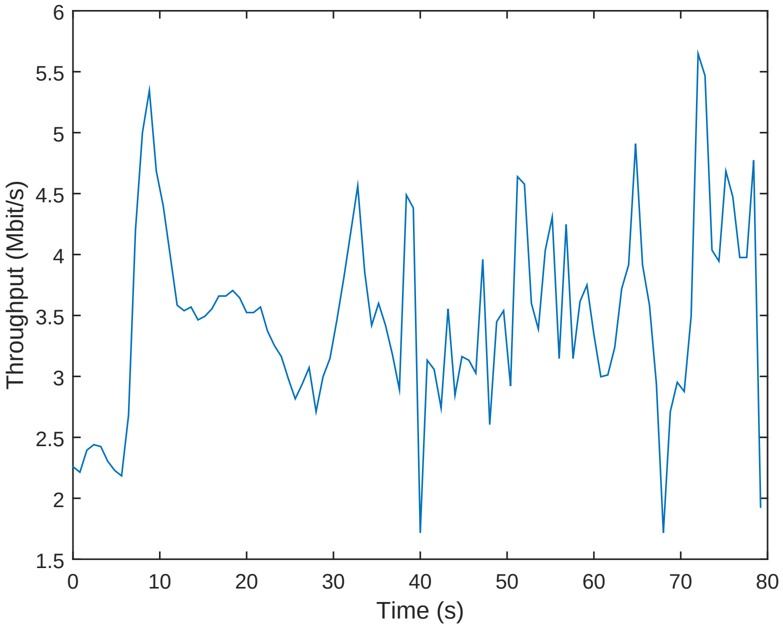

FIGURE 6.23: Transmission Rate for Video Application

Two Node Scenario

Table 6.18 provides the network statistics and Table 6.19 provides the cost of using Interface Diversity for the two node scenario with video streaming input. In addition, the CDF graphs for the delay results are given in Figure 6.24.

Interface Diversity achieves lower delay, jitter and loss values. The amount of PLC overhead is higher than the Wifi overhead. Because most of packets arrive on the wifi link earlier, since the wifi link has a higher transmission rate. Therefore, most of the PLC packets are deleted on the receiver side. The high value of overhead is not a big price for this scenario, since there is not any other connections that could be harmed in the network.

TABLE 6.18: Link Statistics of Two Node Video Transmission Scenario

	Delay (10^{-6}s)	Loss (%) ($d > 0.0013$)	Jitter (10^{-6}s)	Saturation Throughput (Mbit/s)
Wifi	331	1,13	204	30.8
PLC	344	0,64	161	29.1
I. Div.	234	0,004	51	32.1

TABLE 6.19: Interface Diversity Bandwidth Overhead for the Two Node Video Transmission Scenario

	PLC($Mbit/s$)	PLC(Ratio)	Wifi($Mbit/s$)	Wifi(Ratio)
Video Input	2.7	%77	0.7	%21

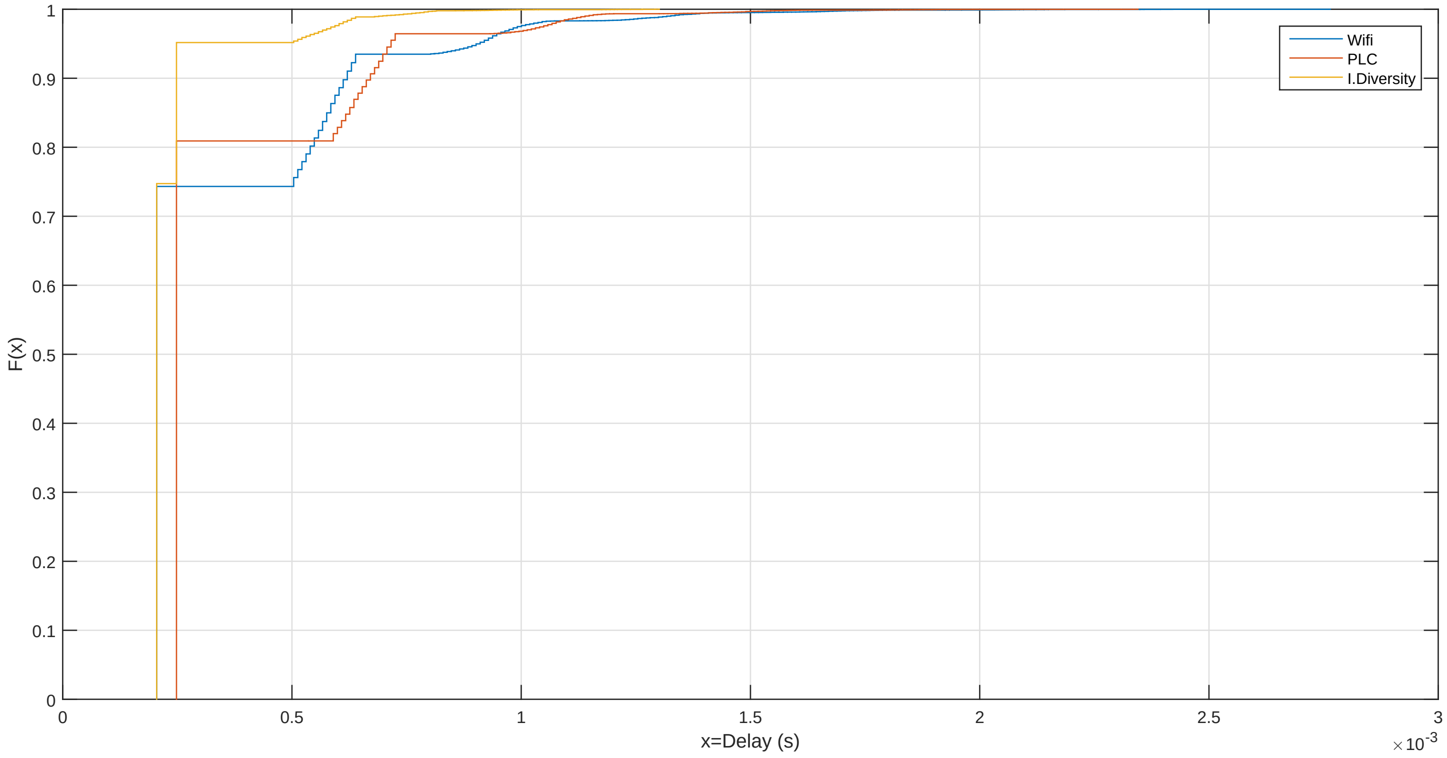

FIGURE 6.24: The Cumulative Distribution Functions for the 2 Node Scenario with Video Input

Three Node Scenario

Table 6.20 provides the network statistics and Table 6.21 provides the cost of using Interface Diversity for the 3 nodes scenario with video streaming input. Also, the CDF graphs for the delay results are given in Figure 6.20. The MIC metric achieves higher rate and lower delay compare to wifi and PLC homogeneous paths, since it provides a heterogeneous path. However, if Interface Diversity is used in addition to the MIC metric, the delay results of the network is better.

Table 6.20: Link Statistics of 3 Node Video Transmission Scenario

	Delay (10^{-6}s)	Loss (%) ($d > 0.0018$)	Jitter (10^{-6}s)	Saturation Throughput (Mbit/s)
Wifi	764	1,50	341	15,2
PLC	794	1,18	289	14,50
MIC	678	0,59	315	29,5
I. Diversity&MIC	610	0,03	150	25,0

Table 6.21: Interface Diversity Bandwidth Overhead for the 3 Node Video Transmission Scenario

	PLC($Mbit/s$)	PLC(Ratio)	Wifi($Mbit/s$)	Wifi(Ratio)
Video Input	5,5	%79	1,4	%25

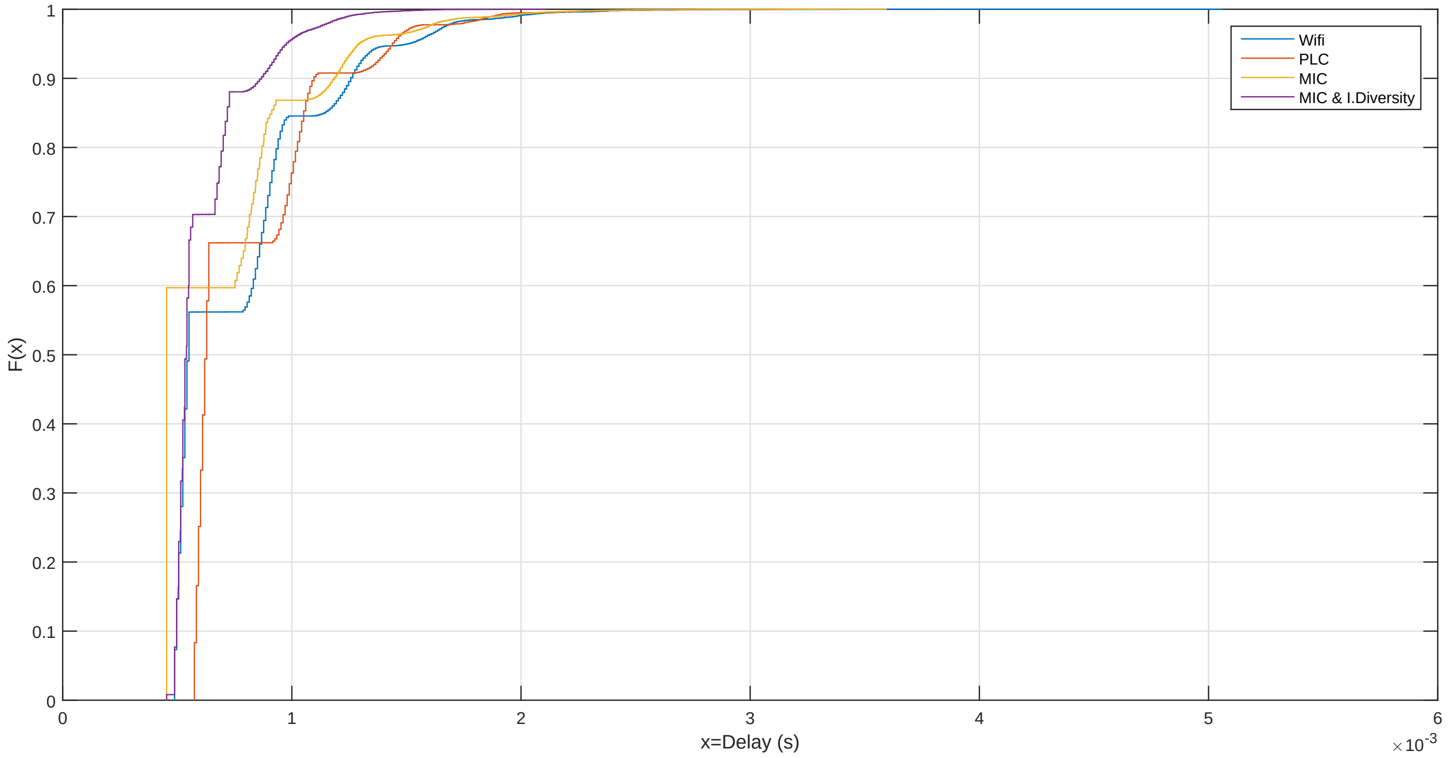

Figure 6.25: The Cumulative Distribution Functions for the 3 Node Scenario

Multinode Scenario with One Flow

Table 6.22 provides the network statistics. Also, the CDF graphs for the delay results are given in Figure 6.26.

The homogeneous paths results are not given in this part, since it is obvious that they would perform poorly. Interface Diversity provides better delay results. However, the use of Interface Diversity decreases the saturation throughput slightly. The reason of this decrease is the effect of auxillary links on the main links. Although the auxillary links contain lower priority assignments, they may still have a bad effect. This issue is discussed in Section 6.2.3.

TABLE 6.22: Multihop Link Statistics for the One Flow Multinode Scenario

	Delay (10^{-6}s)	Loss (%) ($d > 0.002$)	Jitter (10^{-6}s)	Saturation Throughput (Mbit/s)
MIC	1000	1,66	337	17,6
I. Diversity&MIC	975	0,048	236	17,2

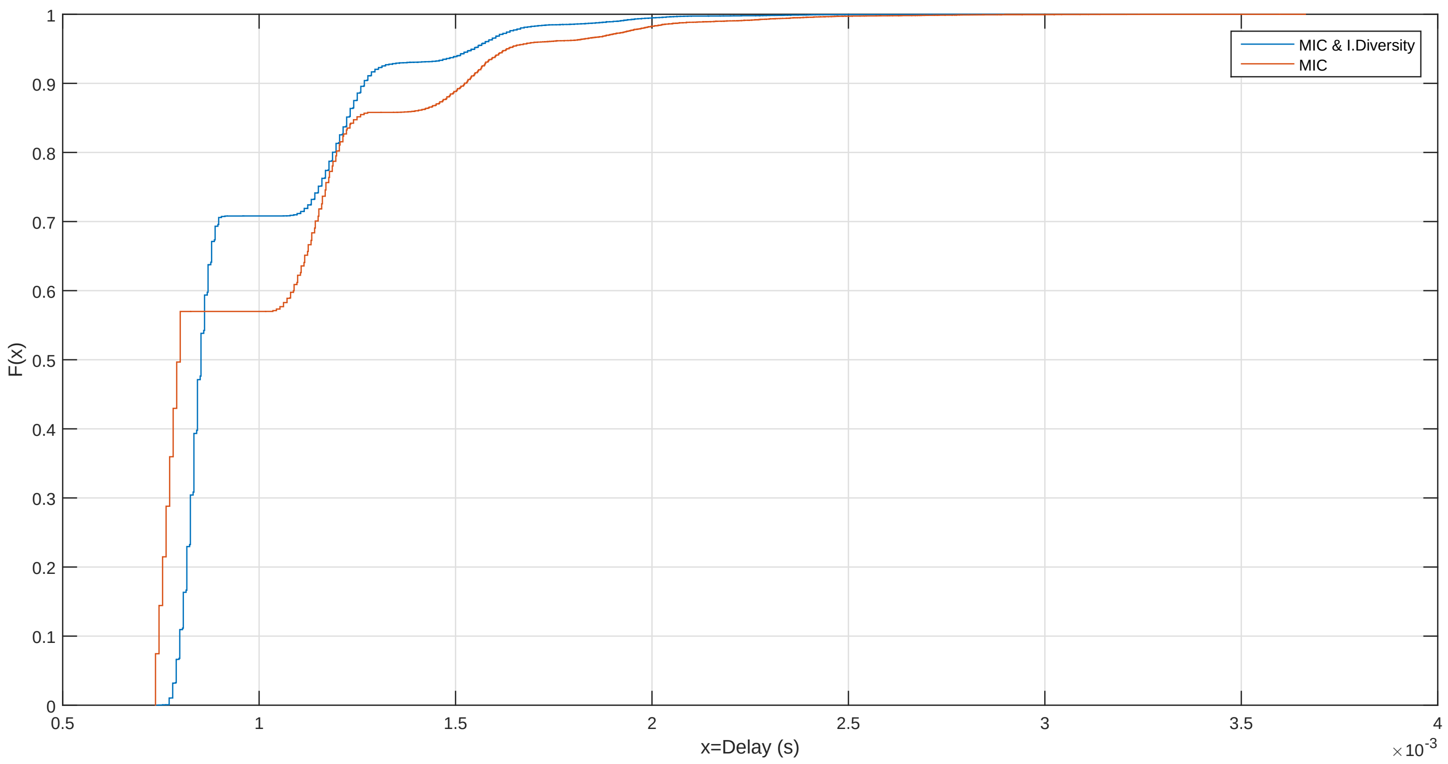

Figure 6.26: The Cumulative Distribution Functions of the One Flow Multinode Scenario

Multinode Scenario with Two Flows

Table 6.23 and Table 6.24 provide the network statistics for each flow respectively and Figure 6.25 provides the cost of using Interface Diversity for the multinode scenario with video streaming input. Also, the CDF graphs for the delay results are given in Figure 6.27 and Figure 6.28.

In this scenario, Interface Diversity gives worse delay results. Since this network contains 6 links all of which interfere with each other, the network is not tolerant to the overhead of Interface Diversity.

Table 6.23: Multihop Link Statistics for the First Flow of the Video Transmission Scenario

	Delay (10^{-6}s)	Loss (%) ($d > 0.003$)	Jitter (10^{-6}s)	Saturation Throughput (Mbit/s)
MIC	1211	0,55	495	7,79
I. Diversity&MIC	1292	0,98	468	8,10

Table 6.24: Multihop Link Statistics for the Second Flow of the Video Transmission Scenario

	Delay (10^{-6}s)	Loss (%) ($d > 0.003$)	Jitter (10^{-6}s)	Saturation Throughput (Mbit/s)
MIC	1275	0,56	477	8.05
I. Diversity&MIC	1341	0,92	454	8,60

Table 6.25: Interface Diversity Bandwidth Overhead for Multinode Video Transmission Scenario

	PLC($Mbit/s$)	PLC(Ratio)	Wifi($Mbit/s$)	Wifi(Ratio)
Video Input	4,1	%35	2,8	%16

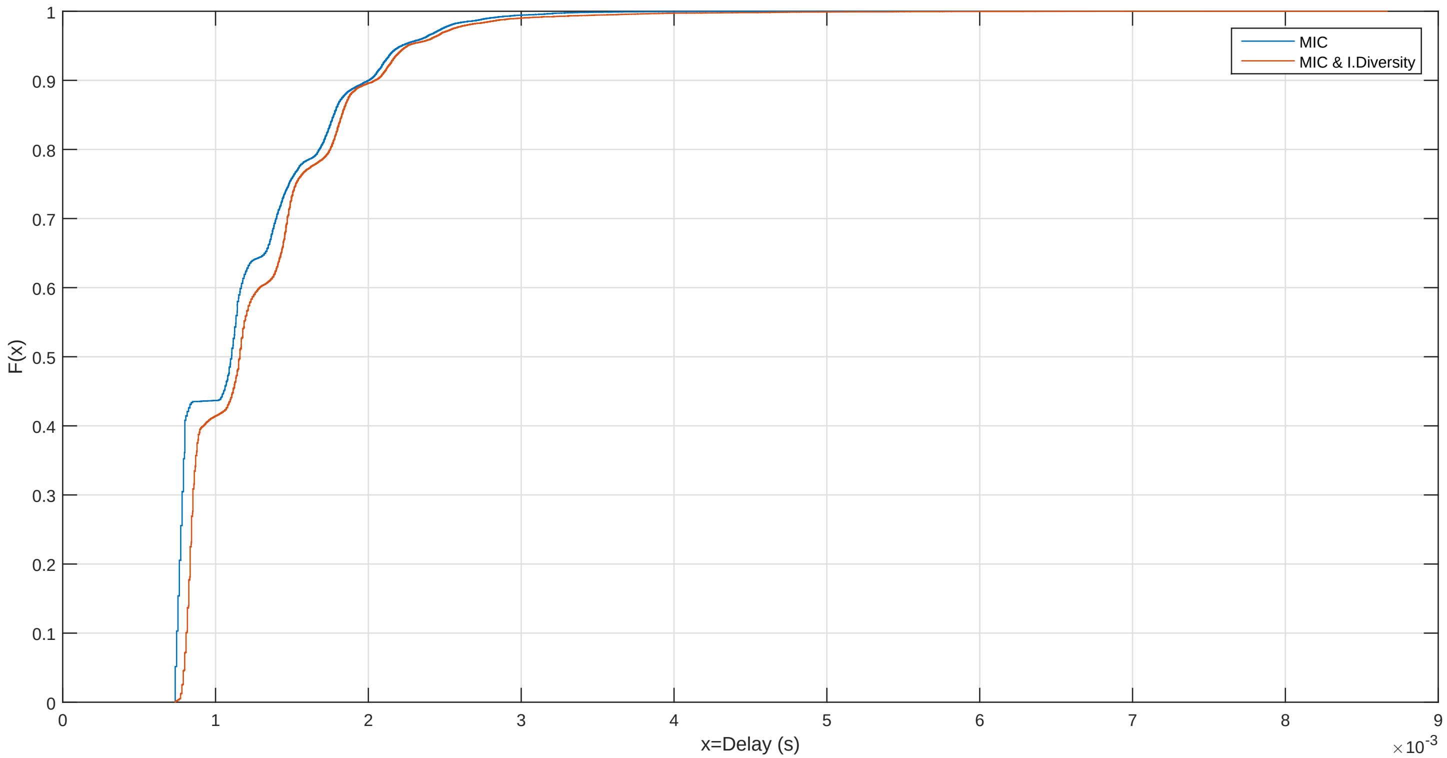

Figure 6.27: The Cumulative Distribution Functions of the First Flow for the Multinode Scenario with Video Input

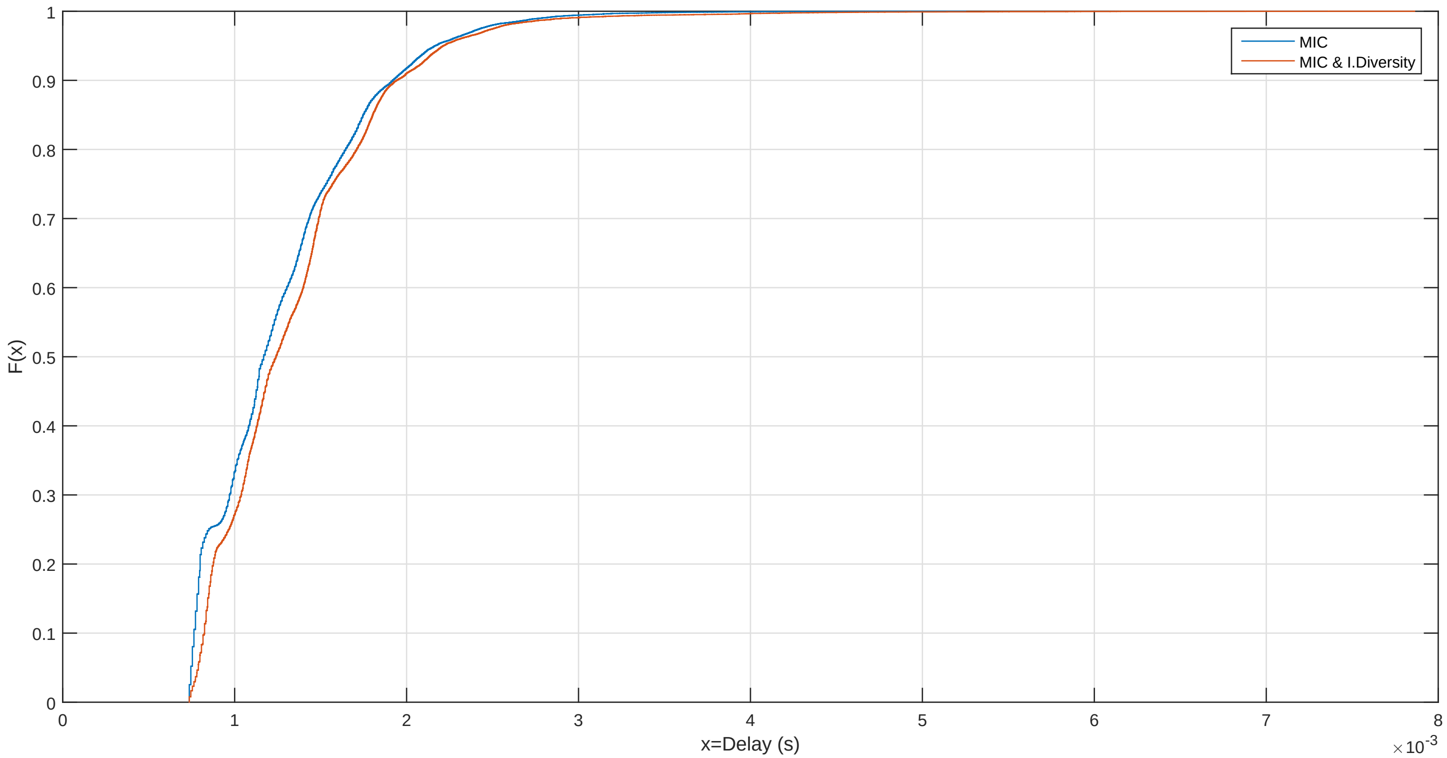

FIGURE 6.28: The Cumulative Distribution Functions of the Second Flow for the Multinode Scenario with Video Input

6.2.5.3 Video Quality Measurement

The QoE of video applications is mostly subjective. In other words, the quality of a video application depends on the observer's expectations. However, an objective quality evaluation is necessary in order to compare and develop different quality improvement techniques.

PSNR is one of the most commonly used objective video quality measurement method. 6.7 gives the PSNR formula of a set of video signal frames, where $V_{peak} = 2^k - 1$, k is the number of bits per pixel and RMSE is the mean square error of the Nth row and Nth column of sent and received video signal frame n.

$$PSNR(n)_{db} = 20log_{10}\left(\frac{V_{peak}}{RMSE}\right) \tag{6.7}$$

In [6], Calyam et.al. provide an offline video quality measurement technique which uses only the transmission parameters, bandwidth, delay, jitter and loss as input. Their proposal is developed using human subjects' rankings and performs close to the PSNR for H.263 and H264 video codecs. Since we are only interested in the transmission conditions and we ignore the encoding/streaming process, their offline video quality measurement technique is a good fit for our purposes.

We provided delay and saturation throughput improvement by using Interface Diversity before. This gives the intuition of video quality improvement. In this section, we present the video quality improvement quantatively by using streaming mean opinion score(S-MOS) developed in [6]. The S-MOS formula is given in 6.8. b_{net} denotes end-to-end network bandwidth, d_{net} denotes delay, j_{net} denotes jitter and l_{net} denotes loss.

$$\begin{aligned} q_{S-MOS} = &2.7048 + 0.0029b_{net} - 0.0024d_{net} - 1.4947l_{net} - 0.0150j_{net} + \\ &0.2918l_{net}^2 + 0.0001j_{net}^2 + 0.0004d_{net}l_{net} + 0.0055l_{net}j_{net} \end{aligned} \tag{6.8}$$

Consider there is a transmitter and a receiver in the network and they are connected with both Wifi and PLC interfaces. There is no interference in the network and 20 Mbit/s constant traffic is generated. The network statistics under these conditions are given in Table 6.26. The values on Table 6.26 are the mean values and they are obtained using OPNET simulations.

Table 6.26: Link Statistics

	Delay (10^{-6}s)	Loss (%)	Jitter (10^{-6}s)	Bandwidth(Mbps)	q_{S-MOS}
Wifi	432	0,807	186	65	190
PLC	457	0,861	161	54	158
I. Div.	307	0,003	100	65	191

Table 6.26 shows that Interface Diversity improves delay, loss and jitter; therefore it improves the video quality.

6.2.5.4 Comparison and Discussion

In Section 6.2.5, Interface Diversity is implemented to different scenarios by providing constant bit rates and video bit rates as input. Also, the effect of inter-flow interference is analysed for two node constant bit rate scenario. While the constant bit rate scenarios enlighten the characteristics of Interface Diversity, they are not comparable, since each of them implement different amount of input traffic. However, considering distributed and centralized results, it can be concluded that, Interface Diversity improves delay and jitter of the network, if there is not high amount of interference in the network.

In this section, we compare scenarios involving different number of nodes. In these scenarios, all of the nodes are connected in cascade. The neighbor nodes have 100 m between each other and all of the nodes interfere with each other. However, a path should contain all of the nodes in the network. Figure 6.23 is given as input. The delay and jitter of these scenarios are given in Figure 6.29 and Figure 6.30.

Figure 6.29 shows the effect of number of nodes on delays for both MIC and Interface Diversity. Figure 6.30 shows the effect of number of nodes on jitters for both MIC and Interface Diversity. Interface Diversity improves MIC's delay and jitter results for all of the scenarios.

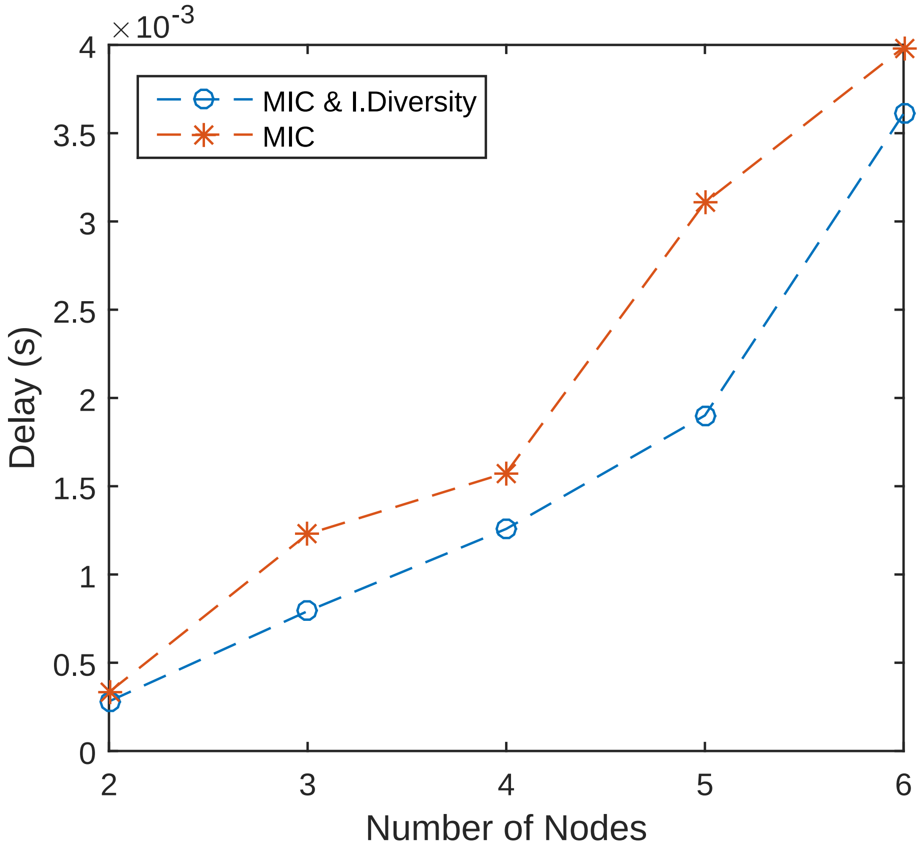

FIGURE 6.29: Delay Comparison

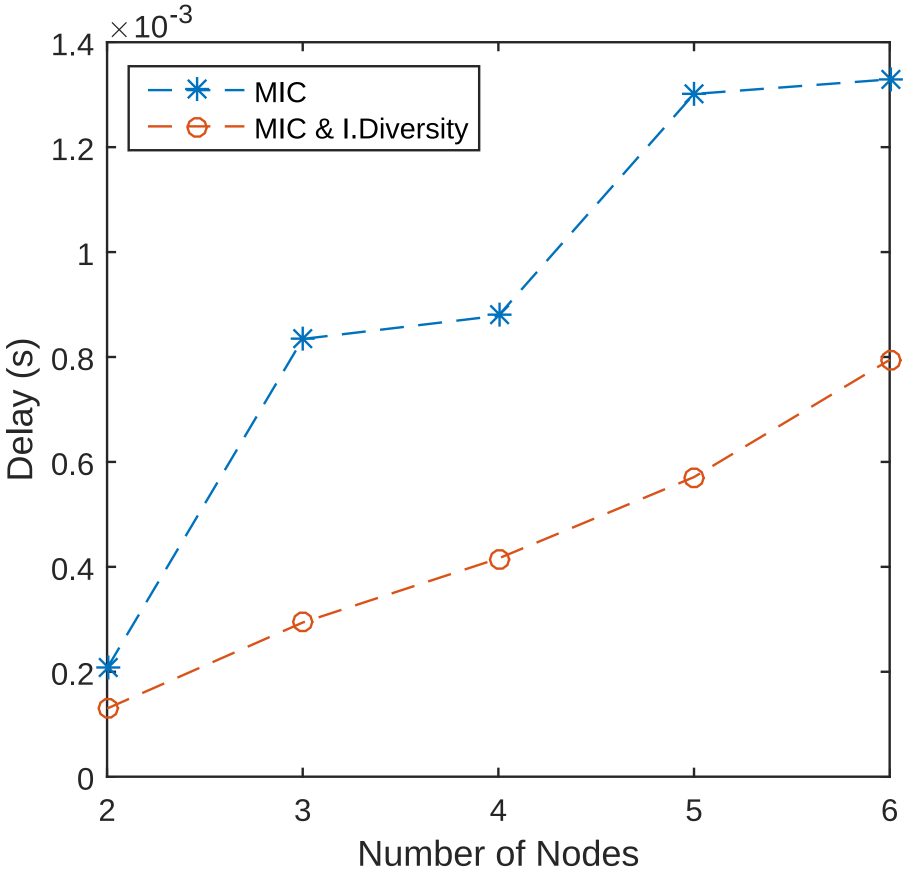

FIGURE 6.30: Jitter Comparison

Chapter 7

Conclusion

In this thesis, we proposed a new interface aggregation method, Interface Diversity, above the MAC layer for multi-radio multi-hop mesh networks. The Interface Diversity method has a similar approach with physical layer frequecny diversity method. Shortly, Interface Diversity provides the transmission of the same packets from the interfaces. Therefore, Interface Diversity provides full redundancy and improves saturation throughput and delay of the network. We benefit from the priority mechanizms of PLC and Wifi in order to implement Interface Diversity to the multi-hop networks. A well known routing metric(MIC) is used and developed in order to implement distributed routing with AODV. We formulated our problem and obtained a centralized solution. Then, using MIC metric and Interface Diversity we simulated distributed routing using OPNET. Both the centralized and distributed simulations show that Interface Diversity improves delay and saturation throughput of the network. Therefore, Interface Diversity improves the video streaming quality.

Implementation of Interface Diversity does not require a significant chance in the MAC layer. Also, there is no extra complexity introduced by Interface Diversity about packet reordering. Therefore, Interface Diversity is an easy to implement method for heterogeneous multi-hop mesh networks.

A future research topic may be using Interface Diversity and other channel aggregation method's considering application's demand. Interface Diversity provides a better QoE for video applications. Other applications, that prefer higher throughput rather than lower delay, may more benefit from other channel aggregation methods. Considering each application's demand and using more than one channel aggregation method may provide higher network performance.

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