Master Thesis

Transmission Scheduling in Wireless Meshed Networks

By

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Abstract

Wireless mesh networks (WMNs) can offer common and affordable broadband access to the Internet in metropolitan and residential areas. However, it suffers from the fairness problem due to the multi-hop characteristic and the throughput should also be improved by proper transmission scheduling. This thesis investigates and implements some state of the art link scheduling algorithms (TDMA based) to maximize the minimal (max-min) flow in WMN. The work can be divided in two main parts.

For the first part, a non-compact model which decomposes the max-min flow problem into a master problem and a sub-problem is studied. The compatible set, the links can be active simultaneously without violated SINR (signal to interference plus noise ratio) constraint, is used in the model of master problem. The compatible set is generated by the sub-problem. The optimal transmission scheduling will be defined by optimally dividing the total operation time to different compatible sets. Furthermore, the new technique of multiuser decoding which can identify and remove the strong interference is embedded to the model. Then, the numerical study shows the optimal transmission scheduling in several different network examples. It is also shown that the multiuser decoding can improve the max-min flow greatly.

For the second part, the simulator NS-2 is used to simulate practical mechanism for transmission scheduling based on IEEE 802.11 standards. The underlay medium access control protocol is detailed analyzed. The simulation results give the throughput for each mesh router. Compared with the optimal solution in the first part, the simulation results are shown less fairness.

In conclusion, this thesis studies and compares our defined TDMA and conventional CSMA/CA based transmission link scheduling mechanisms which may provide scientific basis for network operators to design WMN.

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CHAPTER 1

1 Introduction

1.1 WMN Basics

WMN nodes are comprised of mesh routers, gateways and mesh clients, each node can be a client or router with the capability of routing and forwarding packet. Mesh routers have minimal mobility and form the mesh backbone where mesh clients can be used also as mesh routers in WMN. Mesh clients are connected to WMN with either wireless interface card (NIC) or by connecting to routers through wired link. The gateway/bridge functionality in mesh routers enables usage of various current wireless networks such as cellular, wireless sensor, WIMAX, etc [1, 2].

WMN can be extended without any extra infrastructure compared to simple wireless node because all components are already available in the form of ad hoc network. The main difference is that WMN is multi-hop and as such can cover a larger area with less power. Such key features as high capacity, low cost, self-healing and self-organization make it easy to deploy and efficient in many applications such as broadband wireless Internet access, neighborhood and enterprise networking, transportation system, etc [2].

WMN consists of multiple gateways, for the consideration of robustness; there can be multiple routes for each node. If a node or a link breaks down or even with gateway failure, another route can be used (orphaned nodes will be connected to nearby gateways or routers) to provide access to the Internet. As a result, users will not lose their connectivity if their current connected routers or gateways are disabled.

Currently one challenge in WMN for researchers is providing better quality of services for client. A considerable number of improvements have been done in different network layers. There are also many industrial standard groups such as IEEE 802.11, IEEE 802.15, and IEEE 802.16 that are all actively working on new specifications for WMN [1, 2].

Figure 1 shows the architecture of a WMN with its different components. Careful observation of the architecture shows that mesh routers are usually static but mesh clients like laptops or phones can have movements.

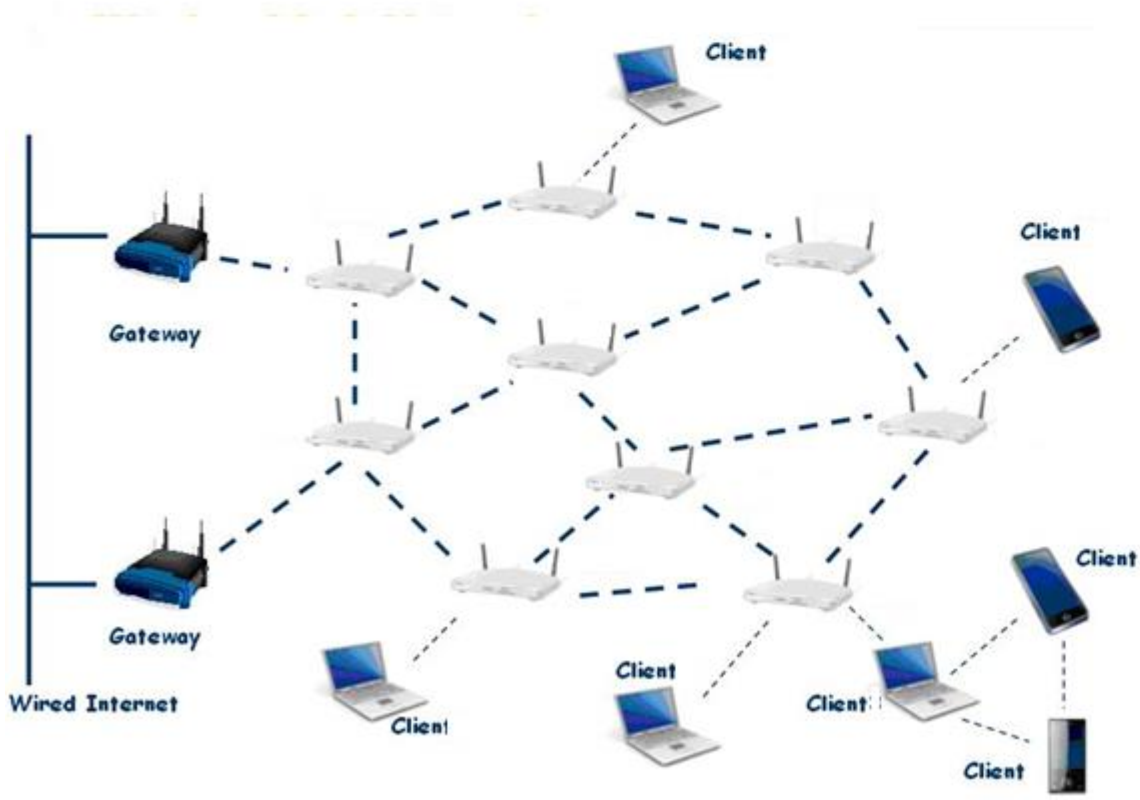


Figure 1. WMN structure

1.2 Problem Statement

The deficiency of transmission mechanism and scheduling in 802.11 standards has made challenge for researchers to overcome on drawbacks of persistence medium access control (MAC) protocol. There are several main disadvantages which must be addressed:

If many routers are going to send packet simultaneously or communicate with each other, the system bandwidth will degrade significantly due to CSMA/CA functionality. For example in a very simple scenario, assume that initially nodes A and B both choose a back off interval in range [0, 31], but their RTSs collide. The contention window will be double and in range [0, 63]. Suppose node A chooses 4 slots and B chooses 60 slots, after A transmits a packet it next chooses from range [0, 31] therefore it is possible that A may transmit several packets before B transmits its first packet. However there is a new MAC in 802.11e which is called hybrid coordination function (HCF) that increases the QOS and better transmission scheme with separate definition of access categories, but the problem still persists [4, 5, 6].

In the context of traffic engineering in WMN, the uncertainty in amount of traffic presents a big challenge because of characteristic persistency in this kind of network. Therefore traffic matrix representing demands to be routed between WMN routers and gateways are virtually unknown. In fact, the classic notation of traffic matrix is not well suited for WMN design as the sets of mesh clients are highly dynamic and their traffic requirement are almost impossible to be known [3].

As a wireless network, WMN also faces interference problem. Interference occurs since there are multiple active transmission links in a network. Therefore, it is necessary to avoid multiple access interference in an entire mesh network and supply coexistence of different links. In random access MAC protocols (CSMA\CA), nodes contend for the communication medium on mesh network to transmit data, hence data collision, namely multiple access interference is possible. In case of interference we face packet drops, although sometimes it may lead to complete link deactivation [6].

Achieving efficient and fair resource allocation in WMN is another issue, CSMA/CA is designed in a way that when collision happens, the involved nodes have to wait for random time and retransmit again. Also the nodes near to the gateway have high throughput while the nodes far away have very low throughput (some nodes may be starved). Therefore we need better link activation mechanism in our mesh network to cope with this problem.

1.3 Goals

This thesis studies the maximal min flow (max-min) problem in wireless mesh network by both theoretical analysis and practical simulations. We consider the down-link flow from the gateway to each router. Assuming that the routing path for each router is fixed; we try to maximize the minimal flow among all the flows for routers. In the theoretical part, we set up a non-compact model which includes a master problem and a pricing problem. A column generation method is implemented to solve the model. Extensive numerical studies have also been done to show the results. In the practical part, we simulate link scheduling based on CSMA/CA and get the practical throughput. In the end, several comparisons between different results are carried out [3].

In optimization models, both single user decoding and multi-user decoding are used. For single user decoding, the signal from active nodes except the respective transmitter is noise. However, the multi user decoding has capability of decoding the strong incoming signals from the active nodes, therefore it’s possible to cancel interferences and increase the throughput subsequently. For this purpose parallel interference cancellation is used.

With methods mentioned above we can define a new transmission mechanism based on mathematical optimization model which is the upper bound of MAC in 802.11 standards, although it can be useable in other kind of IEEE standards e.g. 802.15, 802.15, etc. The transmission mechanism that we present here is contention free like TDMA, however the results that we obtain from optimization part will be a total simulation time divided not equally by acquired compatible sets (is briefly set of active links that is explained later) which is somehow big amount, therefore it creates a problem to node activation and of course buffering limits in handover nodes. Our suggestion here is compatible sets time division on lots of time slots which is explained later.

1.4 Contribution

The reminder of thesis is organized as follows:

In Chapter 2 we briefly discuss about transmission scheduling with basic definition of optimization models implication to maximize the network traffic throughput, then we go further by presenting the assumption which is used in our research. Basic formulation and algorithms are introduced to compute active links in single user decoding receiver (SUD) with generic MIP framework. We also argue about interference cancellation plus its algorithm declaration. Last part of Chapter 2 is assigned to numerical studies and optimization results obtained by using optimizer software plus some comparison between different methods [3]. Channel modeling that is used for topologies in numerical studies part is also discussed.

In Chapter 3, we first discuss about predefined MAC protocols performance and their pros and cons briefly. Then we introduce the network simulator (NS2[16]) that is used and the results of simulation for some mesh topologies in 802.11 MAC standard. Some changes have done in the software core since it was almost impossible to simulate multi gateways mesh networks with static routing.

Chapter 4 is devoted to performance comparison between Chapters 2 and 3; we show detailed improvement in throughput and fairness. Optimization results defined couldn’t be used directly in transmission mechanism therefore some basic thoughts have been given on how this scheduling method is usable in real devices.

Chapter 5 presents concluding remarks and future work.

CHAPTER 2

2 Optimization

2.1 Optimization Model

In this Chapter we model wireless mesh networks through mixed-integer programming (MIP) and linear programming (LP) to solve the problem arising from transmission scheduling in WMNs. Here we define a general way of solving Max-Min flow allocation problem combined with WMN radio link modeling and a non-standard way of dealing with uncertain traffic. Moreover, column generation method for the considered MIP is presented [3].

Max-Min fairness (MMF) is applicable in situations where it is desirable to achieve an equal distribution of certain resources, shared by competing demands. Assume that there are 4 demands with this amount {4,6,8,8} and resource available is 18, it appears 18/4=4.5 to be reasonable but demand 1 only need 4 so assigned resources according to MMF will be {4,4.66,4.66,4.66}[8].

The MMF situation here is assigned to traffic throughput and we call it Max-Min flow allocation. The throughput is a bandwidth vector assigned to all down streams. In WMN, demands are elastic and the mesh clients will use assigned bandwidth as much as they can since the gateway conveys unpredictable amount of internet traffic generated by voice, video and other applications. Also the traffic uncertainty persists in end to end information flow as mesh client are traveling dynamically. This is a big problem in WMN because nodes which are closer to gateways are acquiring more available resources. We assume that the route is fixed for each normal node (not gateway). In the other words, nodes are competing for link capacities and optimization algorithm's objective is maximizing flow or network traffic equally. In our optimization models we are using MIP and LP formulation to precisely characterize the transmission scheduling [3].

Over the past few years, the research in WMN has attracted lots of attentions including transmission scheduling, channel assignment, transmission power adjustment and rate adaptation. We consider maximizing the minimal flow by properly designing transmission scheduling. The problem is formulated as mixed integer programming model with the concept of compatible set. A compatible set is a set of links which can be active simultaneously within a tolerable interference. In the optimal solution, each compatible set is given certain time to be active, that is, the links in this compatible set can be active for such time [3, 12]. Due to interference, it's impossible for all nodes to be active concurrently, therefore the way of scheduling links should be optimized which is the main task of this thesis.

2.2 Topology Assumption

The WMN topology is modeled by the set of nodes V,v $\in V$, consisting of gateways and routers and the set of links E, $e \in E$. $e \in E$. The originating node of link e $a(e)$ is the transmitter while $b(e)$, the terminal node of link e is the receiver. When we have something like $e = vw, v, w \in V$ it means there is a link between node v and w and $a(e) = v, b(e) = w$. We assume that if $vw \in E$ then $wv \in E$, so link e'=wv will be opposite of arc vw. Set of links outgoing from and incoming to node v will be represented as $\delta^+(v) and\ \delta^-(v)$ respectively. Therefore set of all the links incident to node v is defined as $\delta(v) = \delta^+(v) \cup \delta^-(v)$. Quantities that we use here are in linear scale (mw) or logarithmic scale (dBm unit) [9, 3].

We assume p_{vw} is the transmitting power from node v to node w (we can also represent it in dBm scale with $\hat{p}_{vw}$). In numerical studies of this thesis we assume the case of 802.11 WMNs operating with an OFDM PHY in 5 GHZ bandwidth.

We also assume that the power is the same for all transmitters which is 100 mw or in logarithmic scale 20 dBm. First of all, the transmission power for 10 meter distance is calculated and then according to log distance path loss model total received power is being calculated [9].

$$p_{vw}\ (d) \propto (\frac{d}{d_0})^n \quad \text{Or} \quad p_{vw}\ (db) = pl_{vw}\ (d_0) + 10\ n\ \log(\frac{d_{vw}}{d_0}) \qquad (1)$$

In formulation above "n" is path loss exponent, "d_0" is initial distance and "d or d_{vw}" is the distance between transmitter and receiver.

We use path loss exponent 4 in our numerical studies. For simplicity formulation below [10] is used instead of using (1).

$$\hat{p}_{vw} = \hat{p} + \hat{G}_{vw} = \hat{p} - 140 - 40\log(dvw) \qquad (2)$$

where d_{vw} is distance in km.

Noise power density mentioned is calculated through "KTB". Where K is Boltzmann constant equal to $1.38 * 10^{-23}\ \frac{ws}{k}$, T is room temperature that is 20 centigrade or 290 K and B is bandwidth which is 20 MHZ. Therefore noise power density is equal to N=$10^{-10.1} mw$ or in dBm= -101.

According to [10] we can use Table 1 which shows different modulation coding schemes (MCSs) in this thesis although here only single modulation coding scheme is used. In fact, the MCS is link dependent ($M_e \subseteq M, e \subseteq E$) and not all of them could be used because of distance limitation. SINR given in the Table is lowest signal to interference noise that each active link should be satisfied with.

Table 1. 802.11a MCS

MCS	Raw bit rate (Mbps)	SINR threshold (dB)	Max distance (m)
BPSK 1/2	6	3.5	273.5
BPSK 3/4	9	6.5	230.0
QPSK 1/2	12	6.6	22.8
QPSK 3/4	18	9.5	193.7
16-QAM 1/2	24	12.8	160.2
16-QAM 3/4	36	16.2	131.7
64 QAM 3/4	48	20.3	103.8

If we just consider environmental noise, a link can be active if it satisfies SNR constraint.

SNR: $\frac{p_{vw}}{N} = \Gamma'$, $SNR \geq \gamma$ (3)

γ SINR threshold

In WMN and other wireless networks, there will be interference from other devices that are working simultaneously. For each link to be active in our scenario we will define new formula as SINR that is below:

SINR: $\Gamma = \frac{p_{vw}}{N+\sum_{a\in A\{v\}} p_{aw}} = \frac{p_{vw}}{N+I_{vw}}$ (4)

where A is set of active links, $A \subseteq V$. For activation of node vw, we should have

$\Gamma \geq \gamma$ (5)

We have $\Gamma = \Gamma'$ when interference is equal to zero.

2.3 *Optimal Link Activation*

One of the most fundamental problems in wireless engineering is optimizing the set of links that can be active simultaneously to improve the capacity. Such link activation (LA) problem plays a very important role in transmission scheduling and cross layer resource management. It's also important in other aspects such as rate adaptation, power control and routing in ad-hoc and WMNs. The transmission scheduling can be realized by assigning time slots to different link subsets, each of whom corresponds to a link activation problem. Therefore, solving the LA problem becomes the dominant part. In link activation problem, each link is associated with a nonnegative weight and the objective is to maximize that total weight [6].

This Section consists of two main parts; one is single user decoding where we assume receiver has the ability of detecting only one signal and interference from other active nodes will be treated as additive noise. The other one is the multi-user decoding where there is one receiver on each node having the capability of interference cancellation or in other words, cancellation of interference from other active nodes. Consider that interference is being structured from encoded data and can be decoded. [6].

One important assumption is that the modulation and coding scheme we apply here is always constant or, in other words, we are using single MCS.

2.3.1 Single User Decoding

With link activation in single user decoding (SUD), interference from other devices will be treated as additive noise in denominator of SINR. With SUD, scheduling accounts to optimal spatial reuse of time resources. Therefore, scheduling problem considered in this thesis is also referred as spatial time division multiple accesses (STDMA) [12].

2.3.1.1 LA-SUD Formulation

This subsection describes optimal link activation with single user decoding. To achieve this purpose, we introduce mixed integer programming as below.

$$max \sum_{e} y_e \quad , e \in \varepsilon \tag{6}$$

(6): the objective function is maximizing the total number of active links.

$$\sum_{e \in \delta(v)} y_e \leq 1 , v \in V \tag{7}$$

(7): at most one link "e" incident to node "v" can be active or in other words, only one link can be active at each node.

$$\sum_{e \in \delta^{+}(v)} y_e = x_v , v \in V \tag{8}$$

(8): node is active only if its corresponding link is active and going out of it.

$$\frac{p_{a(e)b(e)}}{N + \sum_{v \in V \setminus \{a(e)\}} p_{vb(e)}} \geq \gamma_e , e \in \varepsilon \tag{9}$$

(9): link e can be active if its signal to interference noise ratio is bigger than special threshold defined for that link.

$$\frac{p_{a(e)b(e)}\ y_e}{N + \sum_{v \in V \setminus \{a(e)\}} \ p_{vb(e)} x_v} \geq y_e \gamma_e, e \in \varepsilon \tag{10}$$

(10): we multiply y_e on both side of equation so it will be considered only when link y_e is active, also in dominator of this SINR we are multiplying x_v to interference part that means only interference from active node is considered.

Inequality (10) should be changed in form of two different formulations since it is not linear.

Formulation (10) can be made linear by introducing new variable z_{ev} (first method) which is product of y_e, x_v.

$$z_{ev} \geq y_e + x_v - 1, v \in V, e \in \varepsilon \tag{11}$$

$$z_{ev} \leq y_e, z_{ev} \leq x_v, v \in V, e \in \varepsilon \tag{12}$$

$$z_{ev} \geq 0, v \in V, e \in \varepsilon \tag{13}$$

$$N + \sum_{v \in V \setminus \{a(e)\}} \ p_{vb(e)} z_{ev} \leq \frac{1}{\gamma_e} p_{a(e)b(e)} \ y_e \ ., e \in \varepsilon \tag{14}$$

(15): is the second method. We use big M notation, although there will be no difference in results between using z_{ev} and big M notation.

(16): gives the value of M.

$$\frac{p_{a(e)b(e)} + M_e(1 - y_e)}{N + \sum_{v \in V \setminus \{a(e)\}} \ p_{vb(e)} x_v} \geq \gamma_e, e \in \varepsilon \tag{15}$$

$$M_e = \sum_{v \in V \setminus \{a(e)\}} p_{vb(e)} \gamma_e + N\gamma_e - p_{a(e)b(e)}, e \in \varepsilon \tag{16}$$

Equation (17) has been introduced in [6]. We can use y_f or link multiplication instead of x_v multiplication, although results are the same, but this definition will be easier to implement.

$$\frac{p_{a(e)b(e)} + M_e(1-y_e)}{N+\sum_{f\in\varepsilon\setminus\{e\}} p_{a(f)b(e)}y_f} \geq \gamma_e \quad e,f \in \varepsilon \tag{17}$$

$$M_e = \sum_{f\neq e} p_{a(f)b(e)}\gamma_e + N\gamma_e - p_{a(e)b(e)}, e,f \in \varepsilon \tag{18}$$

2.3.2 Multiuser Decoding

As mentioned before, with multiuser decoding, we are able to remove strong interference signals, and then we can have more links simultaneously. Based on this assumption, links that are close to each other are more likely to be active, so it boosts the performance of wireless network. To fulfill this purpose, we use parallel interference cancelation (PIC) since it is simple and also instructive [6].

In this method receivers first decode interference signals and then remove the decoded signals from interested received signal. For IC to take place, a receiver plays the rule of intended receiver of interference signal, so it's possible to decode interfering signal since receiver has information of interfering signal. The strong interfering signal can be decoded if it has enough power against other signals, in other words "interference-to-signal-of-interest-and-noise" ratio must meet the SINR threshold of the interfering signal [6].

Multiuser decoding (MUD) has not been implemented in practical systems. To realize this mechanism, transmitters must be synchronized in time and frequency and receivers must estimate the channel between themselves and all other transmitters. In our simulations we assume that MUD is implemented perfectly. This means that the node has the capability of decoding strong interference.

MUD and specially IC has been growing up through fundamental studies of the so-called interference channel, which accurately models the physical-layer interactions of the transmissions on coupled. Two basic findings, regarding optimal treatment of interference in the two-link case, can be summarized as follows. One is where interference is very low and can be treated as additive noise and the other one is where interference is powerful so can be decoded and subtracted from interested signal [6].

We could look at MUD from another point of view. If the interference is strong enough to be decoded, that is $\log_2(1 + \frac{p_I}{p_s+n}) \geq R_I \Leftrightarrow \frac{p_I}{p_s+n} \geq \gamma_I$ (where$\gamma_I = 2^{R_I} - 1$, S signal of interest with power p_s, I is interference with power p_I and encoded rate R_I). I decoded and removed from received signal X (where X=S+I+N), therefore we have $\log_2(1 + \frac{p_s}{n}) \geq R_s \Leftrightarrow \frac{p_s}{n} \geq \gamma_s$ (where $\gamma_s = 2^{R_s} - 1$), but when interference isn't strong enough we have $\frac{p_s}{n+p_I} \geq \gamma_s$. Although in these equations we deal with one interfering signal but they can be extended to more interfering links and each receiver that can do IC successfully [6].

As mentioned before, for IC we deal with PIC that will be explained in upcoming subsection but here we also explain briefly Successive Interference Cancellation (SIC). In SIC, each receiver detects one interfering link if it is much stronger than signal of interest and noise, and afterward it will remove it from received signal. This procedure will be continued till there is no interfering link with above mentioned characteristic. From optimization standpoint, SIC is not straightforward to be implemented since the order of cancellation is important.

Note that single link (IC) is limitation of PIC that will allow only one cancellation per receiver by adding one more constraint. We should use this formulation in case that our receiver has capability of decoding two signals (one interest, one interference). Moreover in our simulations we assume that constant link rate and transmission power are the same for all nodes.

2.3.2.1 LA-PIC Formulation

In this Section the basic formulations for PIC and afterward correspondence MIP for link activation is presented.

$$\frac{p_{a(f)\,b(e)}}{N + \sum_{g \in A \setminus \{f\}} \; p_{a(g)\,b(e)}} \geq \gamma_f, e \in A, f \in c_e \tag{19}$$

(19): the interference from node a(f) to node b(e) can be cancelled by node b(e) if the power of such interference is strong enough to full fill the inequality.
In (19), A is active link set, A$\in \varepsilon$ and $c_e \subseteq A \setminus \{e\}$ is the cancelled transmission for each e $\in$A, Consequently, in this model, the strong interference is better [6].

$$\frac{p_{a(e)\,b(e)}}{N + \sum_{f \in A \setminus [\{e\} \cup c_e]} \; p_{a(f)\,b(e)}} \geq \gamma_e, e \in A \tag{20}$$

(20): the new SINR constraint considering the cancellation. In the denominator of (21), the strong interference caused by transmissions in set Ce is removed.

Now we present MIP model for link activation based on PIC.

$$y_{fe} = \begin{cases} 1 \\ 0 \end{cases} e \in \varepsilon, f \in \varepsilon \tag{21}$$

$$y_e = \{0,1\}, e \in A \tag{22}$$

(21), (22): y_{fe} is binary variable. 1 means that link f can be cancelled by link e and 0 otherwise. y_e is also binary variable. 1 means that link e is active and 0 otherwise.

$$max \sum_e y_e \quad , e \in \varepsilon \tag{23}$$

$$\sum_{e \in \delta(v)} y_e \leq 1, v \in V \tag{24}$$

$$y_{fe} \leq y_e, e \in \varepsilon, f \in \varepsilon, f \neq e \tag{25}$$

(25): Link fe can be cancelled only when link e is active.

$$y_{fe} \leq y_f, e \in \varepsilon, f \in \varepsilon, f \neq e \tag{26}$$

(26): Link fe can be cancelled only when link e is active.

$$\frac{p_{a(e)b(e)} + M_e(1 - y_e)}{N + \sum_{f \in \varepsilon \backslash \{e\}} p_{a(f)b(e)}(y_e - y_{fe})} \geq \gamma_e, \; e \in \varepsilon \tag{27}$$

(27): SINR requirement for signal of interest, Note that link f is subtracted from denominator if y_{fe} equals to 1.

$$M_e = \sum_{f \neq e} p_{a(f)b(e)} \gamma_e + N\gamma_e - p_{a(e)b(e)} \quad e \in \varepsilon \tag{28}$$

(28): M_e is large enough, so if y_e is zero, constraint (28) will be always satisfied.

$$\frac{p_{a(f)b(e)} + M_{fe}(1 - y_{fe})}{N + \sum_{g \in \varepsilon \backslash \{f\}} p_{a(g)b(e)}(y_e - y_{fe})} \geq \gamma_f \quad e, f \in \varepsilon, f \neq e \tag{29}$$

(29): checking whether link f can be cancelled. Setting y_{fe} to be zero is always feasible.

$$M_{fe} = \sum_{g \neq e} p_{a(g)b(e)} \gamma_f + N\gamma_f - p_{a(f)b(e)} \quad e, f \in \varepsilon, f \neq e \tag{30}$$

(30): M_{fe} is large enough, when y_{fe} is zero, constraint (29) will be always satisfied.

2.4 Max-Min Flow Allocation Formulas

In this Section we formulate general max-min flow allocation optimization problem. We assume the link capacity reservation variables c= $(c_e : e \in \varepsilon)$ belongs to feasible set c $\subseteq |R|^{|\varepsilon|}$, the set c will be defined as multiplication of each link data rate to its assigned time. Let n= $\{n_1, n_2, n_3, .. n_e\}$ be given the number of routs going through each link. Multiplication $n_e f$ is called load of link. As mentioned in introduction we use independent or compatible set which defined as a subset ε of links $(\varepsilon_i \subseteq \varepsilon)$ that can transmit simultaneously without generating too much interference with each other. In other words, compatible set is defined by ε_i= $\{ e \in \varepsilon; y_e$=1$\}$ for any set of feasible link variable $y_e, e \in \varepsilon$, we call subset C as compatible set C_i , $i \in I, (where\ I = \{1,2, ..., I\})$. I is the given list of compatible sets and z_i denote the time duration which the C_i is actually used, $\sum_{i \in I} z_i = T$. The total amount of data that can be sent over link e during time T is equal to $\sum_{i \in I} z_i B_{ei} = c_e$, where B_{ei}=B if e$\in C_i$, and B_{ei}=0 if not e$\in C_i$, B_{ei} is rate allocated to link $e \in \varepsilon$ in compatible set $i \in I$ [12, 8].

2.4.1 Max-Min Flow Allocation Problem

For the given set of compatible sets C_i , $i \in I$, we formulate optimizing throughput with maximizing the minimum traffic flow on a route and fairness objective below. Let's call this master problem (MP) [6]:

$$n_e f \leq c_e, e \in \varepsilon \tag{32}$$

$$[\propto] \sum_{i \in I} z_i = T \ , z_i \geq 0, i \in I \tag{33}$$

(33): divide the total time T of network between operating sets C_i , $i \in I$

$$c_e = \sum_{i \in I} z_i B_{ei} \quad e \in \varepsilon, i \in I \tag{34}$$

$$[\Pi_e] n_e f \leq \sum_{i \in I} z_i B_{ei} , e \in \varepsilon, i \in I \tag{35}$$

(34), (35): guarantee that the total amount of data sent over arc e doesn't exceed the capacity

The entity shown in bracket denotes dual variable.

Let Π_e^* be an optimal solution of dual problem. A compatible set is generated by solving the following problem. Let's call formulation after this part as compatible set generation (CSG).

$$max \sum_e y_e \Pi_e^* \quad , e \in \varepsilon \tag{36}$$

Here we should provide MIP formulation of one analyzed LA, for example constraints (7), (8), (16), (17) can be replaced here again.

The procedure for solving the considered problem is as follows:

Step 1: given an initial list of compatible set (although initial compatible set can be all zero which means all links are in non-active mode).

Step 2: solve the master problem and get Π_e^*.

Step 3: solve CSG to get a series of new active links (new compatible set).

Step 4: add the new compatible set to the master problem and solve it again.
If multiplication of Π^* with the current compatible set and previous ones is smaller than objective of CSG we add new CS. Otherwise it stops.

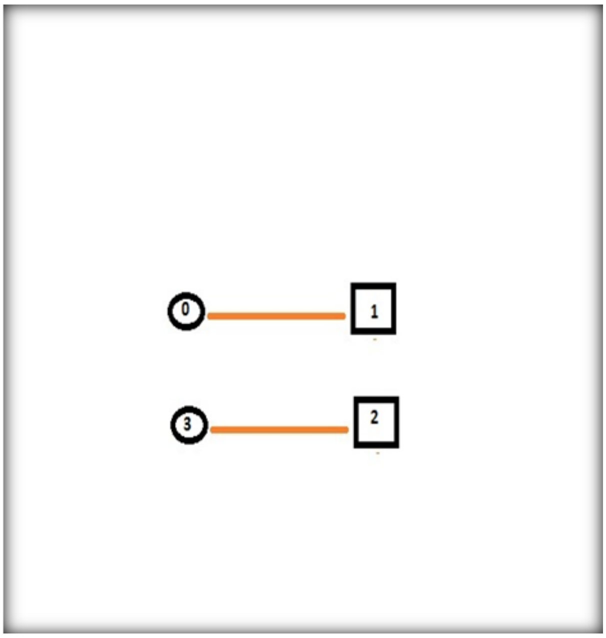
2.5 Numerical Studies

In this Section, we present a comprehensive numerical study for the models and algorithms mentioned before. The illustrated results were obtained from LP and MIP models implemented using python 2.7.3 with Gurobi optimizer 4.6.1 and executed on core i3 2.4 GHZ CPU with 4 GB RAM , Windows seven PC.

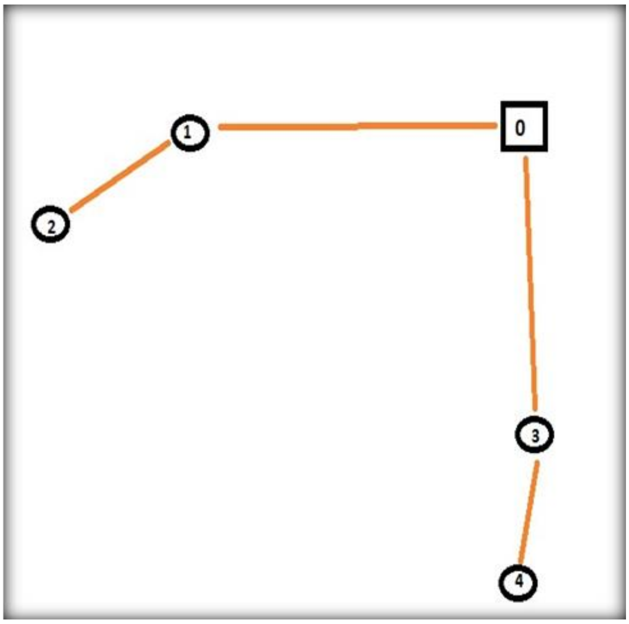
This Section will be divided in two main subsections. First, we present the related models to Link activation, and next we show the results of Max-Min flow allocation including the traffic throughput and its running time.

The topologies used here are randomly generated based on path loss model that was mentioned before. For simplicity, we just show several examples of topologies and other results are available upon request. The test networks can be divided in two kinds; one is the spare network of which the area is 1050*1050 and the other one is the dense network with area 800*800,400*400 to see exactly interference cancellation effect. In Figure 2, Exnet 4, 5, 1 are dense networks and Exnet 2, 3 are spare networks.

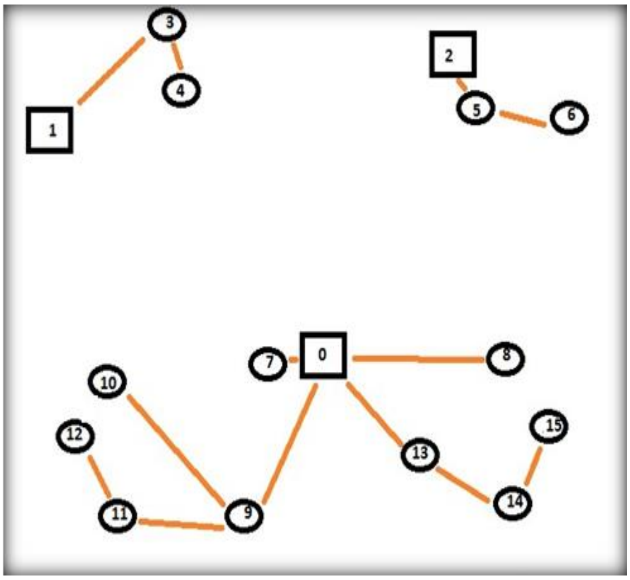
In Figure 2, routers are represented by circles and gateways are squares. Nodes are connected to gateways with links that are shown and the routing path is fixed for each router based on shortest hops. Each router can be connected to only one gateway.



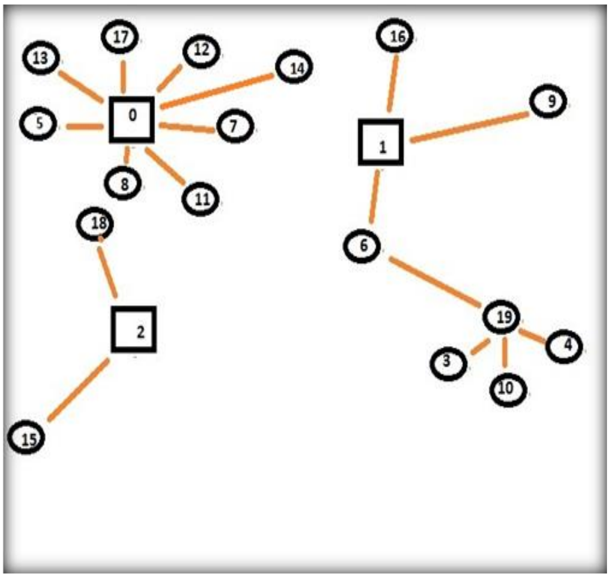
Exnet 1



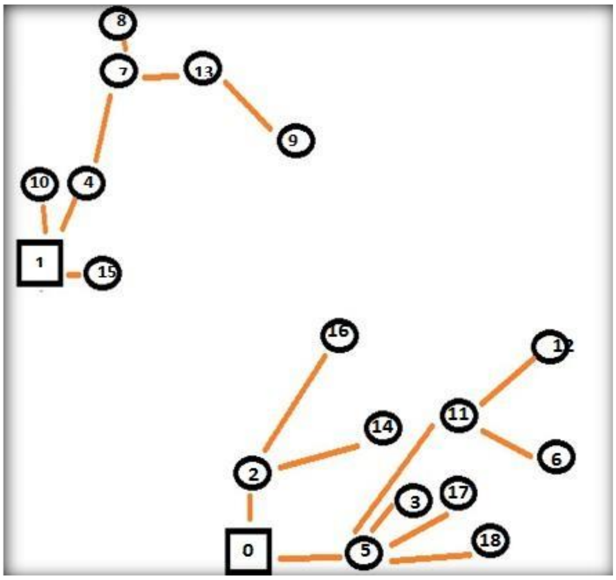
Exnet 2



Exnet 3



Exnet 4



Exnet 5

Figure 2. Topologies

2.5.1 Link Activation

Table 2 shows the results of the MIP models presented for link activation.

Table 2. Maximum number of links which can be active simultaneously

	nodes	link	LA without IC	LA with IC	Running time
Exnet 1	4	2	1	2	<1s
Exnet 2	5	4	2	2	<1s
Exnet 3	15	13	6	6	<1s
Exnet 4	20	17	2	4	<1s
Exnet 5	19	17	4	6	<1s

In “Exnet 5”, 4 interference links can be removed using IC but we can have 2 more active links since SINR equation of interest signals can be satisfy with only 6 links. In “Exnet 2” and “Exnet 3”, according to our algorithms only 2 and 6 links can be active respectively which are maximum active links. Figure 3 shows two possibilities of “Exnet 2” active links.

The running time here for all cases is less than one minute. If we increase nodes and links to around 50 nods with 800 links it will take around 6 hours to get solution.

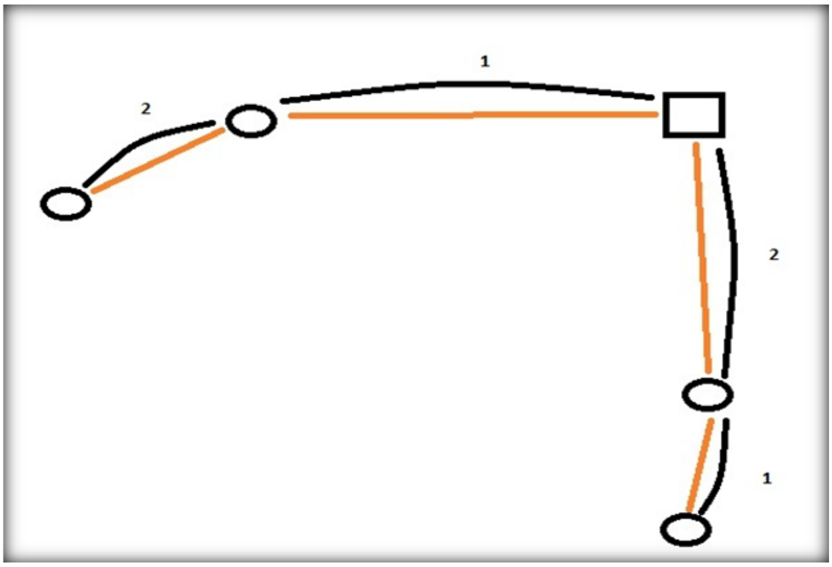


Figure 3. Simultaneously active links

In Figure 3, links labeled with 1 and 2 can be active simultaneously because we don’t have powerful interference. One link can be active at each node and therefore using IC will not increase the number of active links.

2.5.2 Max-Min Flow Allocation

In this Section we illustrate the results of traffic flow through optimization algorithms. Table 3 shows the results for the tested networks with and without IC. We assume the data rate is equal to 1bit/s and T is equal to 10s.

Table 3. Maximum flow with and without interference cancellation.

	nodes	links	Max f with IC	Max f without IC	GCS objective(last step)	GCS objective(last step with IC)
Exnet 1	4	2	10	5	1	0.5
Exnet 2	5	4	2.5	2.5	0.25	0.25
Exnet 3	15	13	1.11	1.11	0.111	0.11
Exnet 4	20	17	1.11	0.909	0.111	0.0909
Exnet 5	19	17	0.7692	0.66	.076	0.066

In topologies exnet3 and exnet5 max-min flow with and without IC will be the same because there is no improvement in active links, but for others networks, we have improvement.

As mentioned before, we can use “big M” and “Z” in our notations although we used “big M” in our simulation till now but in Table 4, we examine five different topologies in both methods to see the differences in running times.

Table 4. Running time difference between Z and big M

	Nodes	links	Zev	Big M
Exnet 3	15	13	7.61s	4.31s
Exnet 6	25	23	12.28s	10.31s
Exnet 7	21	17	7.39s	8.88s
Exnet 5	19	17	9.87s	8.47s

The overall results indicate that models with “big M” have better running time when “Z” can increase the upper bound of corresponding linear relaxation. Big M formulation is mentioned in (16), (17).

At last, we take “Exnet 3” as an example to show how the algorithm works. We set the initial compatible set to $C_1 = \{2\}$ which means that link 2 can be active (T=10s, B=1bit/s).

First iteration: solving master problem and getting optimal dual variable π_e^*= {0,0,0,1}, solving the model of CSG, the obtained compatible set is {4} and f=0, $z_1 = 10, f^* = 0.4$. Now we should decide whether to add new compatible set to the list or not, checking $C_1 * \pi^*_{current} < f^*$, that it is hold, add the new compatible set to the global list and we have a new list $C_i = \{\{2\},\{4\}\}, z = \{z_1 = 10\}$.

Second iteration: solving master problem and getting optimal dual variable π_e^*= {1,0,0,0}, solving the model of CSG, the obtained compatible set is {1,3} and f=0, $z_1 = 10, z_2 = 0, f^* = 0.4$. Now we should decide whether to add new compatible set to the list or not, checking $C_1 * \pi^*_{current} < f^*$, $C_2 * \pi^*_{current} < f^*$ that it is hold, add the new compatible set to the global list and we have new list $C_i = \{\{2\},\{4\},\{1,3\}\}, z = \{z_1 = 10, z_2 = 0\}$.

Third iteration: solving master problem and getting optimal dual variable π_e^*= {0,0.2,0.2,0.2}, solving the model of CSG, the obtained compatible set is {2,3}, and f=2, $f^* = 0.4$. Now we should decide whether to add new compatible set to the list or not, checking $C_i * \pi^*_{current} < f^*$, i$\in I$, that it is hold, add the new compatible set to the global list and we have a new list $C_i = \{\{2\},\{4\},\{1,3\},\{2,3\}\}, z = \{z_1 = 4, z_2 = 4, z_3 = 2\}$.

Fourth iteration: solving master problem and getting optimal dual variable π_e^*= {0.2,0.2,0,0.2}, solving the model of CSG, the obtained compatible set is {1,4}, and f=2, $f^* = 0.4$. Now we should decide whether to add new compatible set to the list or not, checking $C_i * \pi^*_{current} < f^*$, i∈ I, that it is hold, add the new compatible set to the global list and we have a new list $C_i = \{\{2\},\{4\},\{1,3\},\{2,3\},\{1,4\}\}, z = \{z_1 = 0, z_2 = 4, z_3 = 2, z_4 = 4,\}$.

Fifth iteration: solving master problem and getting optimal dual variable π^*_s= {0,0.2,0,0.2}, solving the model of CSG, the obtained compatible set is {2}, and f=2$.5, f^* = 0.25$. Now we should decide whether to add new compatible set to the list or not, checking $C_i * \pi^*_{current} < f^*$, i∈ I, that it is not hold, we can't add the new compatible set to global list and it will be same as previous step. $C_i = \{\{2\},\{4\},\{1,3\},\{2,3\},\{1,4\}\}$,. $z = \{z_1 = 2.5, z_2 = 2.5 , z_3 = 0, z_4 = 2.5, z_5 = 2.5\}$

CHAPTER 3

3 Scheduling in 802.11

In this Chapter we discuss the defects in previous defined medium access control (MAC) for 802.11 standard. We describe how scheduling works and illustrate how to do simulation in the network simulator.

3.1 Transmission Scheduling 802.11

Scheduling in 802.11 standards is happening in MAC layer that provides the possibility for several network nodes to access the shared medium. In 802.11, two medium access mechanisms are introduced. First one named distributed coordination function (DCF) which can be used in infrastructure and ad-hoc model, the second one is called point coordination function (PCF) which can only be used in infrastructure mode. PCF is contention free based mechanism while DCF is contention based mechanism.

There are also some standards that define new MAC mechanism which provide better QOS for some services, better energy consumption and fairness but all of them are not quite efficient [4,13].

3.1.1 Distributed Coordination Function (DCF)

The basic IEEE 802.11 uses DCF to share medium between multiple stations. For accessing the shared medium in network, stations should not collide with each other. For this purpose, different parameters should be defined [13]:

SIFS is a short inter frame space that gives the shortest waiting time before accessing medium. SIFIS is used for high priority frames and it sends before the control message like (RTS), clear to send (CTS) and acknowledgment frames [14].

PIFS is PCF inter frame space and its waiting time is longer than SIFIS. Its usage is for medium priority frames and utilized in an infrastructure mode when one AP is polling other stations. Only stations which are operating under PCF can wait for PIFS [14].

DIFS is DCF inter frame space and it’s longer than PIFS. DIFS is used for low priority frames and they have to wait longer time before accessing medium. Only nodes operating under DCF have waiting time equal to DIFIS [14].

EIFS is the longest time and is used when a failure occurs in communication between nodes which are operating under DCF [14].

DCF employs carrier sense multiple access with collision avoidance (CSMA/CA) and optional 802.11 RTS/CTS to share medium between stations. In simple words, CSMA/CA means that stations or nodes should sense the medium before transmission to see whether it's idle or busy. If medium is busy then they have to wait until the ongoing transmission is finished. Channel sensing is defined by two mechanisms; one is physical sensing and the other one is virtual sensing or network allocation vector (NAV). The important point is that medium is considered to be idle if both physical or virtual sensing consider it as idle, otherwise, if one mechanism denotes that medium is busy, other stations are obligated to defer transmission until medium is idle. Actually they go to back off which is the random number slots that have been chosen from a contention window (CW). The back off counter will be decreased slot by slot when medium is sensed as idle and will be suspended whenever channel gets busy. When counter expires, the station will stand for DIFIS again and, if the channel is still idle they can transmit and contention window will be set to its minimum value (CWm) unless they will go to back off again with the difference that this time they will choose a random slot for waiting from (2* CWm). This procedure reduces the probability of collision happening again. Figure 4 gives a clear understanding about how transmission happening [4, 13].

3.1.2 Point Coordination Function (PCF)

This function is available in infrastructure mode which means it needs AP to access medium and is not commonly implemented in current wireless devices. In this mechanism APs send beacon frame at regular intervals that depends on AP which is normally every 0.1 second. In these beacons PCF defines two periods which are contention free (CFP) and contention period (CP). In CP, PCF are works the same as DCF, but in CFP, the AP manages medium by sending poll packets to nods at each time. Sending poll packets means the stations have a chance to send packets that is somehow like TDMA [4, 16]

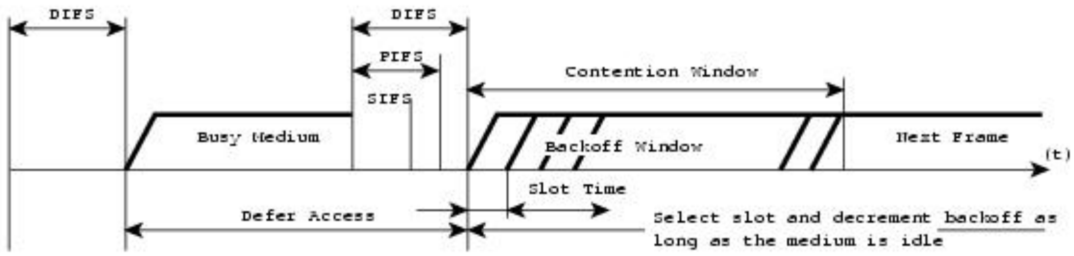


Figure 4. Some IFS realationship in DCF(copied from [15]).

3.2 Numerical Study

In order to evaluate the performance of existing MAC, we used network simulator ns-2 (ns-2.30). The topologies simulated here were exactly the same as the ones that are used in previous Chapter. The difficulty that we faced here was incapability of NS-2 for supporting static routing because we wanted to use exactly the same topologies that are used in optimization model. To reach this purpose, we used "NO Ad-Hoc Routing Agent (NOAH)" packages with some modification to make it support multi gateways. Here we used mostly TCL scripting with some c++ on Ubuntu 12.4 operation system.

For calculating the throughput from trace file generated through simulation, we used "Jtrana" and the "tracegraph 2.2" at first but then we extracted required data by AWK programming which is easier than those software.

3.2.1 Simulation Assumption

In optimization model each link handles the maximum data rate that is set from gateway in its scheduled turn. We set this approach in our simulator or, in other words, we fix the maximum capacity of channel (link) to be the same as chosen data rate. The data rate we used here is 1Mbit/s for all transmitting gateways although, if we change data rate, we have almost same result because of mentioned setting. The transmission range here is around 250 meters that is almost the same as the assumption in optimization models. The connections between routers and gateways are unicast and there is only one channel. We also set simulation time to be 10 second.

To achieve the data rate 1 Mbit/s, we have used constant bit rate traffic (CBR) with size of 512 byte and interval time of 0.004096 which means in each 0.004096 second one packet with size of 512 byte should be sent.

3.2.2 Simulation Results

In this part simulation results in terms of throughput are shown for example topologies in Chapter 2.

Figure 5 belongs to "Exnet 1" topology.

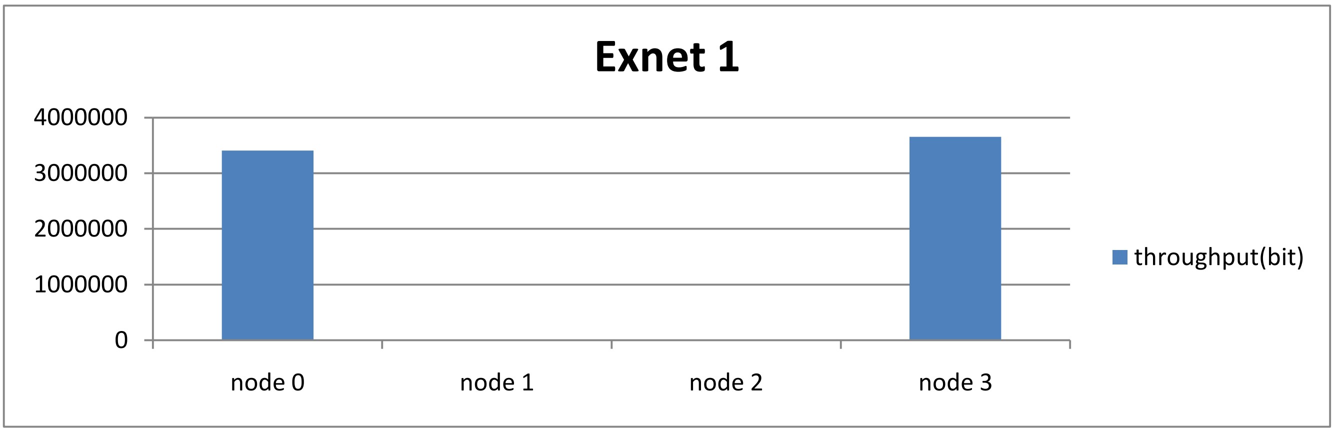


Figure 5. Exnet 1 throughput for each node.

It can be clearly figured out from Figure 5, that even in this small network, we don't have fair resource allocation. There are lots of packets which are in queue for being transmitted but transmission is impossible since gateways are in the sensing range.

Figure 6 shows simulation results for Exnet 2.

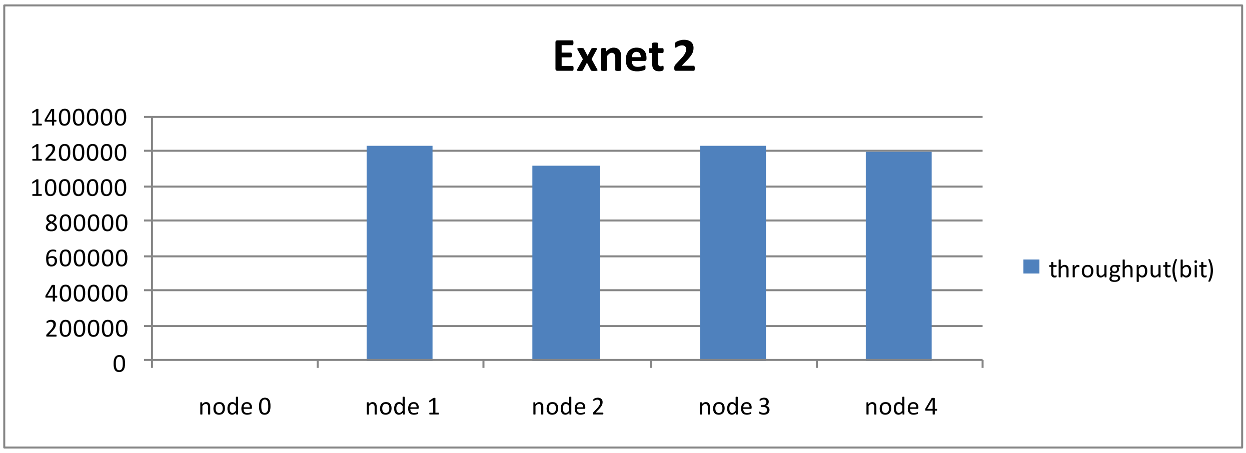


Figure 6. Exnet 2 throughput for each node

In this graph, we can also see the defects of channel access mechanism. It is possible that each router can receive 2.5 Mbit data but they are only receiving around 1.2 Mbit actually.

In Figure 7, simulation results for Exnet 3 are illustrated.

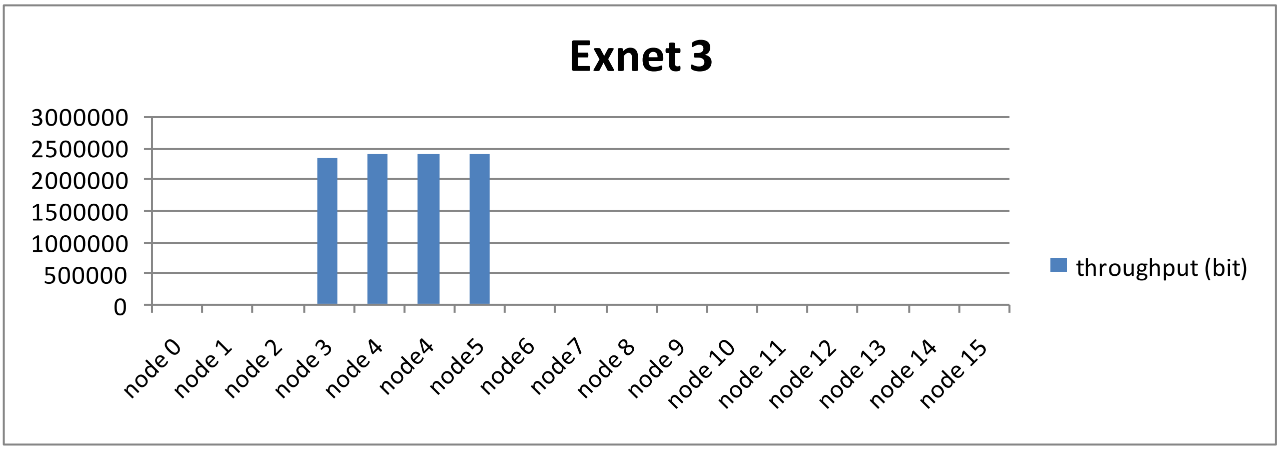


Figure 7. Exnet 3 throughput for each node

We can name Figure 7 as the most amazing one since we receive almost nothing in nodes that are connected to gateway 0. Moreover, it's interesting to know that if we increase the capacity of link or decrease the data rate, we have throughput on those mentioned nodes.

In Figure 8, simulation results for Exnet 4 are shown.

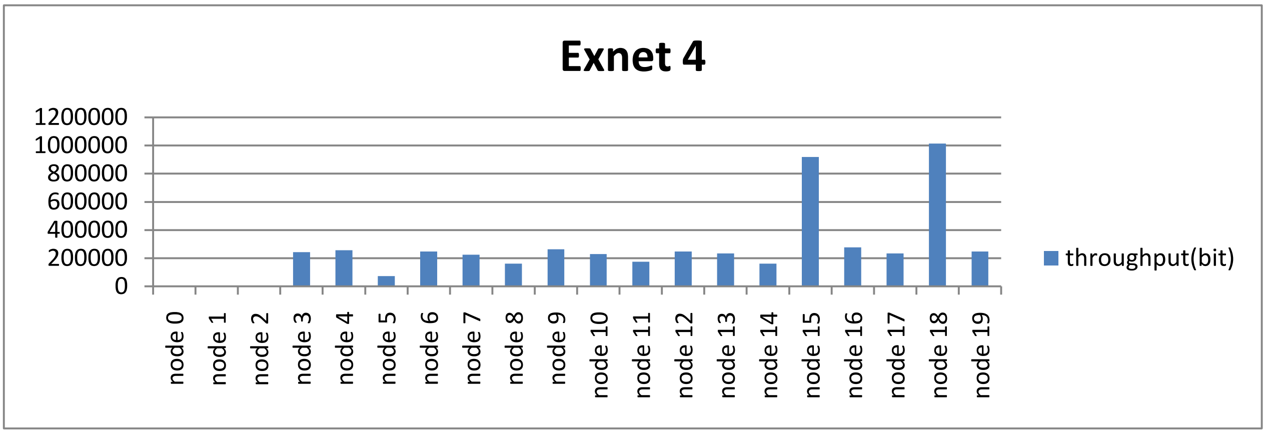


Figure 8. Exnet 4 throughput for each node

In above case, we can see that we didn't reach to fair resource at each node and also the throughput isn't very good.

In Figure 9, simulation results for Exnet 5 are shown.

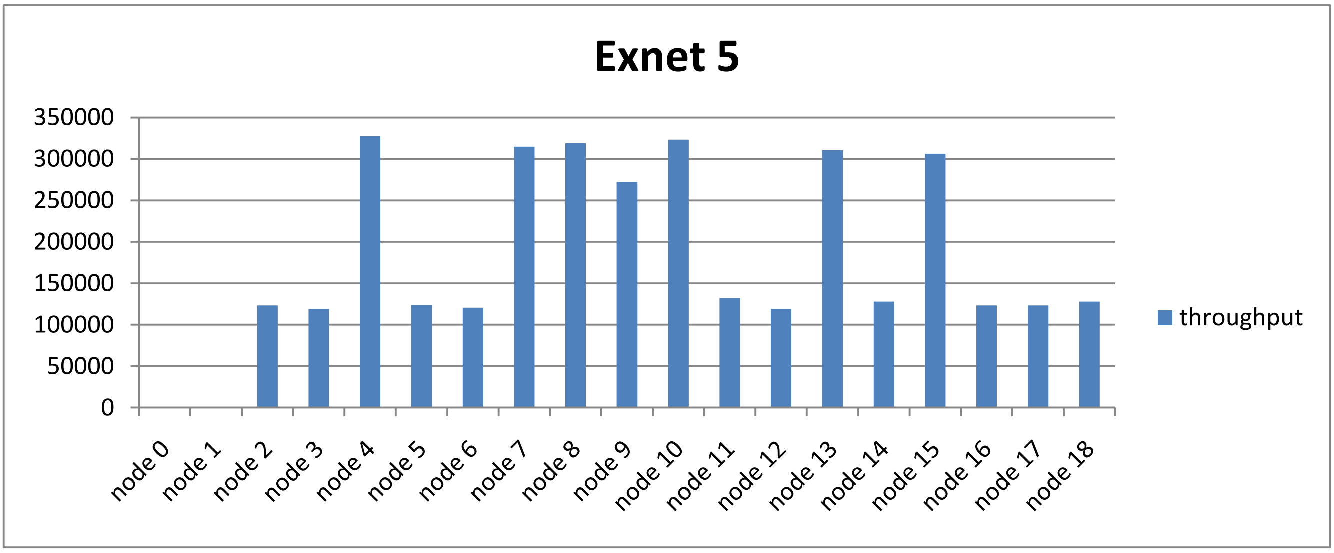


Figure 9. Exnet 5 throughput for each node

In this graph we can also see the defects of scheduling mechanism since throughputs aren't equal and very low comparing to thought.

3.4 Summary

As simulation shows, we can conclude that scheduling mechanism for transmission in current used standard (802.11) for wireless mesh network is not as efficient as it should be because problems in functionality of CSMA/CA that cause packets to be queued or backed off for avoiding collision.

CHAPTER 4

4 Comparison

In this Chapter we first propose a method to implement transmission scheduling that was obtained through optimization into real medium access control (MAC) and then we do comparison in terms of throughput between numerical results of CSMA/CA and our optimized scheduling.

4.1 Optimization Model Implementation

One approach for implementing scheduling in network is using time slot notations and providing the transmission plan for each time slot. This solution can be implemented with a centrally preplanned transmission scheduling like TDMA.

Consider the results obtained from optimization model in example Exnet 2, the optimal compatible set (CS) is $C_i = \{\{2\},\{1,3\},\{4\},\{2,3\},\{1,4\}\}$, and the time for each CS is $Z_i = \{z_1 = 2.5, z_2 = 2.5, z_3 = 0, z_4 = 2.5, z_5 = 2.5\}$ .This means that link {2} will be active for 2.5 seconds then links {1,3} will be active for 2.5 seconds and so on. For using obtained scheduling in time slot notation please consider Figure 10:

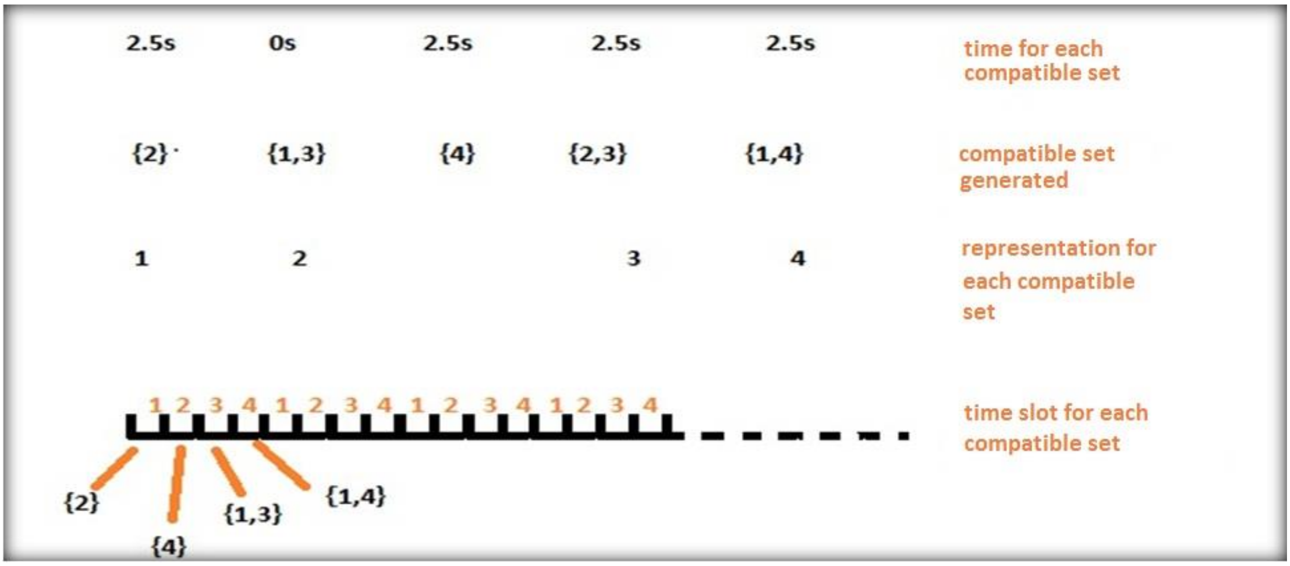


Figure 10. Proposed method for using optimization result

Here each compatible set is associated with a number and we put each number in one slot time. The simulation time is 10 seconds and it is splitted to all the slots, namely, if there are 1000 slot, each one must be 0.01 second. Another issue that should be mentioned here is that in Exnet 2, times for compatible sets are equal 2.5s but normally they are not the same, For example Figure 11 shows slot planning for 3 compatible sets with times 5, 2.5 , 2.5 which are depicted in figure 1, 2, 3 respectively.

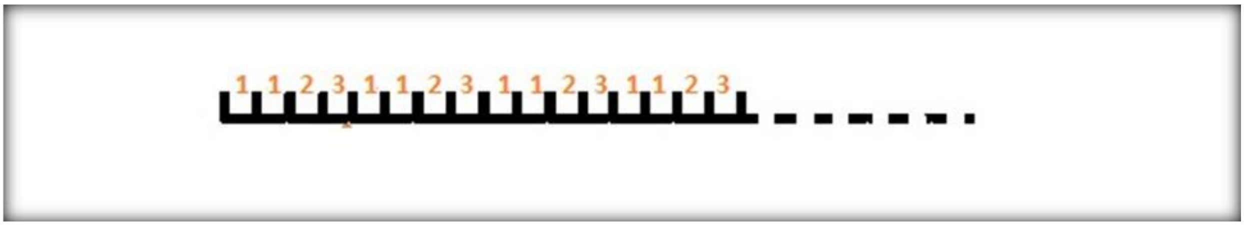


Figure 11. Optimization result implementation proposal with different compatible set times

In the optimal solution of the optimization models, it can happen that the times used for a list of compatible sets are 5.1, 2.4 and 2.5. Then the time slots can take a value from 1000 time slots to 10000 time slots.

4.2 Optimization Model Simulation

Actually, implementing the mentioned method is a difficult job which needs more research works, therefore we did a simulation with another approach that was possible to do in NS-2 with current structure. For this purpose we did simulation on each compatible set (CS) separately since buffer in hand over nodes can't tolerate those big assigned times for each CS. Actually we do not aim to show the whole above topologies simulation results here because the method we use isn't precise and the obtained result is almost equal to the results we got from optimization models. Figure 12 shows the results for Exnet 1 with B=1Mbits.

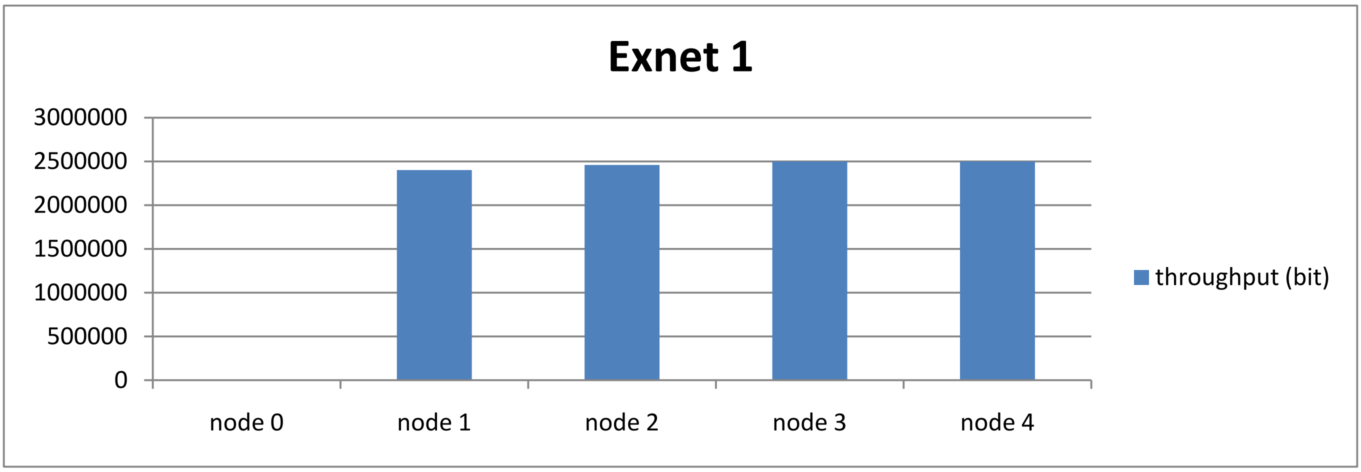


Figure 12. Simulating "Exnet 1" exactly with acquired result with optimization in NS-2

4.3 Comparisons

In all simulations we did in Chapter 2, the data rate assumption was 1bit/s. To make a fair comparison for the transmission scheduling between our optimization methods in Chapter 2 and currently used MAC mechanism in Chapter 3, we should also use the data rate 1Mbit/s. With this assumption, the traffic flow that obtained from the simulation should be multiplied by 1M. Figure 13 shows the comparison in throughput between those mentioned methods in topology “Exnet 2”.

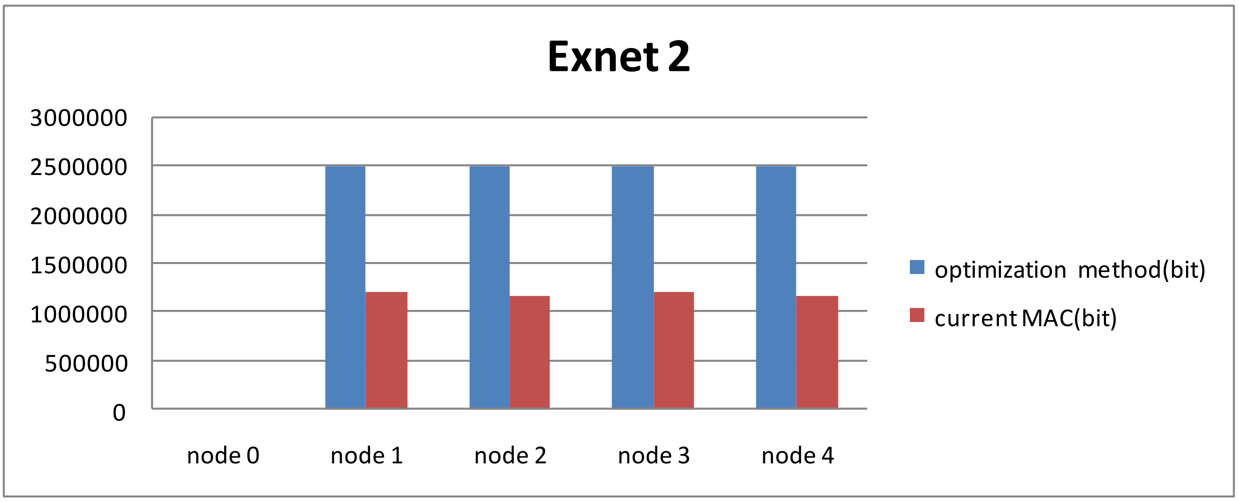


Figure 13. Comparison between current MAC and our optimization result in throughput

From Figure 13, we can easily find that the max-min flow obtained by optimization models is much better than simulation results in NS2 with CSMA/CA. In topologies “Exnet 1”, “Exnet 3”, “Exnet 4” and “Exnet 5”, the max-min flow for each node with interference cancellation is around 10 Mbit, 1.11 Mbit, 1.11 Mbit, 0.7692 Mbit and without interference cancellation is around 5 Mbit, 2.5 Mbit, 1.11 Mbit, 0.909 Mbit, 0.66 Mbit respectively. Besides, we have found that the optimization models can supply better fairness than the simulations in NS2.

CHAPTER 5

5 Conclusions and Future Works

In this thesis, we have studied topics related to transmission scheduling in wireless mesh networks. More specifically, we have tackled the problems of throughput and fairness in these networks.

At first place, we presented optimization models using mixed-integer programming and linear programming formulation for solving MMF flow allocation objective with a non-standard way of dealing with uncertain traffic. We dealt with single user decoding assumption and its link activation algorithms. We analyzed interference cancellation which improves links activation with multi-user decoding supposition. The simulation results were based on single modulation and coding scheme and is illustrate how transmission scheduling was achieved through those algorithms. The compatible set defined method is efficient and can give us good fairness and throughput in every node of our example topologies of wireless mesh network. We also tried to show how interference cancellation improves link activation and traffic objective and to illustrate how using different notions like “bigM” or “Z” is effective in simulation running time.

Some part of work was assigned to show deficits of CSMA/CA in transmission scheduling using the same topologies that was used in the optimization part. The numerical study is showing that throughput isn’t equal between routers in our example mesh networks and nodes which are farther from gateways will gain lesser and when nodes are in range of each other (sensing range) would commonly defer their transmission in random time and it decreases the throughput.

In Chapter 4, we gave our proposal for using optimization results in practical wireless network based on time slot notation and contention free transmission mechanism. We did simulation for one topology example which showed that it could supply the similar max-min flow compared with the one obtained from optimization models. Final part of this Chapter was assigned to comparison between our scheduling method and currently used mechanism in wireless devices which showed surprising result in throughput and fairness.

In future, we could implement the mentioned contention free mechanism in a network simulator which would be of interest. Another extension for the optimization model is to use adaptive MCS or adaptive transmission power.

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List of Acronyms

AP	Access Point
CP	Contention period
CFP	Contention Free Period
CSMA	Carrier Sense Multiple Access
CW	Contention Window
CTS	Clear To send
CSG	Compatible Set Generation
CS	Compatible Set
DCF	Distributed Coordination Function
CIFS	Distributed Inter Frame Space
IC	Interference Cancellation
ISP	Internet Service Provider
IEEE	Institute of Electrical and Electronics
LP	Linear Programming
LA	Link Activation
MMF	MAX –Min Fairness
MCS	Modulation Coding Scheme
MAC	Medium Access Control
MUD	Multi User Detection
MIP	Mixed Integer Programming
NS 2	Network Simulator 2
NP-HARD	Non-Deterministic Polynomial-Time Hard
NOAH	No Ad-hoc Routing Agent
NAV	Network Allocation Vector
NIC	Network Interface Card
OFDM	Orthogonal Frequency Division
PIC	Parallel Interference Cancellation
PHY	Physical
PIFS	Point Coordination Inter Frame Space
PCF	Point Coordination Function
QOS	Quality of Service
RTS	Request To Send
SUD	Single User Detection
SIFS	Short Inter Frame Space
SINR	Signal to Interference Noise Ratio
SIC	Successive Interference Cancellation
STDMA	Spatial Time Division Multiple Access
SNR	Signal to Noise Ratio
TCL	Tool Command Language
TDMA	Time Division Multiple Access
WIMAX	Worldwide Interoperability for Microwave
WMN	Wireless Mesh Network