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Interference and power control in ad hoc wireless networks

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INTERFERENCE AND POWER CONTROL IN AD- HOC WIRELESS NETWORKS

BY

RAUL RAMIRO PERALTA MEZA

B.S. San Agustin National University of Arequipa, 1993
M.S. Pontifical Catholic University Of Peru, 2000

THESIS

Submitted in Partial Fulfillment of the
Requirements for the Degree of

Master of Science
Computer Engineering

The University of New Mexico
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June, 2007

DEDICATION

This thesis is dedicated to my fiancée, “Gisella Llaguno”, who taught me to believe and trust in the God always. Also, this thesis is dedicated to my loving parents: “Raul Peralta” and “Gricelda Meza”, who taught me that all the great challenges can be overcome with courage and perseverance.

“You can know the name of a bird in all the languages of the world, but when you're finished, you'll know absolutely nothing whatever about the bird... So let's look at the bird and see what it's doing -- that's what counts. I learned very early the difference between knowing the name of something and knowing something.”[1]

[1] Richard Feynman (US Educator and physicist 1918-1988)

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Abstract

Wireless networks are growing in number rapidly because they offer mobility with higher data rates at lower prices. Wireless LANs can be implemented with infrastructure. However, ad hoc wireless networks do not need infrastructure, and further, the potential for deployment of ad hoc networks exists in many scenarios including situations where infrastructure is unfeasible or undesirable, like disaster relief, sensor networks or military applications. Since the media is shared, ad hoc networks suffer from interference, which is the one of the most important problems that limits the network capacity.

In order to overcome this problem power control protocols are used. The protocols can adjust the transmission power levels to avoid interference between wireless nodes. Power control protocols aim to increase the capacity of the network by increasing spatial reuse. This thesis looks at the problem of interference when Power Control is applied to maximize the network capacity. In ad hoc networks, the RTS/CTS dialog or virtual carrier sensing is less effective since a transmission takes place over three ranges: interference range, carrier sense range and transmission range. The values of interference range do not interrupt a transmission if it is close to noise floor, however the carrier sense range is capable of disrupting a transmission. Location, packet size and the traffic must be considered as important parameters in power control protocols. The majority of the work is focused at the physical and link layers.

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ACRONYMS AND ABBREVIATIONS

ACK	Acknowledge
AP	Access point
BPSK	Binary Phase Shift Keying
BSS	Basic Service Set
CBR	Constant Bit Rate
CCA	Clear Channel Assessment
CSMA/CA	Carrier Multiple Sense Access with Collision Avoidance
CTS	Clear to send
CW	Contention window
DCF	Distributed coordination function
DIFS	DCF Inter frame spacing
DS	Backbone distribution
EIFS	Extended inter-frame spacing
ESS	Extended service Set
FTP	File Transfer Protocol
IBSS	Independent Basic Service Set
LAN	Local area network
LOS	Line-of-sight
MAC	Media Access Control
MCBPC	Multi-channel Based Power Control ad hoc Network
NAV	Network Allocation Vector
PC	Point of coordination
PCD	Point Coordination Function
PIFS	PCF, inter-frame spacing
PLCP	Physical Layer Convergence Protocol
PMD	Physical Medium Dependent
Pmin	Minimal Power Level
Pmin80211	802.11 Minimal Power Module
PS	Packet Size
RTS	Request to send
SDF	Start frame delimiter
SIFS	Shortest Inter Frame Spacing
SNIR	Signal to noise and interference ratio
STA	Stations
TCP	Transmission Control Protocol
UDP	User Datagram Protocol
WLAN	Wireless local area network

Chapter 1 Introduction

1.1 Background

Wireless networks are become very popular due to technological advances in laptops and mobile devices like PDAs and cell phones. Every day wireless networks offer higher data rates at lower prices, which are the main reasons why this technology is growing up rapidly. Wireless networks use electromagnetic waves or optical means to transmit information in the air in order to connect two or more terminals.

For enabling wireless communications, there are two possibilities: the first uses an infrastructure in which all the nodes in the network depend on a central point. The other options are ad hoc networks whose main characteristic is the absence of infrastructure. In ad hoc networks, nodes interchange data directly. If the transmitter and the receiver are not in the range of one hop then they can use the intermediate nodes. Therefore, packets arrive from one side to the other by using several jumps in the intermediate nodes. The potential for deployment of ad hoc networks exists in many scenarios, for instance, in situations where infrastructure is unfeasible or undesirable, like disaster relief, sensor networks, military applications, etc.

Interference in Wireless ad hoc Networks is one of the most significant factors that limit the network capacity and scalability. Since the media (channel) is shared, co-channel and adjacent interference cannot be avoided; however using Power Control protocols or special hardware on the physical layer including filters or directional antennas can reduce the effects. Power control protocols can adjust the transmission power levels to avoid interference between wireless nodes. Power control protocols aims to increase the capacity of the network by increasing spatial reuse. This thesis looks at the problem of interference when Power Control is applied to maximize the network capacity.

1.2 Problem description

The objective of this thesis is to study the interference in ad hoc networks when Power Control is used to increase the network capacity. In the study the location of the nodes and the traffic load are known. In addition, all the nodes in the network can communicate with each other in one single hop. In the thesis, two parameters are calculated: the minimal transmission power and the optimal transmission power. The minimal transmission power depends on the location and the propagation models. The optimal transmission power is the value that maximizes the network capacity. The optimal transmission power is the minimal transmission power times ALPHA, where ALPHA is equal or greater than one. The intention of this thesis is to recommend parameters to Power Control Protocols and discuss its impact on the ISO model since it is a complex and cross layer problem. The study is centralized in the MAC layer and assumed one IEEE 802.11b interface in the wireless nodes.

The thesis also includes the generation of simulation tools that can be used in further studies of ad hoc networks. All the simulations are based on Network Simulator 2 (Ns-2 version 2.30).

In summary the objectives of this thesis are to:

- Understanding of IEEEE 802.11 standards.
- Analyze the protocols theoretically and through simulations.
- Study the interference with Power Control protocols.

Contributions are made in the form of design principles, study of protocols, simulation studies, architectural suggestions for the stack as a whole, and several tools and libraries.

1.3 Thesis organization

Six chapters and two appendices compose this thesis.

Chapter 2 deals primarily with the related work. The interference in ad hoc networks and the solution based on power control problem are explained. Definitions that are used in the thesis are presented including concepts such as the classification of power control protocols and the principles of power controls protocols. The chapter includes examples of power control protocols that were implemented at the MAC and the network layer.

Chapter 3 examines the IEEE 802.11 standard: architecture organization, the components of a wireless network, the services provided by the standard and the stack protocol. In the link layer, there are mechanisms such as RTS/CTS dialog are used to solve the hidden terminal problem. The components that play a role in the wireless communication are identified.

Chapter 4 shows the methodology employed for calculating the Minimum Power. It is important to mention definitions such as interference ranges, propagation models and thresholds used by the Ns-2 at the physical and link layer to identify noise floor from the valid packets. One module is added to the Ns-2, Pmin80211, to conduct experiments in the channel. At the end of the chapter, there are basic experiments that validated Pmin80211 module. The experiments include CBR and FTP traffics on the top of UDP and TCP protocols respectively.

Chapter 5 shows more experiments based on the Pmin80211 module. Chain, grid and random topologies are used to examine the interference. The location of the node and the traffic load are the main factors that determine the performance of the transmission. Control the minimal power level in the transmission could increase the throughput and the aggregate throughput of the network. RTS/CTS mechanism is created to eliminate interference; however, the experimentation shows that it does not work properly due to various reasons.

The thesis concludes in Chapter 6 with a discussion about how the power control affects the rest of the ISO layers and conclusions about this topic.

Chapter 2 Related Work

Interference in Wireless ad hoc Networks is one of the most significant factors that limit the network capacity and scalability. Since the medium is shared, co-channel and adjacent interference cannot be avoided; however the effects can be reduced by using power control protocols or special hardware on the physical layer that includes filters or directional antennas.

Power control protocols can adjust the transmission power levels to avoid or reduce interference between wireless nodes. Power control protocols aim to increase the capacity of the network by increasing spatial reuse. In order to achieve this challenge, several topologies are used to identify problems and test the solutions: chain topology, grid topology, and random topology.

This chapter presents the related work. At the beginning, the definitions for understanding the power control protocols are presented, then the basic principles, after that a classification for the solutions of the power control problem. The next section presents examples of power control protocols and at the end of the chapter suggestions are presented.

2.1 General Definitions

Assume a wireless ad hoc network where the terminals share a single wireless channel to transmit or receive packets. The network uses IEEE 802.11 and a Distributed Coordination Function (DFC) as access method that serves as the wireless MAC protocol. In addition, IEEE 802.11 uses RTS/CTS (Request to Send / Clear To Send) control handshake, before the transmission takes place (DATA), and finally when it is completed the transmitter sends an ACK (also known as an acknowledgment code) message.

However, the use of this policy leads to other problems such as hidden terminal and exposed terminal problems. In the first case, the transmission from node A to B (A->B) can be disrupted by another terminal (C) that did not hear the CTS message when it tried to establish communication with the transmitters (A). In the exposed terminal problem, the node is overprotected because it can respond to a RTS message before nodes A and B finish their transmission. In this case, the potential transmitter (D) will increase its window size and could suffer from starvation. IEEE 802.11 uses the maximum power of the antenna when it transmits packets.

On the other hand, a change in the transmission power of the antenna impacts the coverage thus it could reduce the interferences to support more transmission in the same network. Thus, changing the IEEE 802.11 standard and testing it under the different topologies should be the starting point in order to improve the network capacity.

The following definitions are used to classify topologies, and the definition of the capacity of ad hoc networks:

2.1.1 Chain topology

In this case, the packets are sent from one extreme to the other. Packets flow along the intermediate nodes until they reach their destination. When successive packets are sent they start to interfere with each other resulting in link layer contention. The exposed and hidden terminal problems appear in this topology, Figure 2.1.

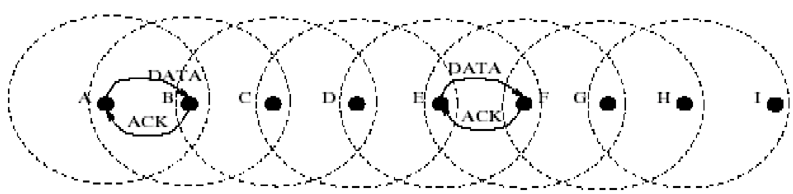


Figure 2.1 Chain topology.

In this topology also it is possible to establish more than one connection at the same time. However, we must calculate the minimum power level to avoid the interference between the connections.

2.1.2 Grid topology

A grid topology is a collection of nodes (in this case wireless nodes) where each node in the network is connected with two neighbors along one or more dimensions. Under this definition chain topology is a special case where the number of dimensions is equal to one. The topology uses two dimensions is shown in Figure 2.2

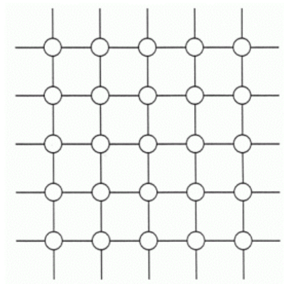


Figure 2.2 Grid topology.

Nodes that are in the borders will have less interference than nodes in the center of the network. Location is an important effect on the traffic performance. The distance between the nodes can be different.

2.1.3 Random Topology

The term of the random topology is used to indicate a topology with no specific pattern. The position of each node is selected in a random range.

2.2 The Capacity of ad hoc wireless Networks

In ad hoc wireless networks, nodes can send and receive information with each other. In addition, one node can rely on the others. There is no backbone infrastructure (no centralized control) and the number of concurrent transmissions is limited by the interference. Under this situation, two questions are very important: How does the network capacity scale with the number of nodes? Is there any way to improve the capacity?

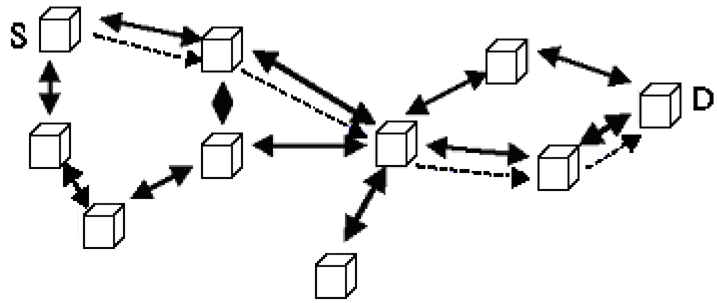
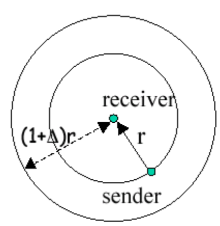


Figure 2.3 End-to-end transmissions.

The network capacity is defined as the achievable rate of end-to-end transmissions. Thus, the capacity depends on the interference as well as the routing and scheduling algorithms. Gupta and Kumar [1] studied the capacity of a static network (in arbitrary and random networks) by using an analytical approach. They mention that the throughput capacity is defined in the usual manner as the time average of number of bits per seconds that can be transmitted by every node to its destination. The authors define two transmission models a protocol model and a physical (interference) model.



$$SNIR = \frac{P_i r_i^{-\alpha}}{N + \sum_{j \neq i} P_j r_j^{-\alpha}} \geq \beta$$

Figure 2.4 Protocol and Physical model.

Figure 2.4 shows both models. In the protocol model a transmission is successful if there are no other senders within a distance (1+Δ)r of the receiver, where ‘r’ is the distance from the sender to the receiver. In the physical model the authors uses the channel propagation model to define the Signal-to-Noise-Interference Ratio, the idea is that the attenuation of the transmitter power level over distance must be stronger than the interference (the sum of thermal noise, N, and the attenuation of the other transmitters in the network over the distance). In the expression; ‘α’ is the attenuation factor (α=2 if the transmission takes place inside the Fresnel zone otherwise α=4).

By using both models, Gupta and Kumar [1] shown that under protocol model, the per-node throughput ($\lambda(n)$) for an optimal node placement is $\lambda(n) \propto \frac{c}{\sqrt{n}}$ (n = number of nodes in the network and c is a deterministic constant). Thus, the capacity of a wireless network is inverse proportional to the number of nodes in the network. In the case of a random node placement is: $\lambda(n) \propto \frac{1}{\sqrt{n \log n}}$. Thus, the per-node throughput falls as the number of nodes grows.

In [8] Jain et al. use another model based in a conflict graph for computing upper and lower bounds on the optimal throughput for the given network and workload. The authors consider the previous work [1] as incomplete approximation since in a realistic setting source (transmitters) nodes do not send data all the time, so nodes will on average transmit at a slower rate than the speed of their wireless link. In this case the inputs are the nodes locations, ranges and traffic matrix (that indicate source and sink nodes) and also the authors consider a physical and protocol model that are close to the models of Gupta and Kumar. Under protocol interference model the method builds a connectivity graph C, where the vertices correspond to the wireless nodes (n_c) and the edges to the wireless links (L_c) between the nodes. There is a direct l_{ij} from node n_i to n_j if d_{ij}<=R_i and i is different from j (d_{ij} is the distance between node n_i and n_j and R_j is the range or coverage of node j). In absence of interference we can compute the maximum achievable flow between a single source n_s and a single destination n_d as follow:

$$
\begin{array}{llll}
\max \sum_{l_{si} \in L_C} f_{si} & & & \\
\text{subject to} & & & \\
\sum_{l_{ij} \in L_C} f_{ij} = & \sum_{l_{ji} \in L_C} f_{ji} & \forall n_i \in N_C \setminus \{n_s, n_d\} & <1> \\
\sum_{l_{is} \in L_C} f_{is} = & 0 & & <2> \\
\sum_{l_{di} \in L_C} f_{di} = & 0 & & <3> \\
f_{ij} \leq & Cap_{ij} & \forall l_{ij} \in L_C & <4> \\
f_{ij} \geq & 0 & \forall l_{ij} \in L_C & <5>
\end{array}
$$

Where l_{ij} represents the connection between node ‘i’ and node ‘j’, f_{ij} denotes the amount of flow on link $l_{ij;}$ Cap_{ij} is the capacity of link l_{ij} and L_c a set of all links in the connectivity graph. Equations <1> to <5> are the constraints that maximize the flow out of the node. In order to incorporate interference the authors define another graph, F with the same vertices of C. In F, there is an edge between the vertices l_{ij} and l_{pq} if the links l_{ij} and l_{pq} may not be active at the same time. The lower bound is compute by finding concurrent transmission over the graph F.

2.3 Power Control Protocols

In wireless ad hoc networks, Power Control Protocols are important since they can impact in a positive way in the traffic carrying of the network and they extend the battery life of the node where the protocol is working.

Subsequent authors have proposed solutions that can be classified [3] into one of the three categories:

- The first one comprises of strategies to find an optimal transmit power to control the connectivity properties of the network or they try to optimize the average end-to-end network throughput by controlling the degree of a node.

- The second category could be called power "aware" routing, the majority of these schemes use some shortest path algorithm with a power-based metric, rather than a hop count based metric. Some suggestions for the metric include energy-consumed per packet, time to network partition, variance in battery life of nodes, and the energy cost per-packet.

- The third class claims a modification at the MAC layer. Some of them suggested a new IEEE 802.11's handshaking procedure to allow nodes to transmit at low power level [3], while others propose enabling nodes to power themselves off when not actively transmitting or receiving.

Some protocols require another channel for controlling the transmission meanwhile the power aware (message exchanging) do not. They try to maximize utilization of the hardware resource, consequently they do not touch the physical layer, which is a strong point in favor because hardware manufactures could maintain the same structure (or probably they made few improvements), and the major changes will take place in the software (drivers or operating systems).

2.4 Principles in power control protocols

According to Kawadia et al. [3], the principles of power control protocols are:

1. To increase network capacity it is optimal to reduce the transmit power level. Any transmission causes interference in the surrounding region due to the shared nature of the wireless channel.

   In [2] Narayanaswamy et al. demonstrated that there is a reciprocal dependency of the throughput (λ) and the distance (r) between two nodes as shown in Figure 2.5.

$$\lambda \leq \frac{16AW}{\pi\Delta^2 L} \cdot \frac{1}{nr} \text{bits/sec}$$

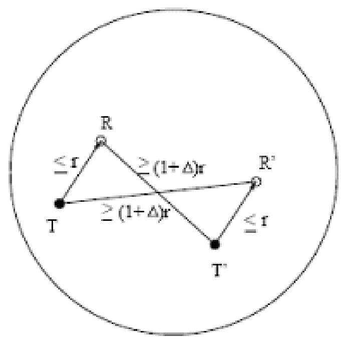


Figure 2.5 Relationship between the throughput and the distance.

   Where 'n' is the number of nodes in a domain of area 'A' square meters, each node can transmit at 'W' bits/sec, 'r' is the range of each node in meters, 'L' is the distance between the source and the destination and 'Δ' is the minimal distance between ranges that makes possible concurrent transmissions.

   The expression justifies the goal of reducing the common power level to the lowest working value at which the network is connected and it improves the value of the network capacity. In addition, [2] consider the same power of level for all the nodes in the network however it is also possible to apply the same principle to power level to each packet that is sent in the network.

2. Reducing the transmit power level reduces the average contention at the MAC layer.

In [2], the authors demonstrated that changing the power level reduce the contention at the MAC layer. They assume that each node has traffic of rate λ (bits/sec) that wants to send to a destination at a distance L. They also assume that each node transmits at W (bits/sec) and there are n nodes in the network. Then, the number of hops per route is L/r (distance among nodes), and each node needs to transmit $L\lambda/r$ (bits/sec). On the other hand, the average number of neighbors per node is $\pi r^2 n/A$. Those nodes need to transmit on average $(L\lambda/r)*(\pi r^2 n/A) = \pi n\ L\lambda r/A$ that can carry at W (bits/sec). Because W is fixed then the contention is reduced when r is reduced. Therefore deducing power level reduces r that also reduces the contention.

3. The impact of power control on total energy consumption depends on the energy consumption pattern of the hardware.

   Power consumption has five components [4]: PRXelec (the power consumed in the receiver electronics), PTXelec (the power consumed by the transmitting electronics), PTXRad (power consumed by the power amplifier to transmit a packet) PIdle (power consumed when the radio is on but no signal is being received) and PSleep (the power consumed when the radio is turned off). PRXelec, PTXelec and PTXRad are present when the wireless communication is working and based in these values we can formulate some design principles:

   A) If PTXRad dominates, then using low power levels is broadly commensurate with energy efficient routing.
   B) When PSleep is much less than PIdle, then turning the radio off whenever possible becomes an important energy saving strategy. Power management protocols seek to put nodes to sleep while maintaining network connectivity and buffering packets for nodes that are sleeping.
   C) When a common power level is used throughout the network, then exists a critical transmission range (rcrit) below which transmissions are sub-optimal with regards to energy consumption.

4. When the traffic load in the network is high, a lower power level gives lower end-to-end delay and when the traffic is lower then a higher power gives lower delay.

End-to-end delay is the sum of processing delay, propagation delay and queuing delay that a packet experiences at each hop. Processing delay grows linearly in the number of hops and is inversely proportional to the range, queuing delay depends on the medium (interference of the neighbors) and propagation delay depends on the end-to-end distance.

Then the higher transmit power the higher queuing delay and the lower transmit power the higher processing delay. If we have a low load processing delay became significant then the use of a higher transmit power reduces its effects. Furthermore, when the load in the network is high queuing delay dominates and it is desirable to use a low transmit power to reduce the total end-to-end delay.

2.5 Examples of Power Control Protocols

Now let take a quick review of the power control protocols

2.5.1 COMPOW

Narayanaswamy et al. [2] propose COMPOW, this protocol aims to operate all nodes at a common power level that is chosen to be the smallest power level at which the network is connected. The implementation is in the network layer with a plug and play capability respecting the IP hierarchy. The main assumption of the protocol is the use of bi-directional links; the solution is built based on homogeneous nodes that transmit at the same power. If two nodes N and M transmit at the same power then M can hear N and M can hear M as well.

The power control protocol is situated as a network Layer protocol and one of the main functions of this layer is routing. As a conclusion, power control protocol impacts on the routes employed by network layer and vice-versa. Figure 2.6 shows the architectural design:

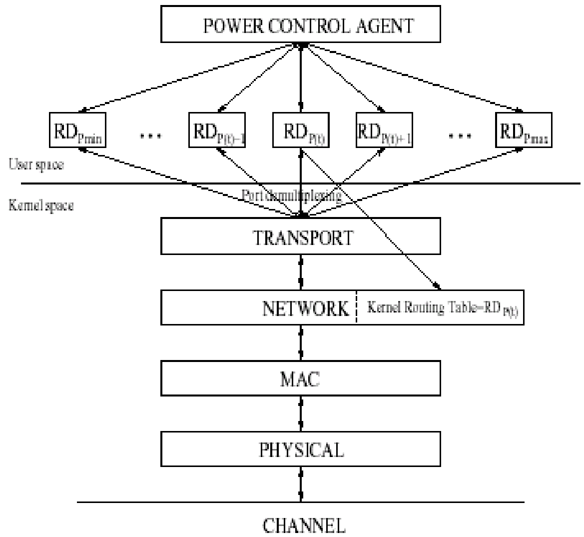


Figure 2.6 COMPOW: architectural design.

According to the architectural design it is necessary to maintain multiple routing tables (RT_{Pi}) in the user space (OS) where each one represent a specific transmit power level available (Pi). The routing tables are update by the routing daemons (RD_{P1},….RD_{Pmax}). Thus, the number of entries in RT_{Pi} gives the number of reachable nodes at Pi. Among the possible entries, a process (power control agent) within the kernel is going to use the smallest power level whose routing table has the same number of entries as that of the routing table at the maximum power level.

Thus, COMPOW protocol offers a simple solution by choosing a common power level to set to the lowest value, which keeps the network connected, therefore the energy consumption is the minimal required. However, the main drawback is COMPOW works well only in homogeneous space distribution. If a single node is far away of the nodes then every node at the network has to use the highest power level. When the distribution of the nodes is not homogenous, COMPOW is not the best solution.

2.5.2 CLUSTERPOW

CLUSTERPOW [3][6] is the enhancement of COMPOW that provide a solution when the distribution of the network is non-homogeneous. In this case each node (d), in the source node and the intermediate nodes, is allow to use a power level (p) that depends on the destination of the packet. Then the node forwards the packets with the minimal power level (p) that guarantees reaching the destination and it is reachable in one or multiple hops. The resulting from running the algorithm is a clustering (Figure 2.7).

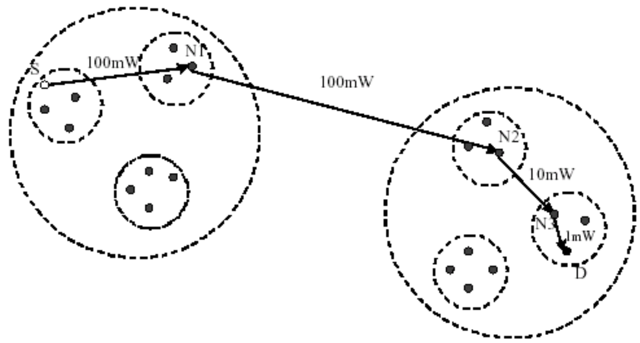


Figure 2.7 Routing by CLUSTERPOW.

The solution has three power levels (1mW, 10mW, 100 mW). To send information from node S to node D the 100 mW power level is used until the packet reach node N2, then it uses 10 mW to reach N3 and finally 1 mW to reach node D.

The architecture is described in Figure 2.8 (similar to COMPOW)

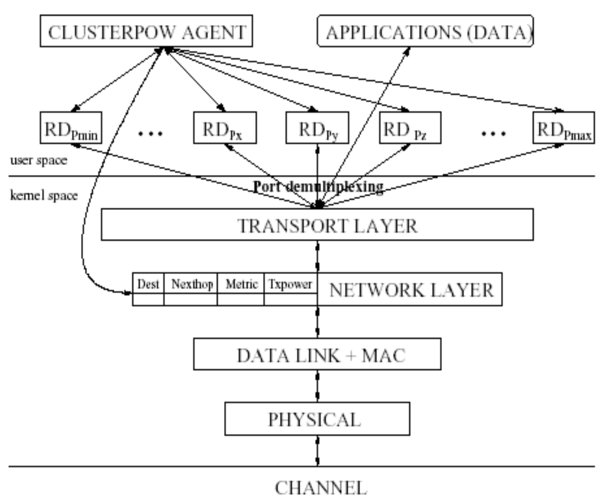


Figure 2.8 CLUSTERPOW architecture.

The idea is to add CLUSTERPOW into the IP stack at the transport layer. The protocol runs several routing daemons one for each power level Pi. Each routing daemon (RD_{P1},….RD_{Pmax}) in each node builds its own routing table $RT_{Pi,}$ by using hello packets transmitted at power level Pi, with its peer routing daemons of the same power level. Figure 2.9 shows how the algorithm works after the routing tables are built.

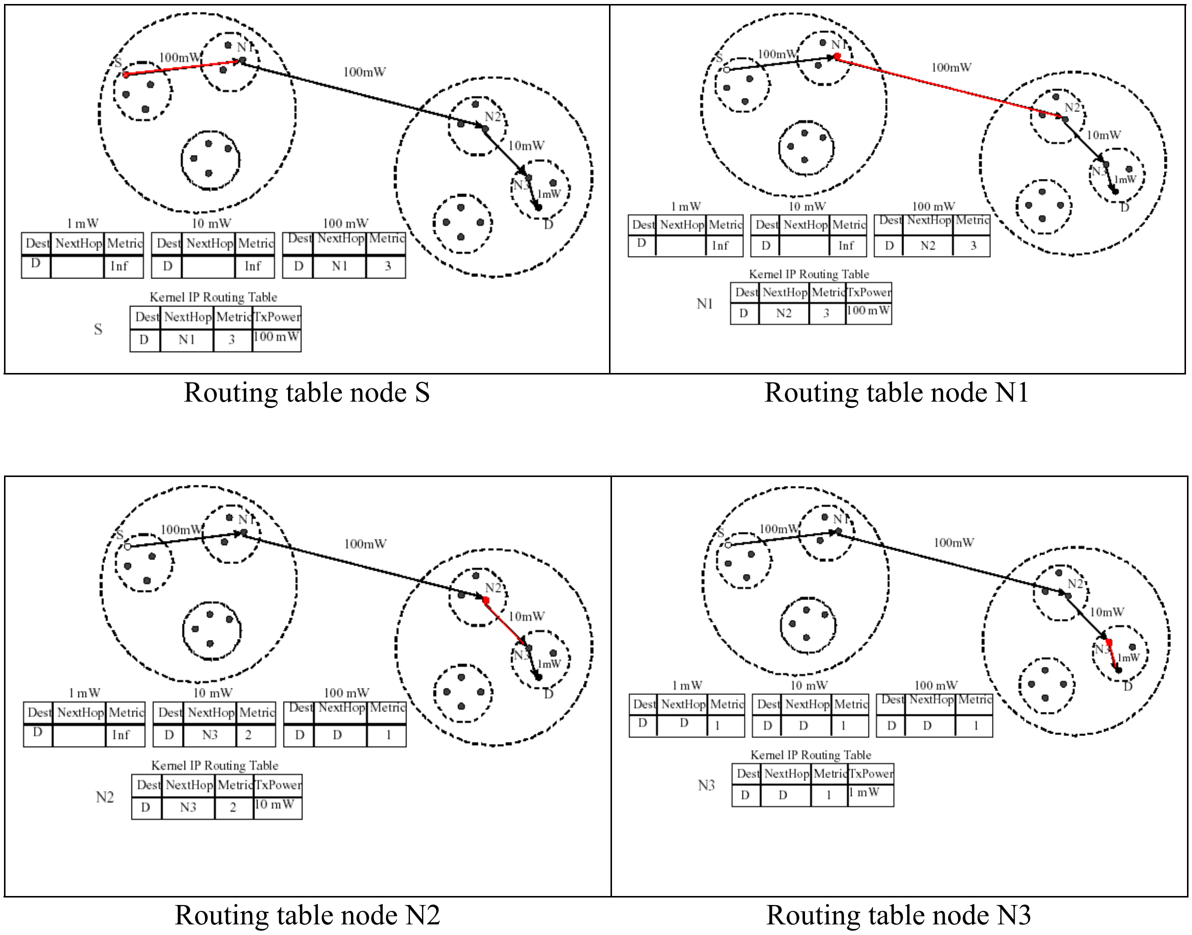


Figure 2.9 Routing tables.

Figure 2.9 shows a field called Metrics. Metrics is a parameter for the algorithm to decide which route is the best when there is more than one option. Metrics can be the energy consumption. Other metrics can be signal strength, transmit cost of the link, the remaining battery life of the nodes. Energy consumption is the best candidate since it does not require support from the physical layer.

2.5.3 The PCMAC Power Control Medium Access Protocol

Lin et al. [9][10] propose an enhancement to the standard IEEE 802.11 MAC protocol by improving the handshaking mechanism and adding one separate power control channel to notify its neighbors its noise tolerance. In that fashion, the neighbors can adjust the transmission power in order to avoid collisions at the receiver.

They analyze the reception area and divide it in two zones: decoding zone and carrier sensing zone. The first one is for decoding a packet correctly and the sensing is for detect the present of the neighbors. Both zones can change when the power level is adjusted then we have an asymmetrical link problem.

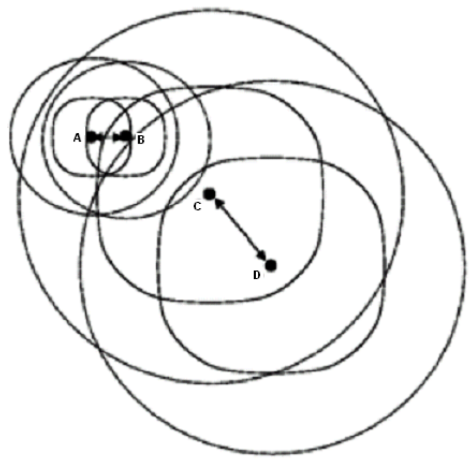


Figure 2.10 PCMAC Protocol.

In the Figure 2.10, A receive data from B and also C from D. C and D are outside the carrier sensing of A and B then C cannot sense the signals sent by A or B. C can cause packet collision to B when the transmission power is high enough. Under this scenario, there is an inefficient usage of the wireless channel resources then it is necessary to eliminate the collisions without sacrificing the network capacity and ensuring the fairness among all neighbors.

Lin's proposal, called power control medium access PCMAC protocol intent to eliminate the negatives effects introduced by the asymmetrical links. A separate power control channel is used to avoid collisions; data and signal (sensing signals: ACK, RTS and CTS) packets are transmitted at the most desirable power level.

The assumptions to be consider are:

1. The new power control channel has no interference on the data channel, thus they assume the use of channels one, six or eleven that have no co-channel interferences.
2. Signal Propagation is the same in both directions.
3. There is also collision in the power control channel.
4. The length of data packet is fixed to 512 bytes.
5. The power transmission is limited by the smallest signal noise ratio in the neighborhood.

Each node at the ad hoc network has two tables, one for sending packets and another for received packets. The sender and receivers records the sequence number and the session ID when a packet is transmitted or arrived; the ID is unique and identifies a source-destination pair.

To evaluate the algorithm they use Ns-2 [5] simulator and increase the traffic in the network until it gets saturation then they consider the parameter Aggregate Network Throughput as the average number of data packets arrives at their destination per second in the network, Figure 2.11. In the figure, PCMAC has the highest throughput; the improvement is about 8-10% compared with the basic IEEE 802.11 MAC protocol without power control. Power control allows concurrent transmissions that increase the network capacity. Besides the basic IEEE 802.11, the authors consider two schemes. In Scheme 1, RTS/CTS are transmitted at normal power level while DATA and ACK packets are transmitted with minimal power. In Scheme 2, all the packets are transmitted at the desired power level.

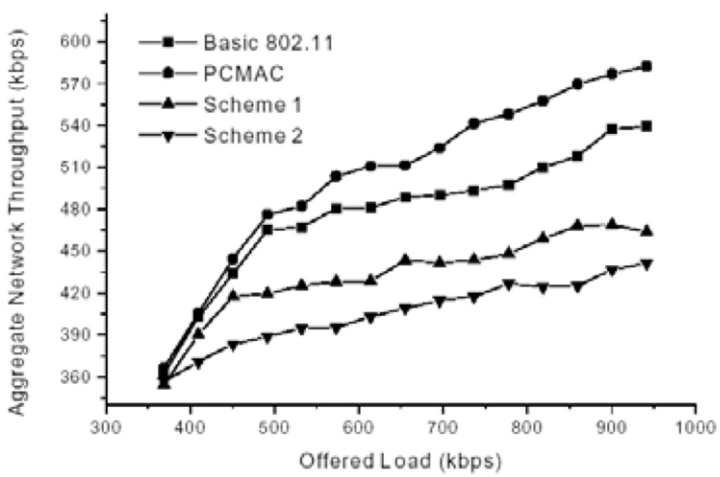


Figure 2.11 PCMAC Throughput vs. Offered Load.

In Figure 2.12, they also evaluate the Average End-to-End Delay as the time for a packet transmitted from its source to the destination.

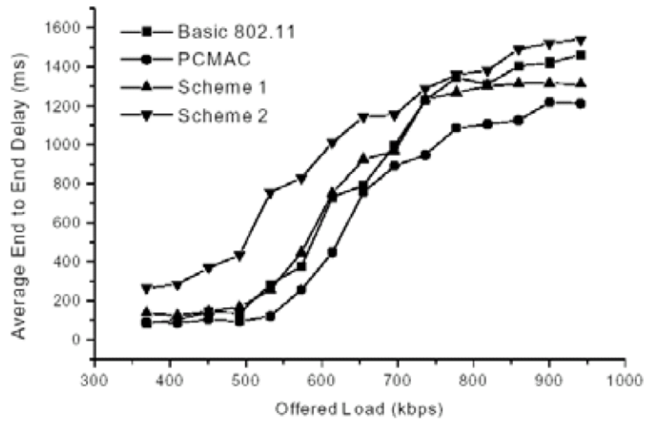


Figure 2.12 PCMAC Average End-to-End Delay vs. Offered Load.

PCMAC increase the throughput by about 10% with respect to Basic 802.11

2.6 Discussion

The number of nodes, which are source of interference in ad hoc wireless networks, limits the capacity of the network. The use of Power Control Protocols can improve the performance and they do not demand modifications in the physical layer. Analytical expressions like Gupta and Kumar [1] provide approximations and the justification for the use of these ideas. There are better approaches such as [8] (Jain et al.) however the problem here is the inputs (localization of the nodes and their workload) to compute the throughput. COMPOW and CLUSTERPOW are examples of how not only the throughput is improvement but also the contention time is reduced. Simulations under Ns-2 provide the quantitative estimate of these parameters. COMPOW protocol is not the more suitable option when the topology is non homogeneous because the transmission range can reach the maximum power level that is close to use the standard 802.11 with a reactive or proactive protocol. Adding the localization of the nodes in CLUSTERPOW protocol can improve the throughput more. The Power control is a cross layer problem that affects all the layers of the ISO model. The Power Control Protocols should be designed for the MAC layer or for the Network layer. The second case provides a more powerful solution since it optimizes several hops. Even through MAC optimizes one hop is must be the start point for moving to the next level.

Chapter 3 IEEE 802.11 Standard

3.1 Introduction

This chapter will review the IEEE-802.11 standard based on [11][12][13].

The IEEE 802.x protocols defined the technology of local area networks (LAN) that transport data with or without cables. IEEE 802.11, WI-FI, is a family of communication protocols that defines the use of the two lower layers of the OSI architecture: the physical layer and the link layer. The standard indicates the structure of wireless local area networks (WLAN).

The original 802.11 standard dates from 1997 when the speeds ranged from 1 to 2 Mbps and worked in the band of 2.4 GHz. The term IEEE 802.11 refers to this protocol and is known as "802.11 legacy." At the present time, wireless cards do not use this standard. The following generation, 802.11b, appeared in 1999 and can achieve speeds of 1, 2, 5.5 and 11 Mbps, in the band of 2.4 GHz.

In 1999, a modification to 802.11a was made. It allowed speeds up to 54 Mbps on the band of 5.0 GHz; however, it was incompatible with 802.11b products. For that reason, it disappeared from the market. A later iteration of the standard, 802.11g, is compatible with 802.11b. Nowadays, most of products follow the specification b and g. The next standard, 802.11n, will increment the speed limit to 600 Mbps. The improvements in 802.11n are not only speed but also security. The other standards of the 802.11 family (c-f, h-j, n) are improvements on the services, extensions or corrections to the previous specifications

The first standard of this family that had an ample acceptance was 802.11b. In 2006, most of the products that were commercialized follow the standard 802.11g with compatibility towards 802.11b. Standards 802.11b and 802.11g use bands of 2.4 GHz that do not need permissions for their use. Nevertheless the networks that work under the standards 802.11b and 802.11g suffer from interferences produced by microwaves, telephones and other electronic equipment that uses the same band.

3.2 Network Architecture

Wireless networks that use standard 802.11, can be classified as ad hoc networks or networks with infrastructure. The networks with infrastructure are characterized by their specialized nodes call Access Points (APs) that are in charge of communication between the nodes. An AP can form a Basic Service Set (BSS). In this case, an AP and one or more nodes compose the BSS. The BSS can be connected to a Backbone Distribution (DS), in that case an Extended Service Set ESS is generated.

On the other hand, the ad hoc networks do not need an infrastructure. That does not imply that the shipment of packages is just in one single hop. If a node, called A, needs to send information to another node, called B, and node A can reach node B then node A can use all the nodes along the path (intermediate nodes). The groups of nodes that interact in this fashion form an Independent Basic Service Set (IBSS). This characteristic makes ad hoc networks suitable for applications like laptop meetings, battlefields or communication with personal devices.

3.2.1 Components of a Wireless Network

Figure 3.1 shows the architecture of a network wireless:

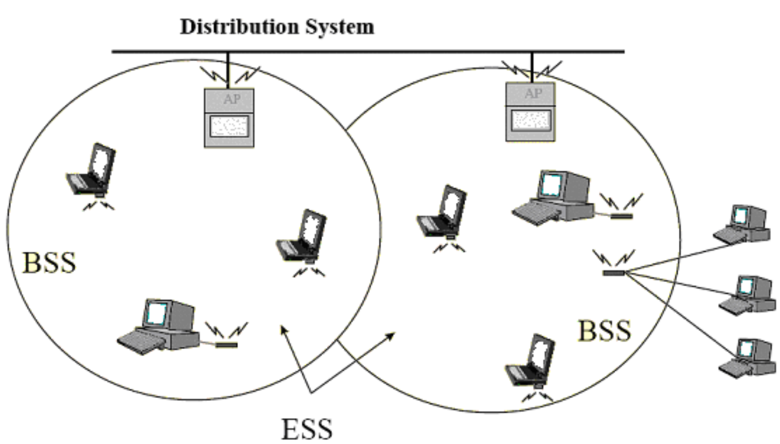


Figure 3.1 Architecture of a Wireless Network.

The elements in the architecture are:

- **Stations (STA):** computers, laptops or devices with a wireless interface.
- **Media**: radio frequency or infrared.
- **Access Point (AP)**: acts like a bridge connecting two networks with similar or different levels of connection; if the frames are different makes them compatible.
- **Distribution System:** provides mobility between APs. It controls the location of a destination AP to the frames.
- **Basic Service Set (BSS)**: Group of stations that can intercommunicate among themselves. There are two types:
    1. Independent: stations intercommunicate directly.
    2. Infrastructure: stations communicate by using an Access Point (AP).
- **Extended Service Set (ESS)**: union of several BSS.
- **Basic Service Area (BSA)**: zone where the stations of a same BSS can communicate.
- **Mobility:** this it is an important concept in wireless networks, indicating the capability to change the location of the terminals, varying BSS. The transition will be allowed if it is made within the ESS. Otherwise, it is not possible.
- **Limits of the network:** The limits of 802.11 networks are diffuse since different BSSs can be overlapped.

3.2.2 IEEE 802.11 Services

The services are offered by the APs and by the STAs. The services that provide the AP within the BBS are:

- Association: reporting to the AP the identifiers of the mobile stations and their MAC address. This task is completed before transmitting or receiving frames in the WLAN and the goal is to facilitate the routing of the frames.
- Reassociation: allows a node (STA) to move from one BSS to another by transferring the association to another AP.
- Disassociation: When an STA leaves the BSS sends a notification to the AP indicating that the association is over.

The services offered by the AP in the DS are:

- Distribution: this service in charge of the routing of the frames. If the transmitter and the receiver are in the same BSS then the frames are transmitted directly. Otherwise, the frames are transmitted using the APs that are between of the transmitter and the receiver.
- Integration: manages frames that are not 802.11. It interprets the formats and the addresses of frames.

The services provided by the STA (including the AP) are:

- Authentication: this procedure makes identity validation of the stations in the wireless network. The mechanisms go from uncertain handshaking schemes of interchange to encrypted keys.
- Deauthentication: this procedure closes an authenticated connection once it has finished the data interchange.
- Privacy: It provides encryption services and private keys. For instance: WEP and WAP protocols.
- Delivery of data: it is the mechanism that transmits and receives data. However, the data delivery does not guarantee that the data is reliable

3.2.3 Mobility and transitions in 802.11

Since the nodes of a wireless network are mobile is possible that transitions take place due to the displacements. A node that belongs to a BSS can move from one BSS to another or from one ESS to another one. When the nodes are restricted, they only can move within a single BSS. When there are transitions from one BSS to another one the MAC layer must support roaming operations. When the displacements go from one ESS to another the service must be interrupted and the network must support IP mobility.

3.3 Description of the layers of the IEEE 802.11 standard

IEEE 802.11 standard covers the layer MAC (connection layer) and the physical layer. According to the standard the MAC layer can interact with three different types of physical layers: Frequency Hopping Sequence Spread Spectrum (FHSS), Direct Sequence Spread Spectrum (DSSS) and Infrared (Figure 3.2).

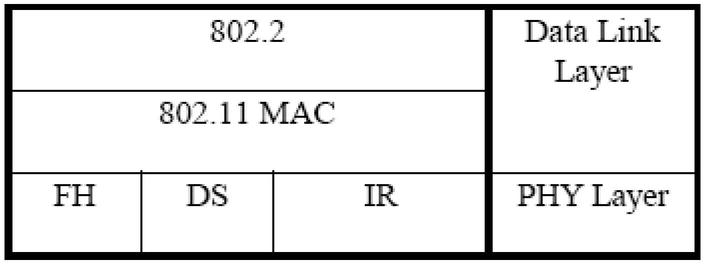


Figure 3.2 Architecture of IEEE 802.11.

The physical layer uses a frequency of 2.4 GHz for the carrier and different techniques for modulation. For 1 Mbps BPSK (Binary Phase Shift Keying) and for 2 Mbps QPSK (Quadrature Phase Shift keying) modulations are used. QPSK can codify as much as twice information as PSK because it uses four rotations to codify two bits of information; PSK codifies one bit.

When DSSS is used by 802.11b, it takes as an input a flow of ones and zeros, and modulates them with a pattern called chipping sequence. In 802.11, this sequence is known as Barker code and it has eleven bits (10110111000). The basic data stream is exclusively OR'd with the Barker code to generate a series of data objects called Chips. Therefore, each bit is codified by 11 bits (Bar Code) and each 11 groups of Chips codifies a bit. In order to reach speeds of 11 Mbps it is mandatory to change the form to codify the data. In this case, CCK (Complementary Code Keying) is used instead of Bar Code. CCK uses a series called complementary sequences codes.

3.4 IEEE 802.11 Protocol Stack

Figure 3.3 shows the 802.11 protocols stack

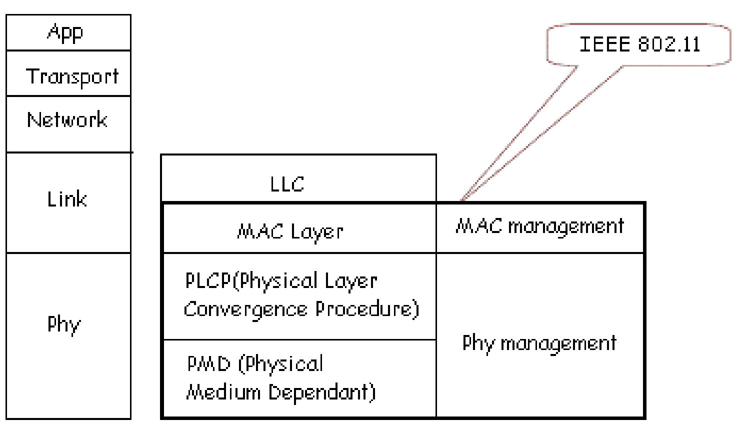


Figure 3.3 IEEE 802.11 Protocols Stack

3.4.1 The physical layer

The physical layer has two parts: PLCP (Physical Layer Convergence Protocol) and the PMD (Physical Medium Dependent). The PMD layer is in charge of coding and decoding bits using Bar Code or CCK modulation. The PLCP sublayer is the interface for the link layer and provides the carrier sensing mechanism and CCA (Clear Channel Assessment). CCA is a signal that the MAC layer needs to identify whether the channel is idle or busy. The frames in 802.11 standard have four fields as shown in Figure 3.4.

Figure 3.4 IEEE 802.11 frame.

The PLCP Preamble field depends on the physical layer. The PLCP Preamble has a sub field for synchronization and another one for delimitation (Figure 3.5). The synchronization field is a sequence of zeros and ones for selecting the type of antenna and for setting up the packet synchronization. SDF (start frame delimiter) is 16 bits used for defining the frame timing in the basis of a pattern whose value is equal to 000 1100 1011 1101. In addition, PLCP preamble is used by the CCA mechanism to establish when the media is idle.

The next field, PLCP header, is always transmitted at 1 or 2 Mbps and includes information used by the physical layer for decoding the frames. The subfields are: 'signal' to indicate the rate ratio, 'service' equal to 0 if the frame is 802.11 compliant, 'length' to indicate the payload length in micro seconds and 'hec' detects error in the transmission (CRC-16). Figure 3.5 shows the fields and its values.

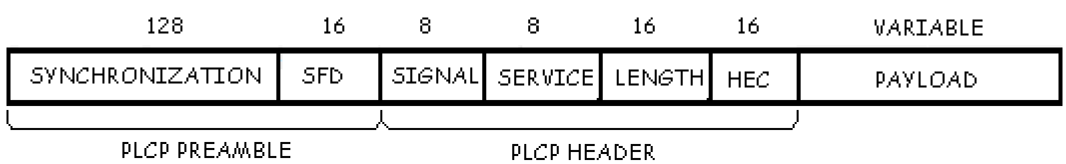


Figure 3.5 IEEE 802.11 frame. PCLP Preamble and PCLP Header

In the case of 802.11b, PLCP preamble consists of 144 bits, 128 for synchronization followed by 16 bits with the pattern 1111001110100000 (SDF), which indicates the start of the PLC header. The next 48 bits are the PLCP header. The subfield ‘signal’ indicates how fast the payload will be transmitted (1, 2, 5.5 or 11 Mbps). The ‘service’ subfield is reserved for future applications. The ‘length’ is in microseconds and depends on the payload. ‘Hec’ is a CRC-16 for the 48-bits of the PLCP header. The fact that the PLCP is always transmitted at 1 or 2 Mbps degrades the performance of the 802.11b.

3.4.2 The Link layer

802.11 implements a MAC layer inside the Link layer. The primary function of the MAC is arbitrating and multiplexing the transmission requirements of the different nodes that operate in the area. This function is important since the media is shared and it is assumed that all the nodes can transmit at any time. Therefore, the MAC layer adopts policies to avoid or reduce collisions and the contention time. Other functionalities are roaming, authentication, and power consumption.

3.4.2.1 Basic service

The basic services are two. The first one serves to send data in asynchronous manner (mandatory) and the second is to send data in real time (optional). The asynchronous service supports unicast and multicast packets. The service of single real time is supported in networks with infrastructure where the AP plays the role of a referee that determinates who has access to the media. The basic service is a CSMA/CA mechanism (Carrier Multiple Sense Access with Collision Avoidance).

In CSMA the nodes work the following way: the transmitters sense the media and if the media is busy then the node backs off for a period of time and returns to sense the media. Once the media is idle, the transmitter sends the data. This policy gives very good results when the media does not have heavy traffic. When the traffic is elevated, there are collisions in the media produced by the transmission from two nodes that found the media idle at the same time.

If the collision is detected in the MAC layer then the packet could be retransmitted at that level and not by the other OSI layers. In that fashion, delays in the transmission are reduced. When a collision occurs in CSMA/CD an algorithm called exponential random backoff is used. This type of algorithm is not adapted for wireless networks since it requires full duplex radios which transmit and receive data simultaneously and which increment the price of the hardware. In addition, in wireless environments it is not possible to assume that all the stations can hear each other because of the possibility of hidden terminals can occur: sensing the media does not guarantee that it is idle.

In the Figure 3.6 the hidden terminals problem is presented. In this case, station A wants to communicate with station B and at the same time station C wants to communicate with station B. Station A does not notice the existence of station C since it is not in its range. A similar assumption is made for station C. Station C may be exposed to collisions because A, B assume that the media is idle all the time.

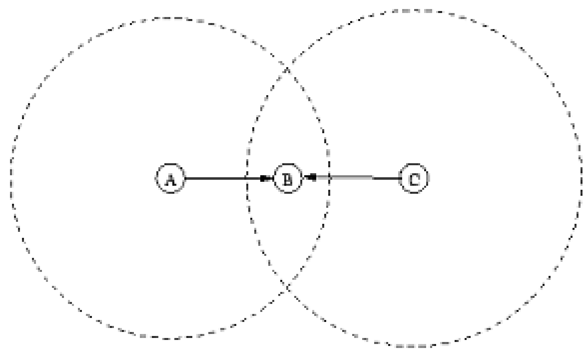


Figure 3.6 Hidden terminal problem.

The Collision Avoidance mechanism works the following way: when one node wishes to transmit data it senses the media for a certain period of time and if it is idle sends the information. The receiving node by its side receives the information and uses the field CRC to review that the data is correct. If the verification of the data is fine, the receiver sends back an ACK packet indicating that everything arrived without errors. In case there are errors, the transmitter will not receive the ACK and therefore it retransmits the data. This process takes effect it is surpasses a limit and then the packet is dropped.

3.4.2.2 802.11 MAC: DCF and PCF

The primary access to 802.11 is by using DCF (distributed coordination function), based on CSMA/CA to avoid the problem of hidden terminals. Another option is to implement the DCF with RTS/CTS where RTS and CTS are signaling packets that eliminate the hidden terminal problems. The third option is to use PCF (Point Coordination Function). In this case, the AP is the ones in charge of coordinating the transmissions according to a priority list.

Interframes Spacing (IFS)

Interframes spacing are the time intervals that happen between the interchanges of data. There are four types appraised in Figure 3.7.

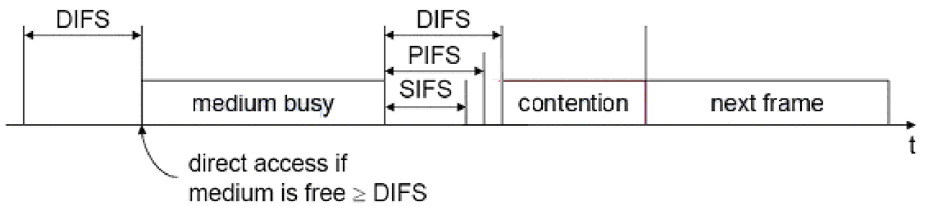


Figure 3.7 Interframes Spacing.

These spaces of time denote the priority access to the channel. When IFS is short, higher priority is assigned so that the time of delay is smaller. The IFS values depend on the specifications of the physical layer.

- SIFS (shortest InterFrame Spacing) is defined for the messages of control like the ACK (acknowledgments). All the packages that are sent must wait at least for a SIF. Typically, it is 20 microseconds for DSSS and 50 microseconds for FHSS.
- PIFS (PCF, InterFrame Spacing) is used for the services of real time and their values are between SIFS and DIFS.
- DIFS (DCF InterFrame Spacing) is employed by the nodes that use a DCF scheme to communicate. This delay is for asynchronous data transfer.
- EIFS (InterFrame Spacing) is the longest IFS (minimum priority). It is used for resynchronization when a problem of reception in the layer is detected.

3.4.2.3 802.11 DCF: CSMA/CA

In this case, CSMA/CA is used. In DCF, the stations that send information must contend with others. Before sending a frame, the station has to sense the channel. If the media is idle for at least one DIFS then the station can use the channel. Otherwise, the station begins a backoff procedure. The backoff time is equal to slot time multiplied by a random number between 0 and CW. CW is the value of the contention window, which is in the range of 15 to 255. Figure 3.8 shows the procedure.

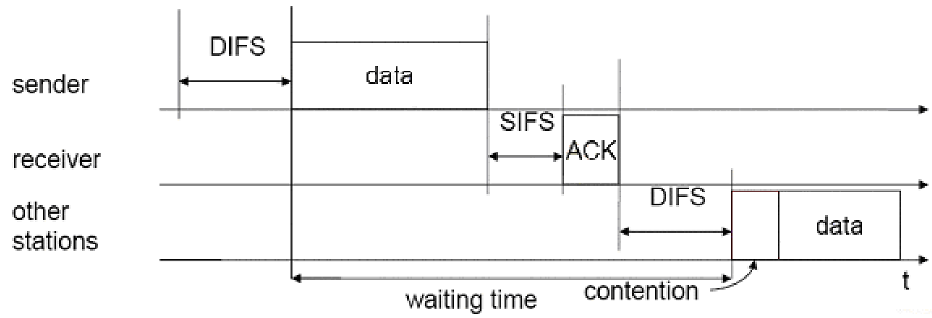


Figure 3.8 802.11 DCF: CSMA/CA.

If the node is in the procedure of backoff and the channel is idle then the time of backoff is decremented. The station that reaches the value of zero in the time of backoff can transmit data. The phase of contention always begins between data transmissions. If the ACK is received successfully, the backoff procedure is reinitiated after receiving the ACK. Otherwise the procedure begins after the timeout of the ACK.

A collision can happen if two or more stations detect that the channel is idle and they wait for a period of DIFS. When the DIFS finish the transmission begins. When a collision takes place, the backoff mechanism is also affected. In order to resolve repeated collisions the value of the contention windows is increased as 2*CW+1 (15, 31, 63, …). If the contention window surpasses the maximum value then the contention window takes the maximum value for CW and new calculations for CW are not necessary.

3.4.2.4 RTS/CTS Mechanism

The hidden terminals problem reduces the performance of a network. Collisions take place when two or more terminals transmit at the same time to the same node. Collisions reduce throughput of the network and should be avoided. In order to alleviate the problem the mechanism RTS/CTS is used (request to send / clear to send). Figure 3.9 shows the RTS/CTS dialog working:

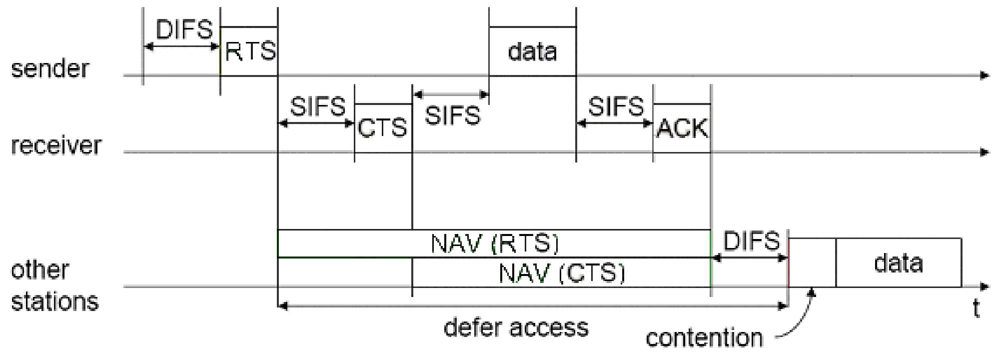


Figure 3.9 RTS/CTS dialog.

If a node is going to send DATA packet then it must sense the channel and the channel must be idle for at least one DIFS. At that moment, a RTS (request to send) packet is sent by the transmitter. The package contains not only the request but also the time Network Allocation Vector (NAV). The NAV indicates the time that the transmitter needs to complete the transmission.

After a DIFS, if the channel is idle on the receiver side then the receiver node responds with CTS (clear to send) packet. After another SIFS, the data transmission begins. If the data arrived without errors then the receiver node is going to send an ACK packet to indicate that the transmission finished successfully. It must notice that the CTS packet informs all the nodes in the receiver range that the channel is going to be busy because the CTS packet includes the NAV as well.

The RTS/CTS dialog avoids the collisions but it has an overhead cost. It is used in agreement with a parameter called 'threshold'. When the size of the transmitter frame is greater than the threshold then the RTS/CTS mechanism is working, otherwise it is disabled. When the packet size is smaller, the probability of a collision is lower. Thus, overhead should be avoided.

Chapter 4 Simulation

The chapter presents the description of the tools used in the research. The goal is to create a platform to simulate wireless networks with adaptive power. Simulation software is based on the Network Simulator 2 (Ns-2) [5].

In order to capture the reused space it is mandatory to build a new module called Pmin802.11. This software component modifies the original 802.11 MAC layer of Ns-2. At the beginning of the simulation, some assumptions are made:

- The location of the nodes and the propagation model are known.
- Channel reciprocity, then the gain between two nodes is approximately the same in both directions.
- The channel gain is stationary for the duration of the control and data packets transmissions.
- The power supply does not affect the gain. The gain from the transmitter to the receiver is the same as the gain from the receiver to the transmitter.
- The slow fading is caused by the path loss because of the separation between source and destination and shadowing due to the objects between the source and the destination. On the other hand, the fast fading is caused by multipath (due to multiple paths between sender and receiver and which are combined at the receiver). During the simulation, multipaths are smaller and path loss and shadowing have no effect because nodes do not move during transmission.
- The software can send every frame in the network with a specific level of power. In addition, each transmitter node has a table that sets the level power needed for the frame to reach the receiver nodes. The receivers send back information with the same power level. To accomplish that, a new field was added to the structure of the packets. This

field contains the transmitter power and from which the receiver node can extract and reuse to send back information to the transmitter.

There are definitions at the beginning of the chapter, (interference ranges and propagations models). After that, the operation of Ns-2 is presented followed by the formulas used in the Pmin80211 module. As a part of the validation of the simulation software, examples are presented which include Ns-2 utilities and basic cases. As mentioned previously IEEE 802.11 is a family of standards that describe the interfaces for wireless LAN networks. IEEE 802.11b was used in the simulations because it is implemented in the Ns-2 simulator and because it is the most popular interface in the market, there is abundant information that details its performance.

The basic cases are simple topologies that include two or four wireless nodes with one or two connections. For traffic Constant Bit Rate (CBR) with UDP and File Transfer Protocol (FTP) with TCP were used. In each case, the RTS/CTS dialog is enabled and disabled. The resulting contrasts show accurate approximations.

4.1 Interference ranges

RTS/CTS mechanism is used to solve the hidden terminal problem. However, there is a drawback because it assumes there is only one range for a wireless transmission [17][18]. Figure 4.1 shows three ranges. The outer circle represents the interference range; in this zone, the signal is not strong enough to be detected but is a source of interference; sometimes it could be compared to the noise floor. The second range is the Carrier Sensing Range; if a terminal is in this area then it could receive packets. The inner range is a secure area for communications. If a node is inside then it can hear all the packets that the transmitter node is sending.

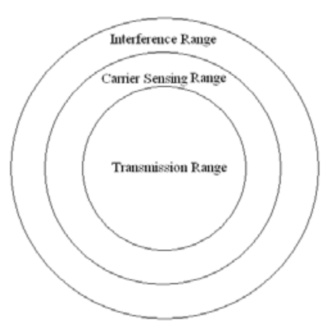


Figure 4.1 Interference Ranges.

RTS/CTS assumes just one transmission area. In real scenarios, the transmission process follows a probabilistic behavior. A node in the carrier sensing range could have a high probability if it is located close to the border with the transmission range. If the node is located close to the border with the interference range then the probability is lower. In addition, a node inside the transmission range could have a low reception probability whether another node is transmitting in the same range. In order to determine when a node is inside the transmission range, physical parameters can be used. For example: the Signal to Noise and Interference Ratio (SNIR) [20].

4.2 Network Simulator 2

According to its creators [5],

> "Network Simulator 2 (Ns-2) is a discrete event simulator targeted at networking research. Ns-2 provides substantial support for simulation of TCP, routing, and multicast protocols over wired and wireless (local and satellite) networks. Ns-2 is written in C++ and an Object oriented version of Tcl (Tool Command Language) called OTcl"

Ns-2 is used by many researchers because it has good technical support and it is open code. Thus, it is possible to add software modules to the existing version. Versions for Windows and Linux are available. In addition, Ns-2 has a group of tools that provide information about the simulation outputs.

4.2.1 Propagation models

There are three propagation models in Ns-2: Free space model (Friss), Two-ray ground reflection model and Shadowing model.

For the simulation, the Free-space model and/or Two-ray ground reflection model is used. In the first case, the model assumes ideal conditions. It means there is only one clear line-of-sight (LOS) between the transmitter and the receiver nodes. The second model considers the direction path and the ground reflection path. This model is more accurate than the Free-space model and it does not consider fading effects produced by multipath propagation models (indoor environments) like Shadowing model. In addition, this model defines a cross over distance 'crossover-dist', and if the distance, 'd,' between the transmitter and the receiver is less than 'crossover-dist' it uses Friss Free space model, otherwise it uses the Two-ray model. The power at the receiver is calculated by the formulas:

- Friis - Free space propagation equation:

$$P_r = \frac{P_t \; G_t \; G_r \; \lambda^2}{(4 \; \Pi \; d)^2 \; L}$$

Where, 'P_t' is the power at the transmitter, 'G_t' and 'G_r' are the transmission and receiving gains of the antennas (it is common to select 'G_t' and 'G_r' equal to 1). The distance between the transmitter and receiver is 'd'. 'L' is the system loss (usually is equal to 1), 'λ' is the wavelength (3E8/freq) and '$\prod$' is equal to 3.1416.

- The Two-ray ground reflection model depends on the equations:

$$crossover\_dist = \frac{(4 \; \prod \; h_t \; h_r)}{\lambda}$$

if d < crossover_dist, use Friis free space model

if d >= crossover_dist, use Two ray model :

$$P_r = \frac{P_t \; G_t \; G_r \; h_t^2 \; h_r^2}{d^4 \; L}$$

Where, 'h_t' and 'h_r' are the antennas heights of the transmitter and the receiver.

4.2.2 Thresholds

Ns-2 uses thresholds to determinate whether one frame is received correctly by the receiver. To know whether the frames arrive successfully Ns-2 used three parameters CSThresh (for carrier sensing range), RXThresh (for receiving sensing range) and CPThresh (for collision sensing):

- CSThresh is used to determinate when one frame is detected by the receiver. If the signal strength (calculated by the propagation model) is less than CSThresh then the frame is discarded in the Phy module (Physical Layer) and it is not visible to the MAC layer.

- RXThresh is used to determinate when one frame is received by the receiver. The signal strength of the arriving frame must be greater than RXThresh in order to be received correctly by the receiver; otherwise, the frame is tagged as corrupted and discarded by the MAC layer.

- CPThresh is used when a collision takes place at the receiver. In that case, the receiver node calculates the ratio of the strongest frame's signal strength to the signal strength sum of the others. If the result is larger than CPThresh, Ns-2 assumes that the frame arrived correctly and the others frames are ignored. Otherwise, all of them are tagged as corrupted and discarded by the MAC layer.

As you can see, Ns-2 applies CSThresh and RXThresh to define the interference ranges. If the signal strength is greater than the CSThresh, then the frame is inside of the carrier sensing range. If the signal strength is greater than RXThresh then the frame is inside the transmission range. CPThresh is a parameter for determining the destiny of a collision.

Ns-2 does not use Signal to Noise and Interference Ratio (SNIR) to determinate whether a frame is correct or not. However, it is possible to calculate SNIR by adding code in the MAC module [15]. To calculate SNIR it is necessary to know the signal strength (computed by the distance and the propagation model) and the value of noise and interference.

According to [15][16], noise comes from the environment (which includes the thermal noise and the platform noise) and the interference is produced when more than one frame arrives at the receiver at the same time. Thus, CSThresh should be identical to the noise floor. SNIR is a parameter for the physical layer; however, the only place to compute that parameter is at MAC module because that is where the level of interference (collisions) is known. The formulas for calculating SNIR are:

$$SNIR = 10 \log \left(\frac{Rx\_Power}{Noise} \right)$$; if only one frame is receiving by the receiver

$$\text{SNIR} = 10 \log \left(\frac{\text{Rx\_Power}}{\text{Noise} + \sum \text{Rx\_Power}} \right) \quad \text{;if a collision takes place.}$$

Therefore, SNIR must be a value equal or greater than RXThreshold. In addition, Ns-2 uses CPThresh to determine whether the frame is correct or not. The drawback here is that the Ns-2 does not replicate exactly the reality because as soon as the signal strength is less than RXThreshold the frames are dropped; however, some of these frames should be interpreted as a correct frames.

4.3 Minimum and Optimal Power

When there are two nodes the transmitter node 'x' and the receiver node 'y' a wireless communication takes place. The Minimum Power 'Pmin(x,y)' is defined as the power level that the transmitter node uses to communicate with the receiver and it is the minimal value that ensures the receiver node is inside the transmission range. This Minimum Power is calculated on the basis of the location of the nodes and the propagation model. The minimal power could not be the optimal power (transmission power that ensures maximal throughput in the network) when the traffic is heavy the network. The more traffic the more interference in the network. The optimal power is the minimal power multiplied by a parameter (called ALPHA) that is equal or greater than one.

4.3.1 How to calculate the Minimum Power

In order to calculate the Minimum Power, 'Pmin', a new module is added to Ns-2 called Pmin80211. The module takes as an input the location of the nodes and the propagation model (which includes the values for 'G_t', 'G_r', 'λ', 'h_t', 'h_r'). At the beginning of the simulation, it assumes the location of the nodes, the propagation model, the transmitter nodes and receiver nodes are known. The main function inside the module is:

FramePowerMin(Tx node, Rx node, RxThresh_, G_t, G_r, lambda, sysLoss, h_t, h_r)

It calculates the Pmin for a transmission between two nodes. The function uses the parameters 'Tx node' and 'Rx node' as the identification of the transmitter and receiver node and the algorithm extracts the location of those nodes. The next value is 'RxThresh', and it represents the minimum signal strength that the MAC module in Ns-2 needs for a valid frame. We can call this value the transmission condition. The others parameters are explained above. The following expressions compute the Pmin:

- Friis - Free space propagation model:

$$Pmin = \frac{RxThresh\ \ ((4\ \ \Pi\ \ d)^2\ \ L)}{G_t\ \ G_r\ \ \lambda^2}$$

- The Two-ray ground reflection model:

crossover_dist = $(4\ \ \Pi\ \ h_t\ \ h_r) / \lambda$;

if d < crossover_dist, use Friis free space model

if d >= crossover_dist, use two ray model

$$Pmin = \frac{RxThresh\ \ (d^4\ \ L)}{G_t\ \ G_r\ \ h_t^2\ \ h_r^2}$$

The module Pmin80211 works at the MAC Layer, specifically it works at the same level of the IEEE 802.11 module (link layer). If the node has for instance three connections then it has to calculate three 'Pmin' values. In order to store the 'Pmin' values a table is defined (one per node) at the MAC layer. At the beginning, the table is empty and each time a new connection occurs, Pmin80211 module calculates the new 'Pmin' and adds that value into the 'Pmin' table. In the process, Pmin80211 module also includes the ID of the receiver node and distance between the transmitter and receiver. This procedure occurs just once. When a new frame is ready to be sent the MAC Layer searches for the ID of the receiver in the 'Pmin' table; if the ID exists then it extracts the 'Pmin' value. The maximum number of entries in the 'Pmin' table is 10. Thus, each node can operate 10 concurrent connections.

It is also important to mention that the original MAC layer was modified. Now, the MAC layer handles a new field in the frames. This field indicates the 'Pmin' used by the transmitter node when it sent the packet. In that manner the receiver node can extract the 'Pmin' and return a message with the same power level.

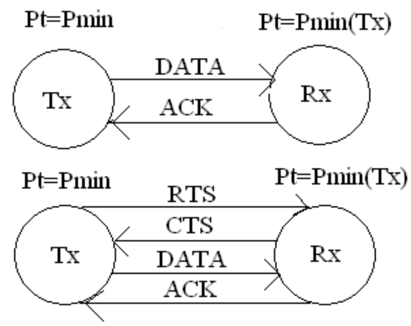


Figure 4.2 New MAC layer.

In the top of Figure 4.2 the transmitter node, calculates the 'Pmin' for sending DATA to the receiver node (in this case the RTS/CTS dialog is disabled). 'Pmin' is included in the frame and the physical layer use the 'Pmin' value. After the receiver node receives the DATA correctly, it sends back an ACK to the transmitter node. The interface is set up with the same 'Pmin' employed by the transmitter. If the RTS/CTS mechanism is enables then the 'Pmin' for the fields provide the CTS packets included in the RTS packets. The packets in general can be classified as broadcast or unicast packets. If the packets do not have a specific destination then they are broadcast packets. The discovery services (routing algorithms) use broadcast packets and RTS and CTS belong to this category as well. Since this is a one-hop topology, the power level for routing packets must be big enough to reach all the nodes in the network. On the other hand, RTS and CTS also include the NAV and if those packets use the same power level as the routing packets then the spatial reuse is impossible. All the nodes in the network could wait since they receive the NAVs.

In the network, the nodes could have more than one connection with one or more nodes at the same time and the distances between the transmitter nodes and the receivers nodes could not be the same. Therefore, the frames need different transmission levels. The simulation software can fulfill that work by using a transmission power table. New entry is added to the table each time the transmitter node needs to send information to a new receiver node. The table is handled by the MAC layer.

4.3.2 Parameters

The first task to fulfill before beginning the simulations is to identify the main characteristics of the standard IEEE 802.11b. It has a series of parameters, such as: multiplexing type, modulation type, maximum dates rate, among others. Table 4.1 shows the parameters that characterize an interface 802.11b [19]:

Parameter	Value
Multiplexing	Direct sequence spread spectrum (DSSS)
Modulation	Complementary code keying (CCK)
Maximum data rate	1, 2, 5.5, and 11 Mbps data rates (payload)
Basic data rate	2 Mbps (RTS, CTS, ACK packets)
PCLP data rate	2 Mbps (preamble)
Operating in	2.472 GHz. ISM band
PLCP preamble	144 bits. Synchronization and SFD (bits and start frame delimiter)
PLCP header	48 bits. PLW (PLCP_PDU length word), PSF (PLCP Signaling Field) and HEC (Header Error Check)
Tslot	20 usec
SIFS	10 us
Cwmin/CWmax	31/1023

Table 4.1 Parameters for IEEE 802.11b.

The parameters would be entered in the simulator by using variables in the physical and MAC layers.

4.3.3 Tuning

Ns-2 allows to simulate interfaces IEEE 802.11. By default, the parameters that the simulator contains are for 802.11 (legacy) interfaces. Therefore, at the physical and MAC layer it is necessary to change the default values with others that simulate the behavior of an IEEE 802.11b interface. The following list of parameters was modified in the Ns-2 simulator [15]:

```
Mac/802_11 set SlotTime_          0.000020        ;# 20us
Mac/802_11 set SIFS_              0.000010        ;# 10us
Mac/802_11 set PreambleLength_    144             ;# 144 bits
Mac/802_11 set PLCPHeaderLength_  48              ;# 48 bits
Mac/802_11 set PLCPDataRate_      2.0e6           ;# 2Mbps
Mac/802_11 set dataRate_          11.0e6          ;# Rate 1,2,5.5,11Mbps
Mac/802_11 set basicRate_         2.0e6           ;# 2Mbps
Phy/WirelessPhy set freq_         2.472e9          ;# freq
```

On the top of 802.11b, there will be connections that simulate transference of packages. Two cases are considered: CBR on the top of UDP protocol and FTP on the top TCP protocol. In both cases, it is necessary to fix the value of packet size. For UDP it is 1000 bytes. For TCP protocol the value of the congestion window (CWINDOW) is fixed to 36. The test was performed with the standard long preamble (144 bits).

Setting up not only the packet size but also the rate can control the load in CBR. In the case of TCP/FTP is not possible to control the load of FTP. FTP does not have a sending rate parameter. FTP is transported by TCP, which has a congestion window and flow control mechanisms of its own. Thus, the FTP rate depends on the performance of the underlying TCP protocol (best effort). If there are just two nodes in the network then TCP is going to take all the available capacity.

Another way to measure the performance of the FTP is by examining a file transfer. That is to say, at a certain moment the Ns-2 simulator begins the transfer of a fixed size file (for instance 10 MB). When the transfer is complete, it is possible to know the total time for the transmission. Also it is possible to calculate throughput and the average delay time per package.

4.4 Validation

To know if the values calculated by the Pmin80211 module are correct certain tests are performed:

- Ns-2 has several programs for checking the mathematical models. Under the directory ns-allinone-2.30/ns-2.30/indep-utils/propagation there is a utility program called 'threshold.o' that calculates the RXThresh:

```
[root@localhost propagation]# ./threshold.o

USAGE: find receiving threshold for certain communication range
(distance)

SYNOPSIS: threshold -m <propagation-model> [other-options]
distance

<propagation-model>: FreeSpace, TwoRayGround or Shadowing
[other-options]: set parameters other than default values:

Common parameters:
-Pt <transmit-power>
```

```
-fr <frequency>
-Gt <transmit-antenna-gain>
-Gr <receive-antenna-gain>
-L <system-loss>

For two-ray ground model:
-ht <transmit-antenna-height>
-hr <receive-antenna-height>

For shadowing model:
-pl <path-loss-exponent>
-std <shadowing-deviation>
-d0 <reference-distance>
-r <receiving-rate>
```

For example for two nodes with a distance of 280.03 meters between them, with a TwoRayGround model, Ptx = 0.000384084, frequency channel = 2.472e9, G_t=1, G_r=1, h_r=1.5, h_t=1.5:

```
[root@localhost propagation]# ./threshold.o -m TwoRayGround -fr
2.472e9 -Pt 0.000384084 280.0257

distance = 280.03
propagation model: TwoRayGround

Selected parameters:
transmit power: 0.000384084
frequency: 2.472e+09
transmit antenna gain: 1
receive antenna gain: 1
system loss: 1
transmit antenna height: 1.5
receive antenna height: 1.5
```

Receiving threshold RXThresh_ is: 3.16228e-13

```
[root@localhost propagation]#
```

The result is RXThresh= 3.16228e-13 (same as Orinoco wireless card). It means that if the card sends a frame with a power level of 0.000384084 it can reach a range of 280.03m.

The Pmin80211 computes the Pmin (or Ptx) when the distance between nodes, RXThresh, G_r, G_t, h_r, h_t, λ (3E8/freq) and L are provided. Some of the results are:

Rx	Tx	Distance	Pmin
1	8	280.03	0.000384084
1	9	55.28	1.03611e-05
1	10	115.17	4.49767e-05
1	11	148.41	7.46788e-05

```
1   12      292.44      0.000456852
1   13       66.30      1.49025e-05
1   14      126.84      5.45507e-05
```

The results confirm that the estimation is correct.

- ALPHA is special parameter inside the 'Pmin80211' used to compute the optimal transmission power.

  - ALPHA is defined as a constant that multiplied the 'Pmin' calculated by Pmin80211 module. Then, all the frames are transmitted in the topology with a power level equal to 'Pmin' times ALPHA. Now, let's assume we know the Pmin for nodes x and y. If ALPHA=1 we must reach node x from y and vice versa if ALPHA <1 it means that the frames are dropped.

  - Another test performed sets up ALPHA equal to 1 and checks the packets in the MAC and application layers. In the output, it is noted that all the data arrive without problems. However, when ALFA is equal to 0.99 dropped packets and timeouts appear in the simulation output.

4.5 Simulations

The next step is to test 'Pmin80211' in simple topologies. Ns-2 simulator with the parameters in table 4.1 ensure that the nodes in the network are using IEEE 802.11b interfaces.

4.5.1 Two nodes - one connection

The first case is the simplest one. It consists of a wireless network that has two nodes separated by 100 meters. The tests consider UDP/CBR and TCP/FTP. The objective of this first case is to verify the correct operation of the parameters that characterize the interface 802.11b and to demonstrate the correct operation of Pmin802.11 module as well.

4.5.1.1 Constant Bit Rate traffic with UDP

In this case, one of the nodes plays the role of the transmitter and the other of receiver. The data transmission is in a single direction and the objective is to set up the CBR data rate and the power of the transmission at the transmitter and then observe the data rate at the receiver. The CBR changes from 1 Mbps to 11 Mbps with a step of 0.5 Mb. The ALPHA parameter (Pmin80211 module) has values of 0.9, 1.0, 1.1, 1.2, 1.4, 1.8, 2.5 and 5.0. Figure 4.3 shows the behavior of the throughput of the network when ALPHA is equal to 0.9 and 1.0. The figure does not display the rest of values of ALPHA because they are approximated to the values of the curve when ALPHA is equal to 1.0. This outputs reflects the fact that there are just two nodes in the network therefore there is no external interference that causes greater variations in the network capacity. In addition, it is necessary to mention that the maximum raw data rate for 802.11b is 11 Mbps, including both cases where RTS/CTS is enabled and disabled.

In the result, it is noted that the capacity of the network is maximized when RTS/CTS is disabled. The presence of RTS and CTS packets produces overhead. In this case, RTS/CTS appears to be a disadvantage; nevertheless, when the network composed of many nodes and multiple connections it is an advantage since it could solve the problems of hidden terminals if and only if the carrier sensing range and the transmission range are the same.

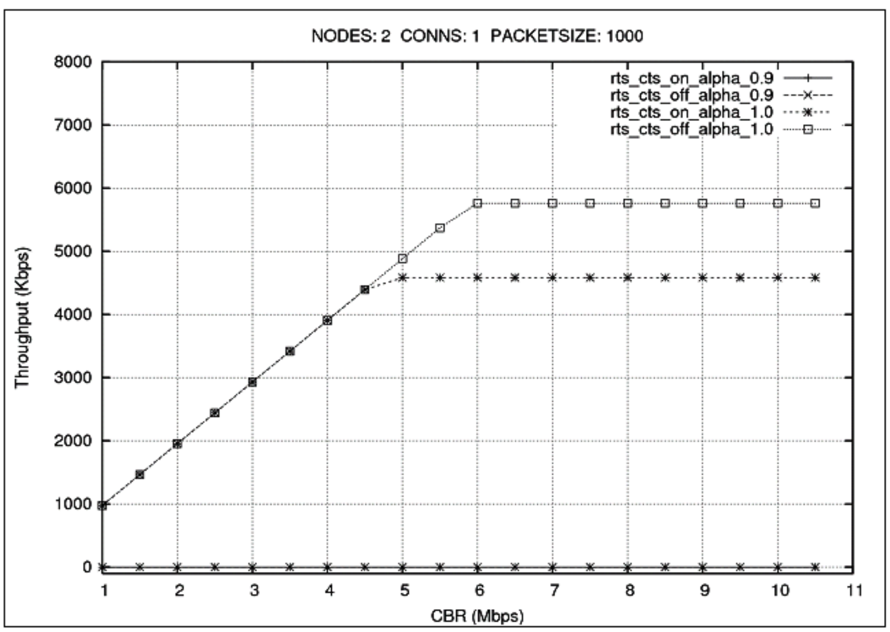


Figure 4.3 802.11b (11Mbps) two nodes, one connection. CBR vs Throughput.

Table 4.2 shows the details of curves presented in figure 4.1 when ALPHA is equal to 1.0. In the table the throughput is observed, the number of packages that arrived intact, the number of packages that arrived with errors and the data rate percent; which is the relationship between the throughput and the CBR offered load.

CBR Mbps	RTS/CTS: ON				RTS/CTS: OFF			
	Throughput (Mbps)	% Data Rate	Error Packets	Total Packets	Throughput (Mbps)	% Data Rate	Error Packet	Total Packets
1.0	0.976	97.60	0	62500	0.976	97.60	0	62500
1.5	1.464	97.60	0	93751	1.464	97.60	0	93751
2.0	1.953	97.65	0	125000	1.953	97.65	0	125000
2.5	2.441	97.64	0	156251	2.441	97.64	0	156251
3.0	2.929	97.63	0	187501	2.929	97.63	0	187501
3.5	3.417	97.62	0	218751	3.417	97.62	0	218751
4.0	3.906	97.65	0	250001	3.906	97.65	0	250001
4.5	4.394	97.64	1	281251	4.394	97.64	0	281251
5.0	4.572	91.44	19858	312500	4.882	97.64	0	312500
5.5	4.572	83.12	51108	343751	5.371	97.65	1	343751
6.0	4.572	76.20	82357	374999	5.752	95.86	6802	375000
11.0	4.572	41.56	394857	687499	5.752	52.29	319300	687499

Table 4.2 Details of the simulation for ALPHA equal to 1.0.

The data rate limit is 4.572 Mbps when RTS/CTS is enable and 5.752 Mbps when it is disabled. Table 4.3 shows to the evolution of the transmission power and the possible reach of the transmitting node when ALPHA goes from 0.9 to 5.0. As can be seen, an increase of order of 10% in the transmission power does not represent a 10% in the reach of the transmitting node since the propagation model is not linear.

Alpha	0.9	1.0	1.1	1.2	1.4	1.8	2.5	5.0
Tx Pwr(W)	5.739e-4	6.377e-4	7.014e-4	7.652e-4	8.927e-4	1.148e-3	1.594e-3	3.188e-3
Range (m)	94.87	100.00	104.88	109.54	118.32	134.16	158.11	223.61

Table 4.3 Relations between Alpha, Transmission Power and Transmission Range.

4.5.1.2 File Transfer Protocol traffic with TCP

The tests executed on TCP assume the same values of UDP tests with the exception of data rate. TCP can support data rates of 1, 2, 5.5 and 11 Mbps. Therefore; it is necessary to evaluate TCP in all those conditions. The congestion window is equal to 36, the packet size is 1460 bytes and the value of ALPHA is equal to 1.0. The test procedure consists of moving a file of 10 MB from the transmitting node to receiver using FPT, which is on the top of TCP. As soon as the packet reception is complete, the throughput, the end-to-end delay and the average delay per packet are calculated. The calculus of the throughput excludes not only IP and TCP headers but also excludes retransmissions. Table 4.4 shows the result.

IEEE 802.11b Data rate (Mbps)	RTS/CTS: ON				RTS/CTS: OFF			
	Throughput (Mbps)	% Data Rate	End to end delay (secs)	Average packet delay (msecs)	Throughput (Mbps)	% Data Rate	End to end delay (secs)	Average packet delay (msecs)
1	0.790	79.00	104.56	230.96	0.787	78.70	105.09	205.86
2	1.413	70.65	58.45	128.75	1.473	73.65	56.14	109.80
5.5	2.838	51.60	29.11	67.71	3.310	60.18	24.99	48.67
11	3.985	36.22	20.73	45.13	5.143	46.75	16.09	31.20

Table 4.4 802.11b Maximum Throughput, End-to End delay and Average delay per packet.

The tests for different values ALPHA greater than 1.0 showed approximate values. Since there is no interference, the variation is insignificant. Again, RTS/CTS affects the performance of the connection.

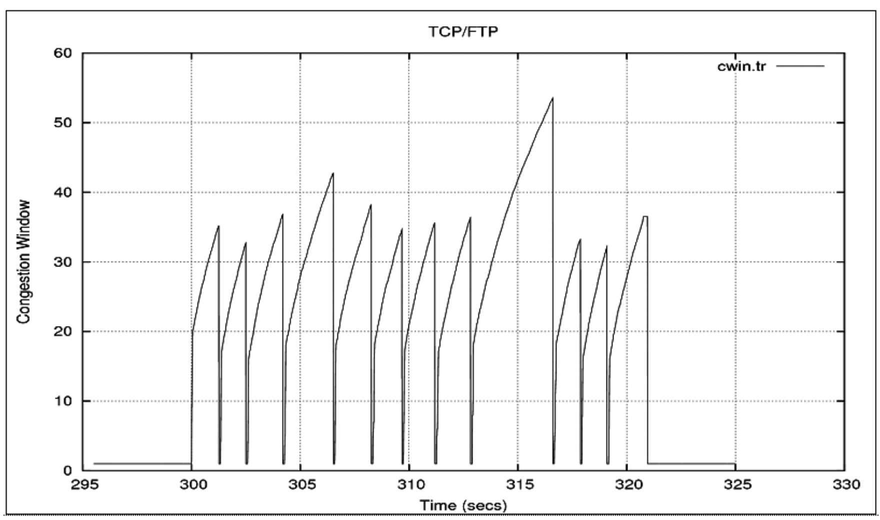


Figure 4.4 802.11b (11Mbps) two nodes, one connection, Congestion Window.

The power transmission and the possible reach of the transmitting node is the same one as in table 4.3. As a part of the result, Figure 4.4 shows the operation of the window of congestion of TCP protocol when the RTS/CTS mechanism is working. It can be seen that the transmission of the file (10 MB) starts at 300 and finished 20.73 seconds later; during this period, there are twelve low starts.

4.5.1.3 Verification

Several authors have studied IEEE 802.11b. In [14] the author collected experimental data from hardware by using a UDP/CBR connection. According to the results, the throughput is 5.49 Mbps when RTS/CTS is off and 4.03 Mbps RTS/CTS is on. In the case of the TCP, [21] presents Table 4.5 where RTS/CTS dialog is disabled.

Data Rate (Mbps)	TCP Throughput (Mbps)	% Data Rate
1	0.790	79.0%
2	1.442	72.1%
5.5	3.014	54.8%
11	4.276	38.9%

Table 4.5 802.11 TCP verification values.

Comparing these values and the values produced by the simulator the following differences are noted: CBR with RTS/CTS 13.44% and CBR without RTS/CTS 4.77%. For the TCP/FTP the differences are: 0% for 1 Mbps, 1.45% for 2 Mbps, 3.2% for 5.5 Mbps and 2.68% for 11 Mbps. Therefore the differences are in an acceptable range.

4.5.2 Four nodes - two connections

Figure 4.5 shows a chain topology composed by four nodes. The distance from node 0 (n_0) to node 1 (n_1) and the distance from node 2 (n_2) to node 3 (n_3) is equal to 100 meters. On the other hand, the distance from n_1 to n_2 is equal to 105 meters. In the topology there are two concurrent flows; flow 0 from n_0 to n_1 and flow 1 from n_2 to n_3.

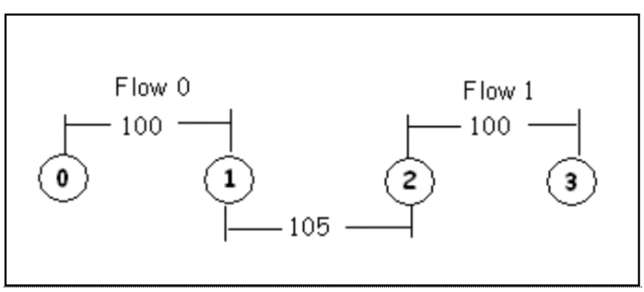


Figure 4.5 Chain Topology to verify the operation of Pmin80211 module.

The primary goal of the topology is to verify the correct operation of the Pmin80211 module. In this case the transmission range and the carrier sensing range are the same (CSThresh equal to RXThresh). When Alpha is equal to 1.0, Pmin80211 calculates the minimal power that connect n_0 to n_1 and n_2 to n_3. The power level must be the same since both distances are 100 meters. At the same time there should not be interference among the flows because there are 5 extra meters that ensure isolation from one flow to the other. In short the 5 meters act like a firewall. If the module is operating correctly then the throughtput in each flow will be close to the result found it in case 1. After that, ALPHA changes from 1.0 to 1.4. Values equal or greater than 1.2 ensure enough power transmission to reach more than 109 meters. Therefore, the thoughput is going to decrease.

4.5.2.1 Constant Bit Rate traffic with UDP

Figure 4.6 shows the results for UDP/CBR. The superior curves samples the behavior of the network when there is no interference between both flows (ALPHA equal to 1.0). The maximum throughput is close to 4.57 Mbps when RTS/CTS is off and 5.76 Mbps when is on. The values are the same as the values of the first case. The Pmin80211 module demonstrates that is feasible to reuse the channel frequency when the minimum power is used in the transmission. The curves in the low part of Figure 4.6 show how the throughput is affected when the interference takes place. When ALPHA is equal to 1.4 the flows are overlapping. Now the nodes can reach further than 105 meters.

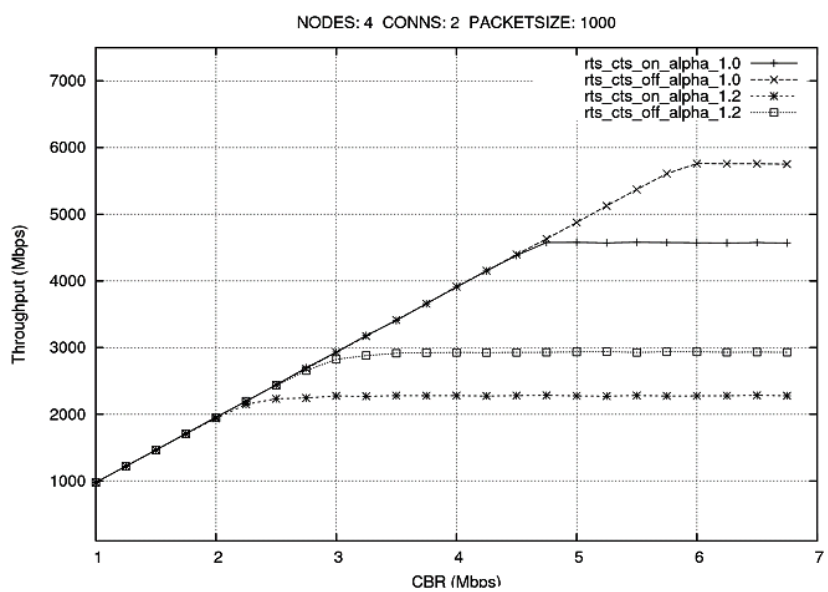


Figure 4.6 Four nodes two connections. CBR vs Throughput.

Table 4.6 displays the details for different values of ALPHA. It is important to mention that the simulator has certain limitations. For instance, when ALPHA is equal to 1.1 each node can reach 104.98 meters. In real conditions, it means that some of the frames can produce interference in the flows; however, Ns-2 ignores that. A probabilistic model should be more realistic. If there is no interference, the aggregate throughput is 11.515 Mbps and 9.151 Mbps with and without RTS/CTS dialog respectively. Otherwise, it falls to 5.855 Mbps and 4.566 Mbps, which represent 49.15% of loss. The sharing of the channel by both flows causes the loss. The throughput for RTS/CTS off is always greater than RTS/CTS on because of the overhead. In this case, there are no presences of hidden terminal problems. Therefore, in this particular topology disabling the RTS/CTS mechanism is the best option.

Alpha	Power (W)	Range (m)	RTS/CTS: ON			RTS/CTS: OFF		
			Throughput Flow 0 (Mbps)	Throughput Flow1 (Mpbs)	Aggregate Throughput (Mbps)	Throughput Flow 0 (Mbps)	Throughput Flow1 (Mpbs)	Aggregate Throughput (Mbps)
1.0	6.376e-4	100.00	4.584	4.567	9.151	5.771	5.743	11.515
1.1	7.014e-4	104.88	4.584	4.567	9.151	5.771	5.743	11.515
1.2	7.652e-4	109.54	2.216	2.350	4.566	2.874	2.980	5.855
1.4	8.927e-4	118.32	2.216	2.350	4.566	2.874	2.980	5.855

Table 4.6 Four nodes, two connections. Details of the simulation for ALPHA equal to 1.0, 1.1, 1.2 and 1.4.

The interference is introduced just in the n_1 and n_2. However, the throughput could be lower if ALPHA grows too much. If the transmission power is higher then the nodes in the ends could introduce more interference. Thus, probably the throughput should be one fourth of the maximum throughput.

4.5.2.2 File Transfer Protocol with TCP

Table 4.7 shows the results when the protocol is TCP and the agent is FTP. If ALPHA is equal to 1.2 then the interference causes a decrement in the aggregate throughput, from 10.262 Mbps to 5.593 Mbps without the RTS/CTS dialog and from 7.932 Mbps to 5.172 Mbps with RTS/CTS dialog. That represents 45.50% and 34.80 % respectively. The end-to-end delay is increased because of the collisions in nodes 1 and 2. This is an example of exposed terminal problem. The activation of mechanism RTS/CTS improves the performance of the network. The nodes in the network could know in advance if the channel is going to be busy or not. Since NAV is a part of the RTS and CTS then the nodes in the neighborhood know the time and backoff until the channel is free.

Alpha	RTS/CTS: ON				RTS/CTS: OFF			
	Throughput Flow 0 (Mbps)	Throughput Flow1 (Mpbs)	Aggregate Throughput (Mbps)	E2E delay (s)	Throughput Flow 0 (Mbps)	Throughput Flow1 (Mpbs)	Aggregate Throughput (Mbps)	E2E delay (s)
1.0	3.968	3.963	7.932	16.0/15.9	5.119	5.142	10.262	20.6/20.6
1.1	3.968	3.963	7.932	16.0/15.9	5.119	5.142	10.262	20.6/20.6
1.2	1.702	3.470	5.172	32.4/28.3	2.608	2.984	5.593	28.6/23.7
1.4	1.702	3.470	5.172	32.4/28.3	2.608	2.984	5.593	28.6/23.7

Table 4.7 Four nodes two connections. Details of the simulation for ALPHA equal to 1.0, 1.1, 1.2 and 1.4

4.6 802.11b without power control mechanism

Throughout the thesis, it has been mentioned that 802.11b has a greater performance when a power control mechanism exists. The network displayed in Figure 4.5 is used again in the simulation to verify that this affirmation is correct (CBR traffic). If the mechanism does not exist to control the transmission power, then the 802.11b works with the maximum value allowed by the hardware. This power transmission (3.3962e-2 mW) can reach 570.5 meters. Therefore, any package produced by any node in the network is received by the other nodes.

Figure 4.7 shows the results of the network of Figure 4.5 with basic 802.11b standard (working with its maximum power). The average throughputs with and without RTS/CTS dialog are 2.67 Mbps and 1.794 Mbps. On the other hand, Table 4.6 shows the results of Figure 4.5 with power control. With ALPHA equal to 1.0 (no interference) the average throughputs calculated from flows 0 and 1 are 4.57 Mbps and 5.76 Mbps (with and without RTS/CTS mechanism).

The fact that the throughputs are greater with power control mechanism than basic 802.11b demonstrates that the power control mechanism increase the capacity of the network by increasing spatial reuse.

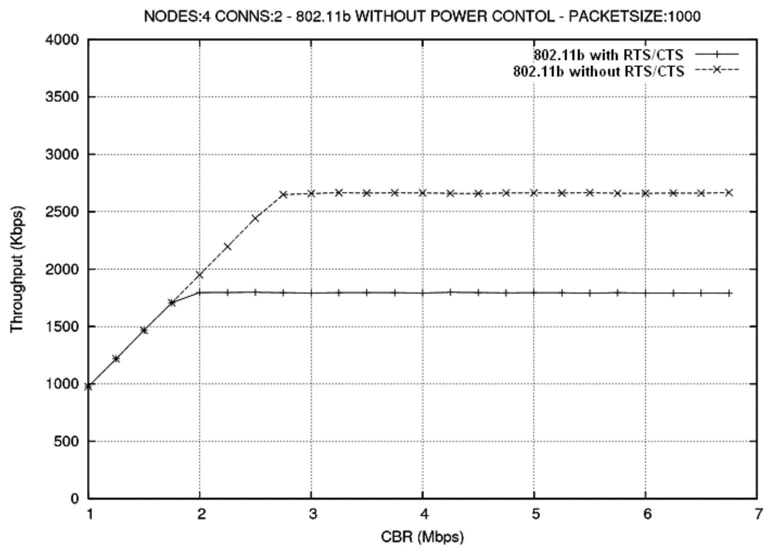


Figure 4.7 Four nodes two connections without power control mechanism. CBR vs Throughput

4.7 Analysis of the interference

The results for CBR/UDP traffic are in Table 4.6, when ALPHA is equal to 1.0 or 1.1 there is no interference between the flows. When ALPHA is equal to 1.2 or 1.4 the transmission ranges of n_1 and n_2 are overlapped. Let us examine the table by parts. With RTS/CTS dialog and no interference, the average throughput is 4.57 Mbps (flows 0 and 1). Also without RTS/CTS dialog and interference (transmission ranges of n_1 and n_2 are overlapped when ALPHA is equal to 1.2 or 1.4), the average throughput is 2.28 Mbps. Figure 4.8 shows the transmission ranges: CTS packets sent by n_1 to n_0 (flow 0) and RTS packets sent by n_2 to n_3 (flow 1).

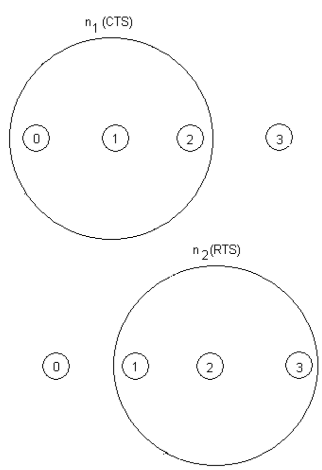


Figure 4.8 n_1(CTS) and n_2(RTS) ranges

Let assume the RTS/CTS dialog is enabled. One characteristic of the RTS and CTS packets is that they include the network allocation vector (NAV), see Figure 3.9. NAV indicates how long is going to delay the transmission which forces the other nodes that receive the message (nodes in the transmission range) to wait in order to avoid collisions with the DATA and ACK packets. That is to say, the nodes are forced to take turns in the access to the channel. The channel capacity is divided between both n_1 and n_2. The RTS/CTS mechanism forces to n_1 and n_2 to organize itself in the access to the media. Which explains why the throughput falls almost to half. In the figure also note that n_0 all the time recognizes the channel as idle then it can transmit RTS packets to n_1 but n_1 could not respond with CTS packet if n_1 received a RTS packet before (coming from n_2) with a NAV that forces it ($n_{1)}$ to keep silence.

When RTS/CTS is disabled there are no NAVs, therefore does not exist a previous coordination to access to media between the nodes. Without RTS/CTS the only packets are DATA and ACK. Figure 4.9 shows the possible collisions between the flows. The top part of the figure shows the collision between the DATA messages sent by n_0 to n_1 with the DATA packets sent by the n_2 to n_3, collisions take place in $n_{1;}$ n_0 senses the channel idle all the time. On the other hand, n_2 senses the channel idle almost all the time except when it receives a ACK packet from n_1 (n_1 sent ACKs to n_0). The size of ACK packets is 14 bytes then its interference is minimal. The If both transmitter nodes work at the same time it explain why the throughput is reduced to the close to the half.

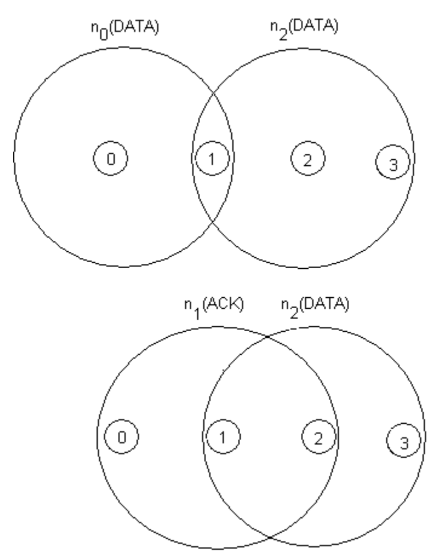


Figure 4.9 n_0(DATA) n_2(DATA) and n_1(ACK) n_2(DATA) interferences

Chapter 5 Performance

The objective of the present chapter is observing interference in an ad hoc network by using the Pmin80211 module (chapter 4). In this chapter, many simulations are presented in order to identify which ones are the main parameters on the ad hoc network and how they affect its performance.

At the beginning, by using a chain topology the carrier sensing range is studied. Simulations show that as soon as the carrier sensing range of one connection reaches the transmission range of another connection the performance is reduced in both connections. Another variable to consider is the location. The location is very important since if the node is located in a high traffic zone inside the network then the throughput is reduced. In addition, the direction of the flow plays an important role.

At the end of the chapter, a random network is presented to review the influence of ALPHA. Each network should have some optimal ALPHA values that can maximize the throughput (the optimal transmission power) since it depends on the topology as well as the traffic. The optimal value for ALPHA is also smaller for an increased number of nodes. The optimal ALPHA depends on the traffic, density and location of the nodes. The chapter presents a series of figures and their details are presented in appendix A.

5.1 Interference and carrier sensing range

In the last chapter, some basic examples validate the Pmin80211 software. However, at that moment the examples assume that the Carrier Sensing Range and the Transmission Range have the same size. The carrier sensing range (CS range) is different from the transmission/reception range (Rx range). CS range depends always on the antenna sensitivity; meanwhile Rx range depends on the power transmission and the radio propagation properties [18]. Is there a relationship between CS range and Rx range? According to experimental values in [19], their

Orinoco Cards present a CS range equal to 2.78 times the Rx range. On the other hand, the authors in [18] did analytical work for this relationship.

Let P_r be the receiving power of the signal from the transmitter and let Pi be the power of interference signal at the receiver. SNR=P_r /P_i. They ignore the thermal noise and assume the transmitter and receiver having the same radios or interfaces, then:

$$SNR = P_r / P_i = (r / d)^4 \geq SNR\_THRESHOLD$$
$$r \geq (SNR\_THRESHOLD)^{1/4} * d$$

'd' is the distance between receiver and transmitter and 'r' distance between the interference node and the receiver node. This implies that in order to successfully receive a signal, the interfering nodes must be -(SNR_THRESHOLD)¼ *d away from the receiver [18]. They define this as the interference range R_i. Usually SNR_THRESHOLD is set to 10 (CPThresh in Ns-2). Thus:

$$R_i = 1.78 * d$$

which implies CS Range is 1.78 times Rx range. Note that in our model the interference range is the noise floor. The range for CS range goes from 1.78 to 2.78 times Rx range but in order to maintain consistency we assume CS range equal to 1.78 times Rx Range from now on. To set those ranges we need to adjust the values of CSThresh and RXThresh in Ns-2.

Figure 5.1 shows a chain topology composed by six nodes and two flows. Flow 0 goes from n_0 to n_1 and flow 1 goes from n_3 to n_4. The top zone of the figure shows the traffic without the virtual carrier sensing mechanism (RTS/CTS).

The bottom part of Figure 5.1 shows the problems between receiver n_1 and transmitter n_3. The area in white color represents the CS range; meanwhile the zone in gray color represents the Rx range. The distance between all the nodes in the topology is equal to 100 meters. Notice that the distance between n_1 and n_3 is equal to 200 meters. Then, if the flows use the minimal power to send information, there is no interference between them because we assume CS range equal to 178 meters and Rx Range equal to 100 meters. Node n_2 is in a high traffic location with interference. In addition, if the power control is increased then the interference will affect all the nodes in the network.

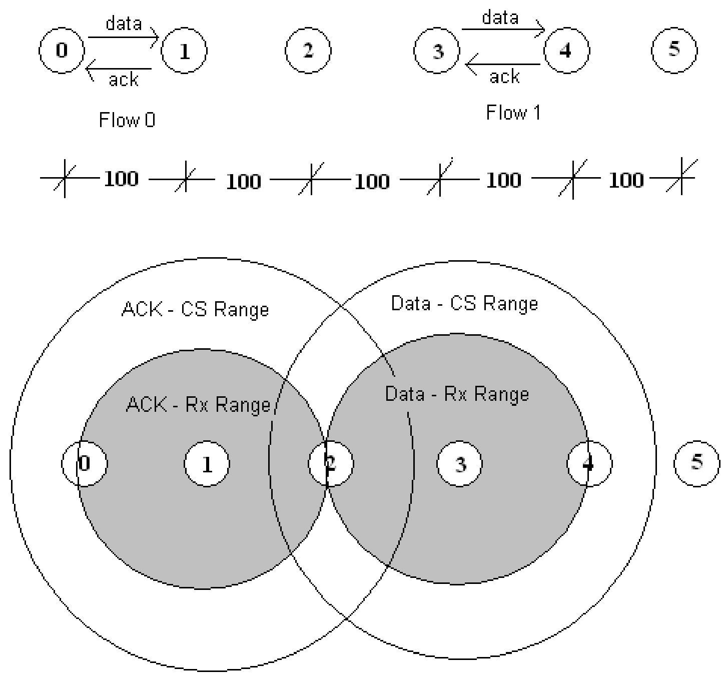


Figure 5.1 Transmission and carrier sensing range.

Table 5.1 presents information about the flows without RTS/CTS dialog when ALPHA changes from 1.0 to 1.3, 4.8, 15.0, and 48.0. Those values are to be selected because they produce different levels of interference:

- Case ALPHA = 1.0:

  There is no interference between flows 0 and 1.

- Case ALPHA = 1.3:
  - $n_3 \rightarrow n_4$ $^{(DATA,CS)}$ ► $n_1 \leftarrow n_0$ $^{(DATA,Rx)}$ CS Range of DATA packets sent by n_3 to n_4 interferes with DATA packets (sent by n_0) receiving at n_1 and,
  - $n_1 \rightarrow n_0$ $^{(ACK,CS)}$ ► $n_3 \leftarrow n_4$ $^{(ACK,Rx)}$ CS Range of ACK packets sent by n_1 to n_0 interferes with ACK packets (sent by n_4) receiving at n_3.

Here, symbol ► stand for the relation of interference. When Alpha is equal to 1.3 the CS range in both flows is 200.8 meters, interference of both DATA and ACK packets of is present; CS ranges from nodes n_1 and n_3 overlapped. At that moment, the throughputs of the flows reduced from 5141.8 and 5160.1 Kbps to 4435.2 and 2358.5 Kbps, respectively. The reduction occurs in node n_3 because the noise (produced by CS ranges of ACK packets sent by n_1) is close to the signal strength of ACK packet produced by n_4. Then, n_4's ACK packets need retransmission. A similar situation takes place at node n_1 but in this case, the data packets need retransmission. As a consequence, the delays are increasing. However, the delay in flow 0 is shorter than flow 1, which means that interference in ACK packets is worse than interference in DATA packets. If the ACK packet is not receiving in n_0 then n_0 retransmit the DATA packet. It the situation persist then n_0 will wait until a timeout takes place. Timeouts in ACK packets represent dropped packets in the upper layers of the OSI model.

- Case ALPHA = 4.8:

  - $n_3 \rightarrow n_4$ $^{(DATA,Rx)}$ ► $n_1 \leftarrow n_0$ $^{(DATA,Rx)}$ Rx range of DATA packets sent by n_3 to n_4 interferes with DATA packets (sent by n_0) receiving at n_1.
  - $n_3 \rightarrow n_4$ $^{(DATA,CS)}$ ► $n_1 \leftarrow n_0$ $^{(DATA,Rx)}$ CS range of DATA packets sent by n_3 to n_4 interferes with DATA packets (sent by n_0) receiving at n_1.
  - $n_1 \rightarrow n_0$ $^{(ACK,Rx)}$ ► $n_4 \leftarrow n_3$ $^{(DATA,Rx)}$ Rx range of ACK packets sent by n_1 to n_0 interferes with DATA packets (sent by n_3) receiving at n_4.
  - $n_1 \rightarrow n_0$ $^{(ACK,CS)}$ ► $n_3 \leftarrow n_4$ $^{(ACK,Rx)}$ CS range of ACK packets sent by n_1 to n_0 interferes with ACK packets (sent by n_4) receiving at n_3.

When Alpha is equal to 4.8 the CS range of DATA packets sent by n_3 can reach n_0 and those DATA packet can be received by n_1, as well At the same time, the CS range of ACK packets sent by n_1 can reach n_4 and the packets are received by n_3. That means an increment in the interference n_3 affects n_0 and n_1 whereas n_1 affects n_3 and n_4. The throughput decrease and the delay increase, but now the channel access is fair. The difference between throughput of flow 0 and flow 1 is 174.7 Kbps, which represent 6.5% of flow 1's throughput. The signal strength of CS ranges prevents DATA and ACK packets arrived without errors.

Although the transmitting nodes (n_0 and n_3) are under interference due to carrier sensing ranges, they detect the channel idle almost all the time. In the right side of the figure, n_0 does not have to contend with other nodes by the channel. Meanwhile n_3 senses the channel idle except when it receives ACK packets produced by n_1. ACK packets are smaller (14 bytes). The transmitters try to send information as fast as they can because the do not have to contend for the channel. Then the probability of collision is high and reduce the throughput

- Case ALPHA = 15.0:
  - $n_3 \rightarrow n_4$ $^{(DATA,Rx)}$ ► $n_1 \rightarrow n_0$ $^{(ACK,Rx)}$ Rx range of DATA packets sent by n_3 to n_4 interference with ACK packets sent by n_1 to n_0.
  - $n_3 \rightarrow n_4$ $^{(DATA,Rx)}$ ► $n_0 \rightarrow n_1$ $^{(DATA,Rx)}$ Rx range of DATA packets sent by n_3 to n_4 interference with DATA packets sent by n_0 to n_1.
  - $n_1 \rightarrow n_0$ $^{(ACK,Rx)}$ ► $n_4 \rightarrow n_3$ $^{(ACK,Rx)}$ Rx range of ACK packets sent by n_1 to n_4 interference with ACK packets sent by n_4 to n_3.
  - $n_1 \rightarrow n_0$ $^{(ACK,Rx)}$ ► $n_3 \rightarrow n_4$ $^{(DATA,Rx)}$ Rx range of ACK packets sent by n_1 to n_0 interference with DATA packets sent by n_3 to n_4.

Now, the throughputs in both flows (2687.0 Kbps and 2709.0,7 Kbps) are bigger than the previous (2496.6 Kbps and 2671.3 Kbps). At this moment the transmitting nodes must contend for the channel because the DATA packets sent by n_0 are heard in n_3 and vice versa. Now the collision avoidance mechanism (CA) is working; nodes have to contend for the channel. CA mechanism prevents collisions that improvement of the performance of the network.

- Case ALPHA = 48:
  - n►n : All the nodes can received all the DATA and ACK packets. This case shows what happen when the 802.11b standard is working without a power control mechanism (basic 802.11b). When the nodes contend they consider all the packets produced within the network. Since the ACK packets are smaller (14 bytes) it causes a little reduction in the network performance.

Alpha	1.0	1.3	4.8	15.0	48.0
Throughput Flow 0 (Kbps)	5141.8	4435.2	2496.6	2687.0	2666.3
Throughput Flow 1 (Kbps)	5160.1	2358.5	2671.3	2709.7	2639.0
Delay Flow 0 (s)	15.9	18.6	33.6	30.5	30.7
Delay Flow 1 (s)	16.0	35.1	31.4	30.2	31.0
Avg. Thp (Kbps)	5150.9	3396.9	2584.0	2698.4	2652.6
Agg. Thp (Kbps)	10301.9	6793.7	5167.9	5396.7	5305.3

RX range (m)	100.0	112.7	217.9	300.4	401.8
CS range (m)	178.2	200.8	300.8	400.9	536.3

Table 5.1 FTP/TCP without RTS/CTS (packet size 1460, Congestion Window 31).

When ALPHA is equal to 15 all nodes can hear the carrier sensing of the other nodes in the network, there are no significant variations in the results. Therefore, the major interference impact is produced as soon as the carrier sensing ranges start to overlap. When Alpha is equal to 48.0 the transmission range overlaps. In this case, they can hear clearly the packets from each other and have to contend for the access to the channel. The time delay is twice as the delay time when Alpha is equal to 1.

Table 5.2 presents the same topology with RTS/CTS dialog. Now the transmitter nodes sent RTS and DATA packets and receivers nodes sent ACK and CTS packets. Also there are different levels of interference:

- Case ALPHA = 1.0:

  There is no interference between flows 0 and 1.

- Case ALPHA = 1.3:
  - $n_3 \rightarrow n_4$ $^{(RTS\ DATA,CS)}$ ► $n_1 \leftarrow n_0$ $^{(RTS\ DATA,Rx)}$ CS range of RTS and DATA packets sent by n_3 to n_4 interferes with RTS and DATA packets (sent by n_0) receiving at n_1 and,
  - $n_1 \rightarrow n_0$ $^{(CTS\ ACK,CS)}$ ► $n_3 \leftarrow n_4$ $^{(CTS\ ACK,Rx)}$ CS range of CTS and ACK packets sent by n_1 to n_0 interferes with CTS and ACK packets (sent by n_4) receiving at n_3.

  With 200.8 meters in the CS range CTS and DATA packets sent by n_3 to n_4 produce interference in n_1. On the other hand, CTS and ACK packets sent by n_1 to n_0 produce interference in n_3. The difference is the packet size. RTS and CTS packets have 40 bytes, ACK packets 14 bytes and DATA packets have 1460 bytes. Then the CS range is present more time in n_1 than n_3 (packets at n_1 have a higher probability of collision than packets at n_3). It causes interference (errors) in the packets and the throughput of flow 1 (3664.8 Kbps) is bigger then the throughput in flow 0 (1716.5 Kbps)

- Case ALPHA = 4.8:

  - $n_3 \rightarrow n_4$ $^{(RTS\ DATA,Rx)}$ ► $n_1 \leftarrow n_0$ $^{(RTS\ DATA,Rx)}$ Rx range of RTS and DATA packets sent by n_3 to n_4 interferes with RTS and DATA packets (sent by n_0) receiving at n_1.
  - $n_3 \rightarrow n_4$ $^{(RTS\ DATA,CS)}$ ► $n_1 \leftarrow n_0$ $^{(RTS\ DATA,Rx)}$ CS range of RTS and DATA packets sent by n_3 to n_4 interferes with RTS and DATA packets (sent by n_0) receiving at n_1.
  - $n_1 \rightarrow n_0$ $^{(CTS\ ACK,Rx)}$ ► $n_4 \leftarrow n_3$ $^{(RTS\ DATA,Rx)}$ Rx range of CTS and ACK packets sent by n_1 to n_0 interferes with RTS and DATA packets (sent by n_3) receiving at n_4.
  - $n_1 \rightarrow n_0$ $^{(CTS\ ACK,CS)}$ ► $n_3 \leftarrow n_4$ $^{(CTS\ ACK,Rx)}$ CS range of CTS and ACK packets sent by n_1 to n_0 interferes with CTS and ACK packets (sent by n_4) receiving at n_3.

With 217.9 meters as a Rx range, CTS packets sent by n_1 to n_0 can be heard at n_3 and RTS packets sent by n_3 to n_4 are receiving at n_1. RTS and CTS include the network allocation vector (NAV) then n_1 and n_3 know the duration of the transmissions. The difference between the flow is in the transmitters nodes, n_0 does not contend for the channel meanwhile n_3 does. It explains why the throughputs are 3709.4 Kbps in flow 0 and 1990.7 Kbps in flow 1. Of course, the CS range of RTS and DATA packets sent by n_0 to n_1 produce interference in n_3 but it is minimal compare to the reduction produced by the RTS/CTS mechanism (NAVs)

- Case ALPHA = 15.0:

  - $n_3 \rightarrow n_4$ $^{(RTS\ DATA,Rx)}$ ► $n_1 \rightarrow n_0$ $^{(CTS\ ACK,Rx)}$ Rx range of RTS and DATA packets sent by n_3 to n_4 interference with DATA and ACK packets sent by n_1 to n_0.
  - $n_3 \rightarrow n_4$ $^{(RTS\ DATA,Rx)}$ ► $n_0 \rightarrow n_1$ $^{(RTS\ DATA,Rx)}$ Rx range of RTS and DATA packets sent by n_3 to n_4 interference with RTS and DATA packets sent by n_0 to n_1.
  - $n_1 \rightarrow n_0$ $^{(CTS\ ACK,Rx)}$ ► $n_4 \rightarrow n_3$ $^{(CTS\ ACK,Rx)}$ Rx range of CTS and ACK packets sent by n_1 to n_4 interference with CTS and ACK packets sent by n_4 to n_3.
  - $n_1 \rightarrow n_0$ $^{(CTS\ ACK,Rx)}$ ► $n_3 \rightarrow n_4$ $^{(RTS\ DATA,Rx)}$ Rx range of CTS and ACK packets sent by n_1 to n_0 interference with RTS and DATA packets sent by n_3 to n_4.

Now, the throughputs are 2064.4 Kbps and 2056.8 Kbps. The access to the channel is fair because the transmitter nodes can heard the RTS packets in the network. So it allows to the nodes takes turns in the access to the media

- Case ALPHA = 48:

    - n►n : All the nodes can received all the RTS, CTS, DATA and ACK packets. This case is like basic 802.11b, which works without a power control mechanism. The throughputs are smaller than previous case (ALPHA equal to 15) since the ACK sent by n_1 can be heard at n_4 and vice versa. So, it adds more overhead to the flows.

Alpha	1.0	1.3	4.8	15.0	48.0
Flow 0 (Kbps)	4002.1	1716.5	3709.4	2064.4	2051.2
Flow 1 (Kbps)	3988.9	3664.8	1990.7	2056.8	2071.8
Delay Flow 0 (s)	20.5	48.0	22.2	39.7	39.9
Delay Flow 1 (s)	20.5	22.5	41.4	39.8	39.5
Avg. Thp (Kbps)	3995.5	2690.6	2850.1	2060.6	2061.5
Agg. Thp (Kbps)	7991.0	5381.3	5700.2	4121.2	4122.9
RX range (m)	100.0	112.7	217.9	300.4	401.8
CS range (m)	178.2	200.8	300.8	400.9	536.3

Table 5.2 FTP/TCP with RTS/CTS (packet size 1460, Congestion Window 31).

5.2 Interference in grid topologies

The Figure 5.2 presents a grid topology:

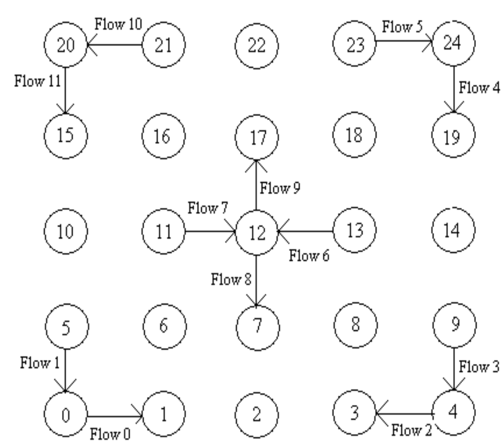


Figure 5.2 Grid topology of 25 nodes with 12 connections

The grid is composed of 25 nodes and 12 connections (500x500 meters). In the center of the grid, n_{12} has 4 connections while n_0, n_4, n_{20} and n_{24} have 2 connections. There is a hidden terminal problem in n_{12}. Grid topology is like an extension of chain topology since it is bi-dimensional. In order to study the response of the network CBR with UDP is used. The experiment sets up a constant value for ALPHA and changes the requested load of the network. Figure 5.3 presents the CBR traffic versus throughput. ALPHA equal to 1 refers to the minimal power. Then, Alpha changes to 1.2, 1.6, 2.0 and 2.5. The increment in the value of ALPHA is reflected in the increment of the transmission and carrier sensing ranges. The minimal power is not the best option all the time because concurrent connections could cause interference in the connections (could be another value, the optimal transmission power). Thus, it is important to provide an extra power to the transmitter nodes to overcome the interference. If the traffic is light, the minimal power is a right option (less than 2 Mbps), otherwise the best option is to set ALPHA equal to 1.6 (optimal transmission power is 1.6 times the minimal transmission power). It is important to note that this optimal value of ALPHA is not fixed; it depends on the density of the network. For instance, if the network has few nodes and they have few connections the value of ALPHA can be set to higher value. On the other hand, if the network has many nodes with also many connections then the ALPHA value must be lower. In fact, there will be an optimal ALPHA (optimal transmission power) if and only if the density is high; otherwise, it is difficult to find a fixed value for ALPHA.

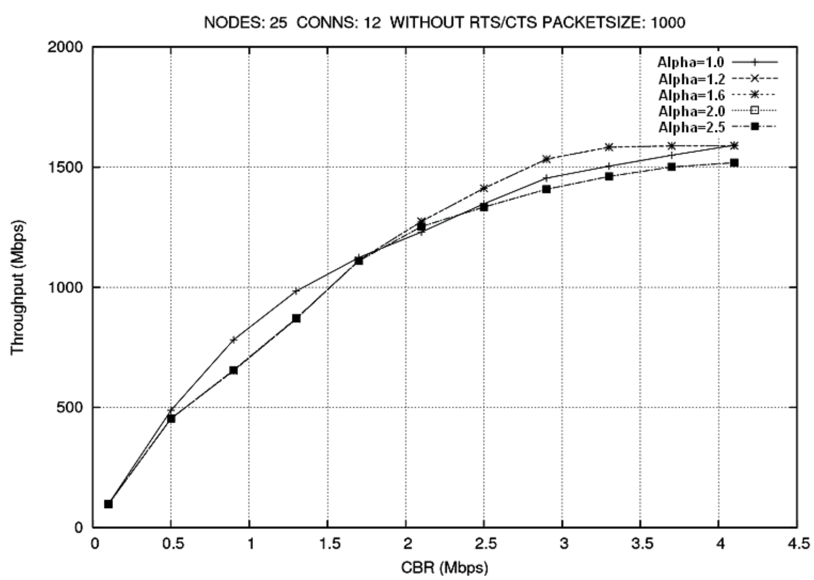


Figure 5.3 Grid topology. 25 nodes 12 connections without RTS/CTS dialog

Figure 5.4 shows the results for the same network with RTS/CTS dialog. The optimal ALPHA is still 1.6. The output is better without RTS/CTS because the carrier sense ranges are overlapped.

Thus the effectiveness of the virtual carrier sensing is in doubt [19][20][21]. In both Figures 5.3 and 5.4 three zones can be identified. The first one corresponds to light traffic when the request load is less than 2 Mbps. The next one between 2 Mpbs and 3 Mbps is for an average load. And the last one goes from 3 Mbps to 4.5 Mbps which is considered as heavy traffic.

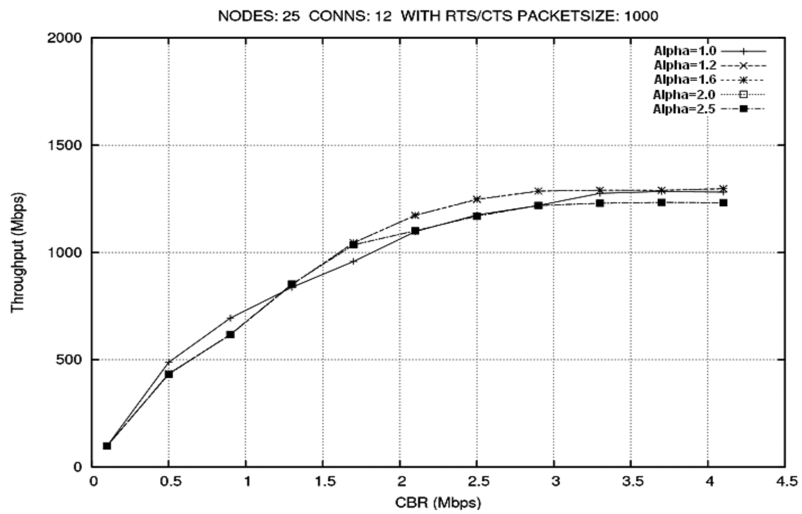


Figure 5.4 Grid topology. 25 nodes 12 connections with RTS/CTS dialog

The next experiment fixed the CBR traffic and changed the ALPHA values from 1 to 10 with a step of 0.5. Figure 5.5 shows the results, where 2 Mbps, 3 Mbps and 5 Mbps were the requested load with the presence or absence of RTS/CTS dialog.

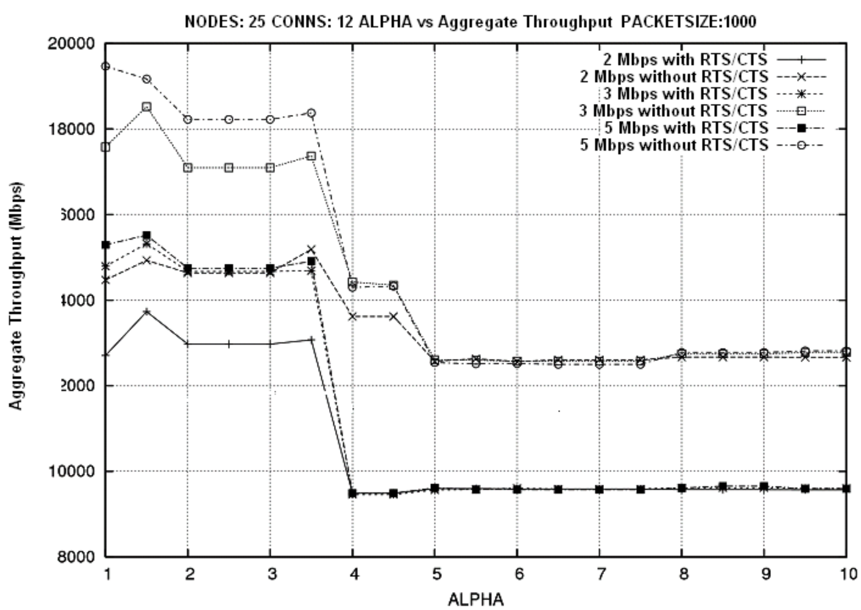


Figure 5.5 Grid topology. 25 nodes 12 connections. ALPHA vs Aggregate throughput

All the waveforms show a similar pattern: the best value for ALPHA is 1.6. When ALPHA is equal to 5 the carrier sensing range is close to 500 meters and the transmitter range is close to 288 meters then all the nodes in the network can hear the carrier sensing of the other nodes. Thus, again the RTS/CTS mechanism just became the extra overhead.

Figure 5.6 presents the throughput of the network shown in Figure 5.2 when a basic 802.11b interface is used. The card has a transmission range of 570.5 meters (see 4.6). In the figure, the throughput falls to 800.1 Mbps with RTS/CTS and 1095.7 without RTS/CTS. The use of a power control mechanism improves the network capacity. The values with power control mechanism are: 1550.7 Mbps (RTS/CTS on) and 2018.31 (RTS/CTS off) that represent an improvement of 93.8% and 84.2% respectively for this particular case.

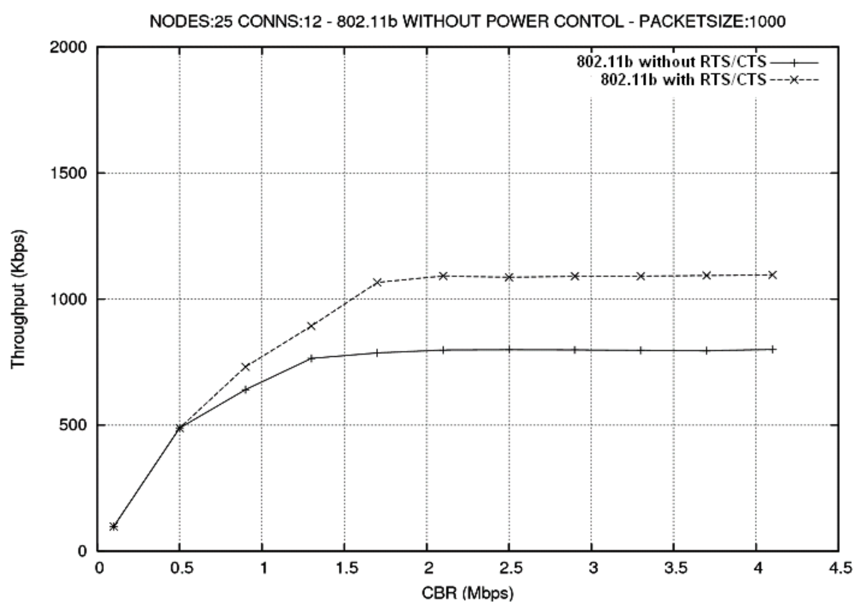


Figure 5.6 Grid topology. 25 nodes 12 connections with ordinary 802.11b interface

5.3 Interference and ALPHA

ALPHA is a parameter defined in Pmin80211. The goal is find the optimal ALPHA (optimal power) that maximizes the network capacity. In the previous section, the optimal ALPHA is equal to 1.6. In order to see what happened in a network with high another network is used. The network is composed by 60 nodes and 69 flows (Figure 5.7, 900x800 meters). Each node has more than one connection with potential hidden and exposed terminal problems. Notice that the distance between the nodes is not the same each packet has a different transmission power, then in this case the power table at the MAC layer is going to work. Figure 5.8 presents an experiment of FTP traffic with TCP.

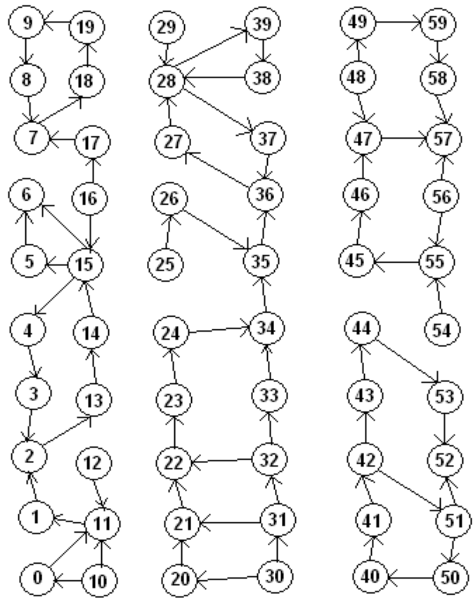


Figure 5.7 Random topology. 60 nodes 69 connections

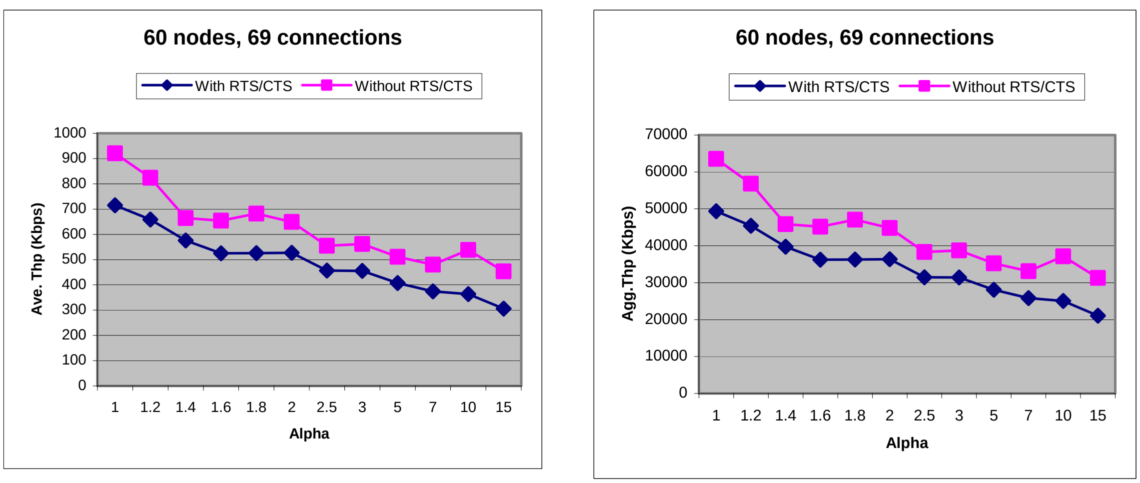


Figure 5.8 60 nodes 69 connections. ALPHA vs Average and Aggregate throughput.

The virtual carrier sensing mechanism (RTS/CTS) reduces the performance of the network by 25%. The values for ALPHA change from 1 to 15. Since the density in this example is higher, the optimal ALPHA is close to the minimal power.

In order to confirm the observation, CBR traffic with UDP is presented in Figures 5.9 and 5.10. The first figure shows the relationship between CBR and the throughput with ALPHA equal to 1.0, 1.2, 1.6, 2.0 and 2.5 without RTS/CTS dialog. The light traffic goes from 0 to 1.1 Mbps, in this range ALPHA equal to 1.0 is the best option. For the average traffic, between 1.1 and 2.1 Mbps, there are two options ALPHA equal to 1.0 and 1.2 for the lower and higher part of the range respectively. When the traffic is heavy, greater then 2.1 Mbps, ALPHA is equal to 1.2 obtains the best performance of the network (optimal transmission power). In the present of heavy traffic, the minimum power (ALPHA=1) is not the best option. For a successful transmission is needed extra power to overcome the interference coming from carrier sensing. Figure 5.10 shows the throughput when the dialog RTS/CTS is activated. In the figure, the best performance of the network is when ALPHA is equal to 1.0 (light, average or heavy traffic). In this case, the network allocation vectors in RTS and CTS packets allow the nodes to organize the access to the channel. However, it does prevent the carrier sensing effect produced by the packets sent by other nodes that cannot receive the NAVs. That reduces throughput of the network although the nodes take turns in the access to the channel.

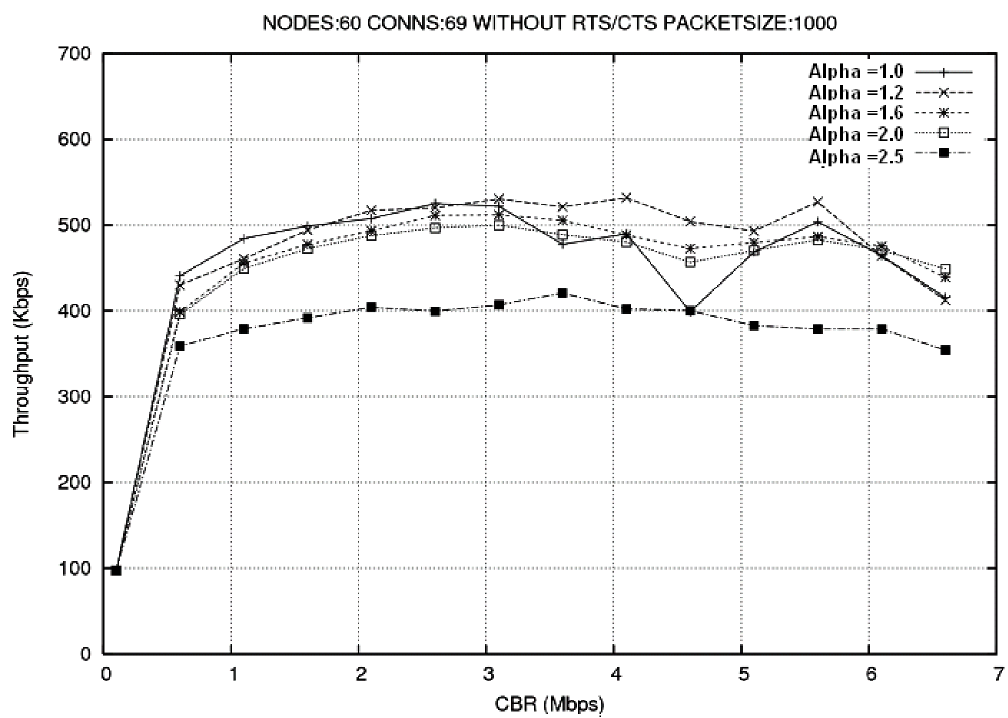


Figure 5.9 60 nodes 69 connections without RTS/CTS dialog

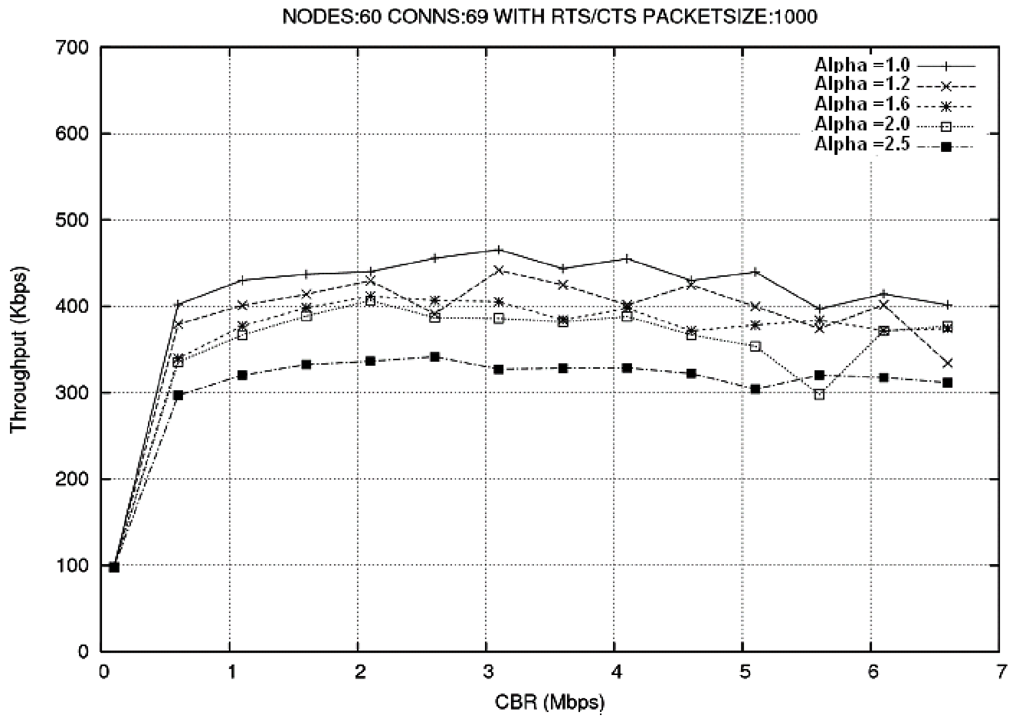


Figure 5.10 60 nodes 69 connections with RTS/CTS dialog

Figure 5.11 presents a relationship between ALPHA and the aggregate throughput with light (1.1 Mbps), average (2.1 Mbps) and heavy traffic (4.1 Mbps). In all cases, the aggregate throughput descends (with or without RTS/CTS dialog). Notice that the ALPHA values goes from 1.0 to 6.0 with a step of 0.5. Unlike the previous case, the optimal ALPHA is closer o 1.0. Therefore, when the density of the network rises the optimal ALPHA is close to the minimum transmission power (1.0).

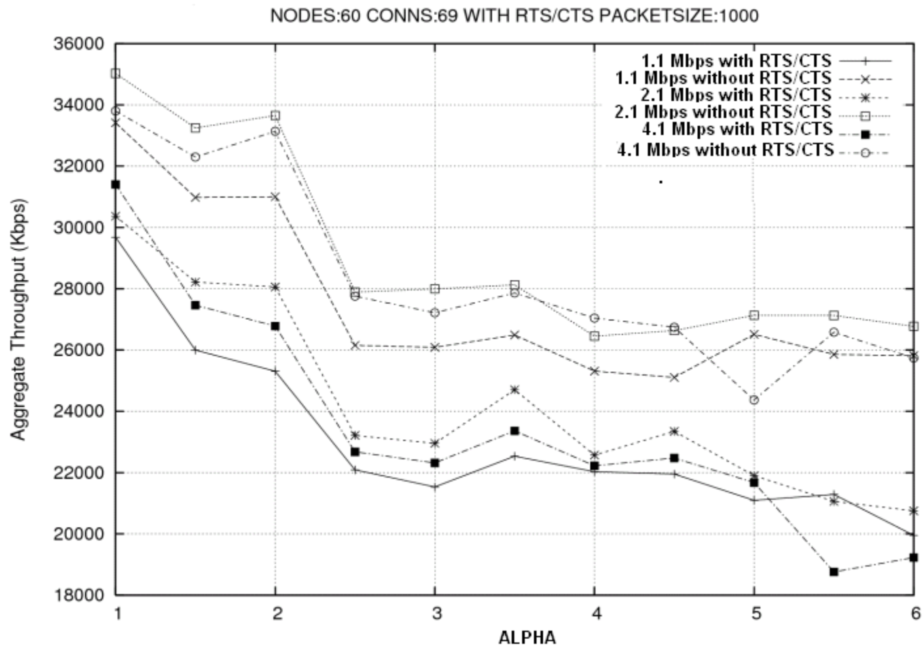


Figure 5.11 ALPHA vs throughput with fixed offered loads (0.4, 0.6 and 12. Mbps)

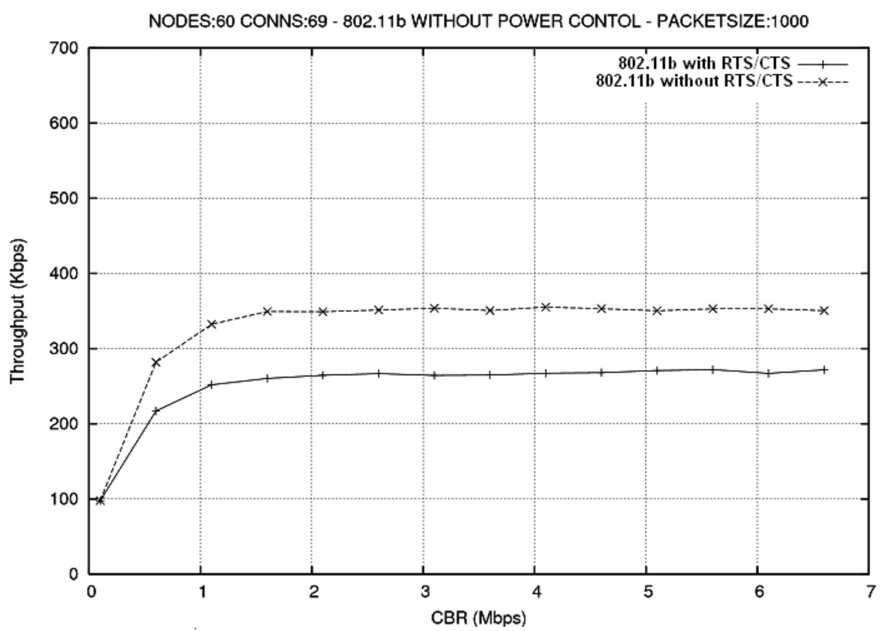


Figure 5.12 60 nodes 69 connections with ordinary 802.11b interface

In order to verify the advantage of the power control mechanism over the basic 802.11b interface Figure 5.19 is presented. The throughputs are 271.94 Kbps and 355.17 Kbps with and without RTS/CTS dialog. With power control mechanism, the throughputs are

465.46 Kbps (Figure 5.9) 525.15 Kbps (Figure 5.10) respectively. It is 71.1 % and 47.9 % of improvement.

5.4 Interference and the packet size

In [21], the authors studied the capacity of ad hoc wireless networks, pointing out how can be affected the performance by the packet size. According to [21], when the number of nodes is higher the packet size must be small. The more nodes in the network, the more traffic in the channel. Then if the packet size is big there is a high probability of collision with another packet produced with another node.

The topology of 60 nodes with 69 connections with CBR traffic is used again to observe the relation between the interference and the packet size when a power control mechanism exists. The values for the packet size are 1000, 500, 250 and 100 bytes. Two cases are considered light traffic (1.1 Mbps) and heavy traffic (4.1 Mbps) without RTS/CTS dialog. The figure 5.13 shows the aggregate throughput when the traffic is light. In the figure, ALPHA changes from 1 to 6 with a 0.5 step.

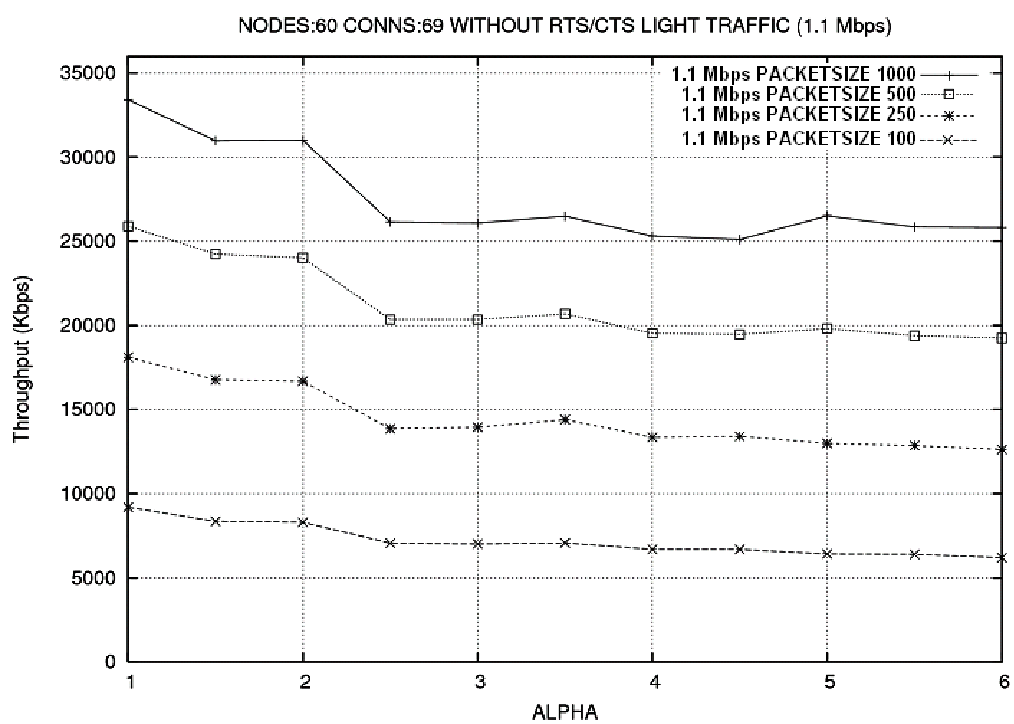


Figure 5.13 60 nodes 69 connections. Light traffic and packet size = 1000, 500, 250 and 100

The increase of the transmission power (ALPHA) increases the interference in the network. Notice that curve “1.1 Mbps PACKETSIZE 1000” has the same values of the curve “1.1 Mbps without RTS/CTS " of Figure 5.18. As it is appraised the curves are not crossed, they remain separated all along what indicates that the packet size is not relevant. Packet size equal to 1000 bytes produces the best aggregate throughput; if the package is small (100 bytes) then the aggregate throughput is minimum. Overhead is greater in small packets.

The figure 5.14 shows aggregate throughput when the traffic is heavy (4.1 Mbps).

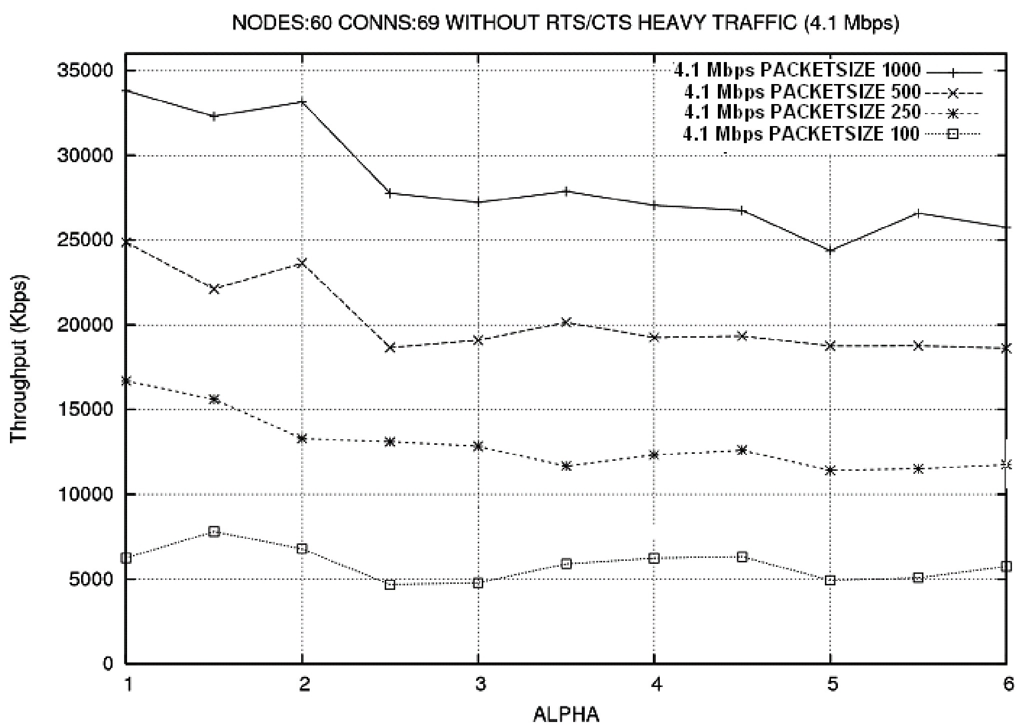


Figure 5.14 60 nodes 69 connections. Heavy traffic and packet size = 1000 , 500, 250 and 100

Curve “4.1 Mbps without RTS/CTS” of Figure 5.18 has the same values of curve “4.1 Mbps PACKETSIZE 1000”. The curve corresponding to the packet size equal to 1000 bytes is still producing the maximum aggregate throughput. Now, the aggregate throughput is smaller since the interference is bigger in the network. The results are different from the found ones in [21] because the authors used interfaces 802.11b that did not use the power control mechanism therefore their simulation used the maximum allowed power whereas this thesis using the minimum transmission power.

5.5 Basic 802.11b and ALPHA

The basic 802.11b do not use the power control to fix the transmission power at the transmitter nodes then it uses the maximum power. The maximum power, 3.3962e-2 mW, can reach 570.5 meters. Figure 5.15 shows three cases; n_A and n_B are separated by 570.5 meters, n_0 and n_1 50 meters and n_2 and n_3 150 meters. If n_A and n_B use basic 802.11b then they use the maximum power. If n_0, n_1, n_2 and n_3 use the 802.11b with power control then the power level is 0.002033 mW and 0.01830 mW. If ALPHA start to increase from 1 to 1.1, 1.2 and so on, at some point it will reach the 570.5 meters but ALPHA in link n_0 to n_1 and link n_2 to n_3 are going to be different since the minimum power (initial value) is also different. This is the reason why we need to test the topologies with basic 802.11b.

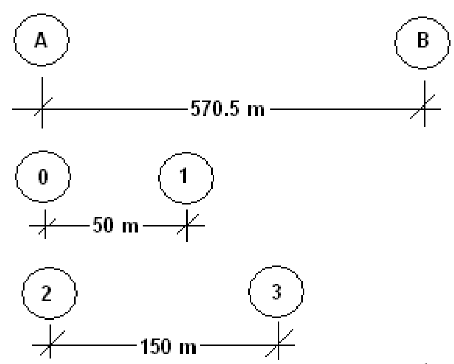


Figure 5.15 Basic 802.11b and power control mechanism

5.6 Interference in different scenarios

If a node is in the range of other transmission ranges then its capacity is reduced since the noise floor is higher or the channel is busy. Figure 5.16 presents a wireless network with 6 nodes and three flows. Flow 0 takes place between n_0 and n_1, flow 1 between n_2 and n_3 and flow 2 between n_4 and n_5. The distance "dist" is 100 meters, the transmission range use the minimal power (ALPHA equal to 1) and the carrier sensing range is 1.78 times the transmission range.

The flows could go from left to right or from right to left; for instance, it could be from n_0 to n_1 or from n_1 to n_0. The number of possible combinations is 8. However, the cases can be reduced to just three.

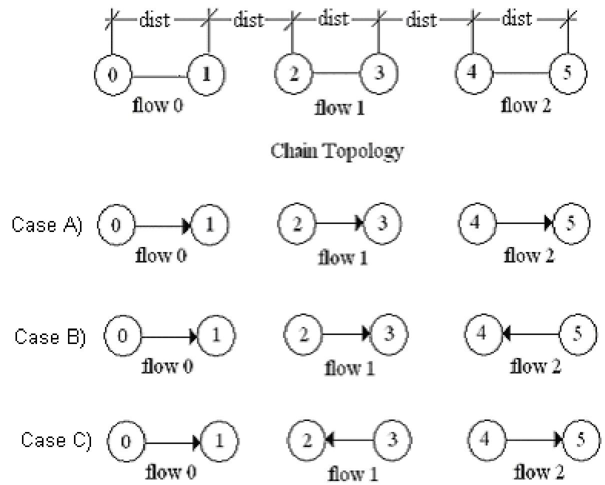


Figure 5.16 Interference in different scenarios

All the cases present hidden terminal problems and interference due to the use of minimal power for the transmission range and the carrier sensing range. There is many possibilities to analyze what happen when the direction of the flows change: FTP or CBR traffic each one with or without RTS/CTS dialog. CBR traffic without virtual carrier sensing is chosen to make the explanation. In Figure 5.16, case A and B are similar because the transmitter nodes n_0, n_2, n_4 (case A) and n_5 (case B) do not contend for the channel. The collision avoidance (CA) mechanism has no effect in the transmitters. Node n_0 is not affected by the others nodes, n_2 is affected by the ACK packets sent by n_1 to n_0 however the interference is minimal due to ACK packet size (14 bytes), n_4 (case A) is in the same situation of n_2 respect to n_3 and n_5 (case B) do not contend for the channel (like n_0). Case C is different because n_3 and n_4 can heard their DATA packets then the collision avoidance mechanism is working between n_3 and n_4.

Figures 5.17 and 5.18 show the throughputs of the flows.

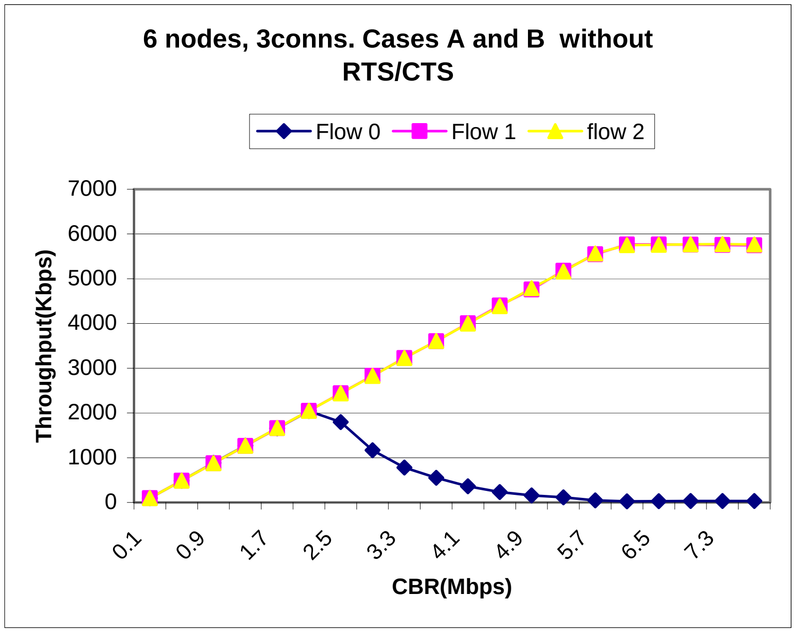


Figure 5.17 6 nodes, 3 connections. Case A, B

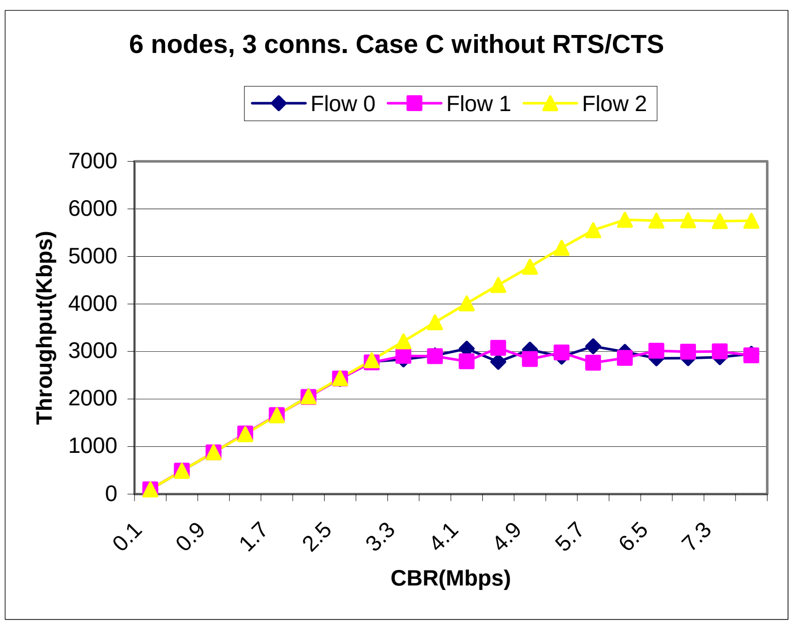


Figure 5.18 6 nodes, 3 connections. Case C

In cases A and B DATA packets sent by n_0 to n_1 have a high probability of collision with the DATA packets sent by n_2 to n_3. Node n_2 cannot hear n_0's packets, no CA conducts to high probability of collisions in n_1. If the offered load is increased then the n_0's throughput is worst since the channel is busy more time by n_2. DATA packets sent by n_0 to n_1 arrived to n_1 with errors (due to collisions) n_1 do not send back ACK messages to n_0. Flows 1 and 2 use the maximum capacity of the channel (5.7 Mbps).

In case C, Figure 5.18, n_3 and n_4 share the media because the CA mechanism is working. They can detect when the channel is busy and backoff it is necessary. In addition, n_1 and n_2 have interference in the ACK packets; since the packets have the same size the probability of collisions is 50% in each flow (0 or 1). Notice that n_5 do not have interference then all the ACK packets are send back to n4 with low probability of error because the size of ACK packets. Flow 2 has the best performance meanwhile flows 0 and 1 have similar values.

5.7 Interference in random topologies

Figure 5.19 shown a network composed of 60 nodes (900x800 meters) where the type of the topology is random. The number of connections is 69 and the distribution of the connections is the same one presented in Figure 5.7. For example node 0 has two connections: one with node ten and the other one with node 11. In this case, the network has high density and interference. Under those conditions, it is possible to appreciate that each connection has a minimum power that depends on the location and the model of propagation. In Pmin80211 module is defined a power control table at level of the layer MAC, the table can handle up to ten connections with different minimums powers.

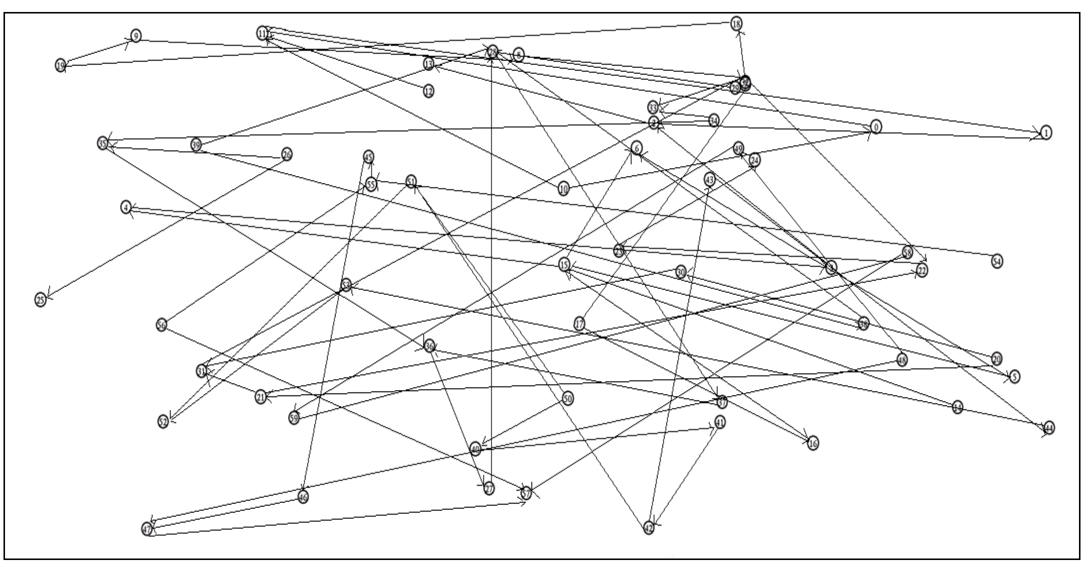


Figure 5.19 60 nodes, 69 connections with random topology

Again, the experiments are repeated looking for the optimal power. Figure 5.20 presents the CBR traffic versus the aggregate throughput. For this topology, aggregate throughput has been chosen instead of throughput since the changes in the performance of the network are more notorious in the waveforms of the aggregate throughput. In the figure, ALPHA varies from 1.0 to 2.0 with a 0.2 step, whereas the CBR goes from 10 Kbps to 140 Kbps. When ALPHA is equal to 1 (minimum power) the aggregate throughput of the network is also minimum since the density is elevated; inclusively when the traffic is light (10 to 50 Kbps). The minimum power is not the best option, if the packages are sent with the minimum power they cannot reach their destination because the inteference coming from the other transmitting nodes. This random topology has many connections that crossed their Line-of sight (LOS); which is the source of interference. In the experiment all the connections has one hop since we are in the MAC layer but it is possible to use a routing protocol at the network layer in order to improve this condition.

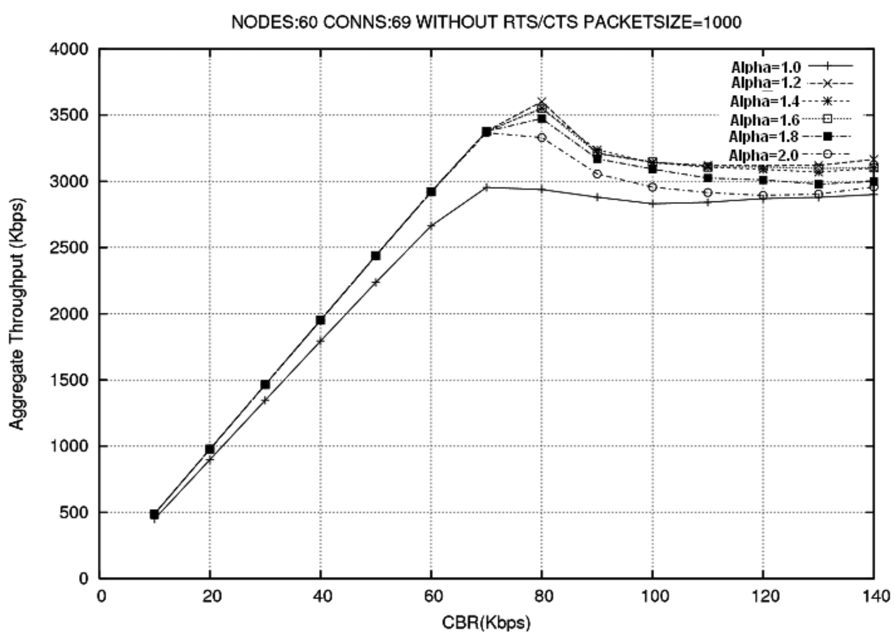


Figure 5.20 Random topology without RTS/CTS dialog

When ALPHA is equal to 1.2 it obtains the optimal power the aggregate throughput reaches 3600 Kbps (the maximum value). When ALPHA changes to 1.4, 1.6, 1.8 and 2.0 the aggregate throughput is reduced again. Figure 5.21 shows the same topology with the RTS/CTS a dialog. ALPHA goes from 1.0 to 1.6 with a 0.2 step. Like in the previous case, it is observed that the minimum power (ALPHA=1.0) is not the optimal power. In fact, the performance is the worse one with the minimum power. Again, the optimal power is produced when ALPHA is equal to 1.2.

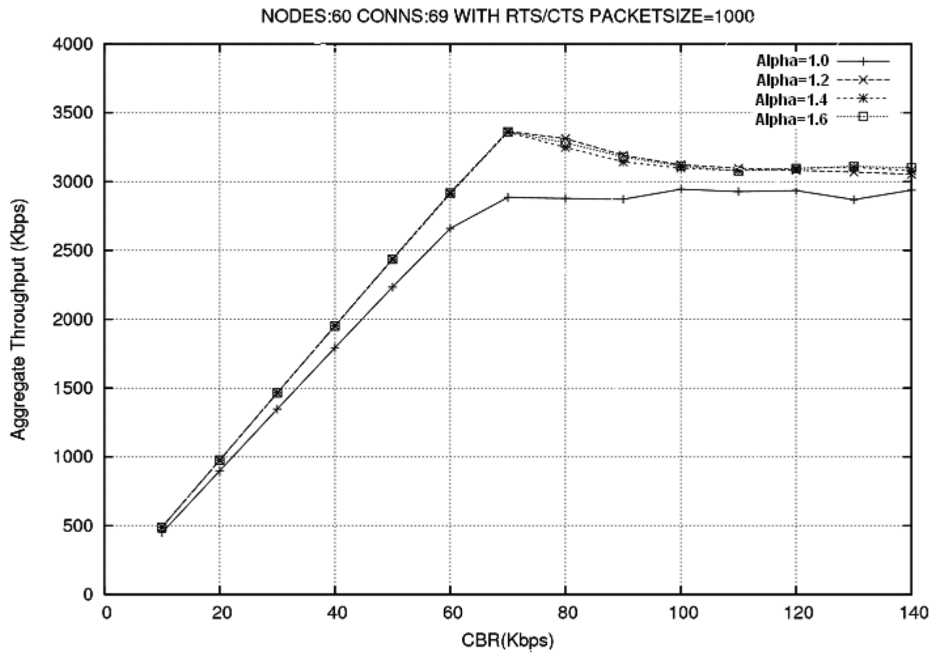


Figure 5.21 Random topology with RTS/CTS dialog

The variations without the RTS/CTS (Figure 5.20) mechanism are greater than the variations with RTS/CTS (Figure 5.21). The virtual carrier sensing RTS/CTS allows a fair access to the channel. Without RTS/CTS the number of collisions is high because the majority of the nodes in the network are in the transmission range.

Figure 5.22 and Figure 5.23 show the relation between ALPHA and the aggregate throughput with and without RTS/CTS dialog when the offered load is fixed. Three values for the load are chosen: 50 Kbps for light light, 70 Kbps for average traffic and 140 Kbps for heavy traffic. ALPHA varies from 1.0 to 2.0 with a 0.1 step. In both cases the optimal power is when ALPHA=1.1.

Previously, the optimal ALPHA was 1.2 but now the step is 0.1 then when ALPHA is equal to 1.1, it produces the best aggregate throughput. With high density or heavy traffic load the optimal ALPHA (optimal power) is closest to the minimum power (ALPHA =1.0).

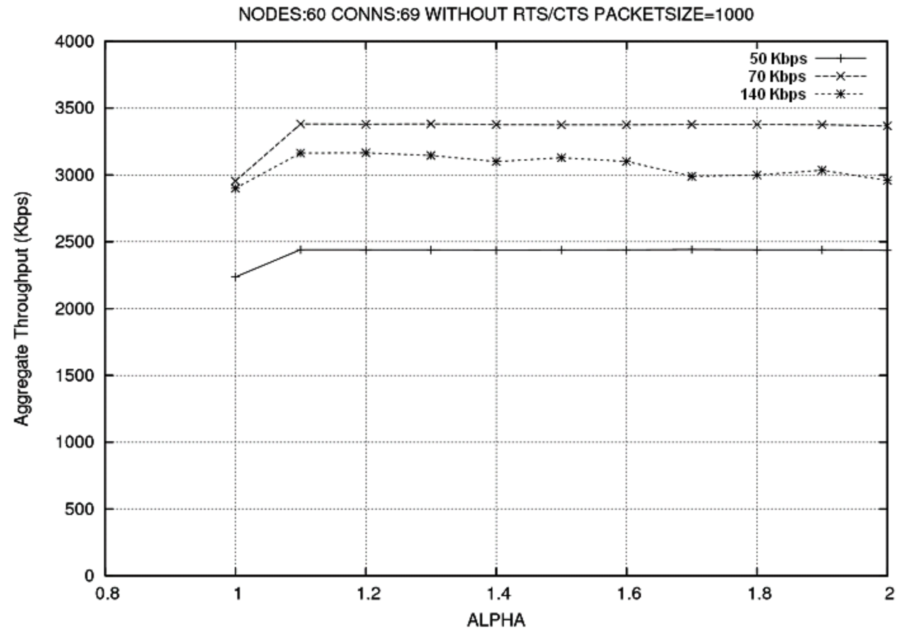


Figure 5.22 Random topology. ALPHA vs Aggregate Throughput without RTS/CTS

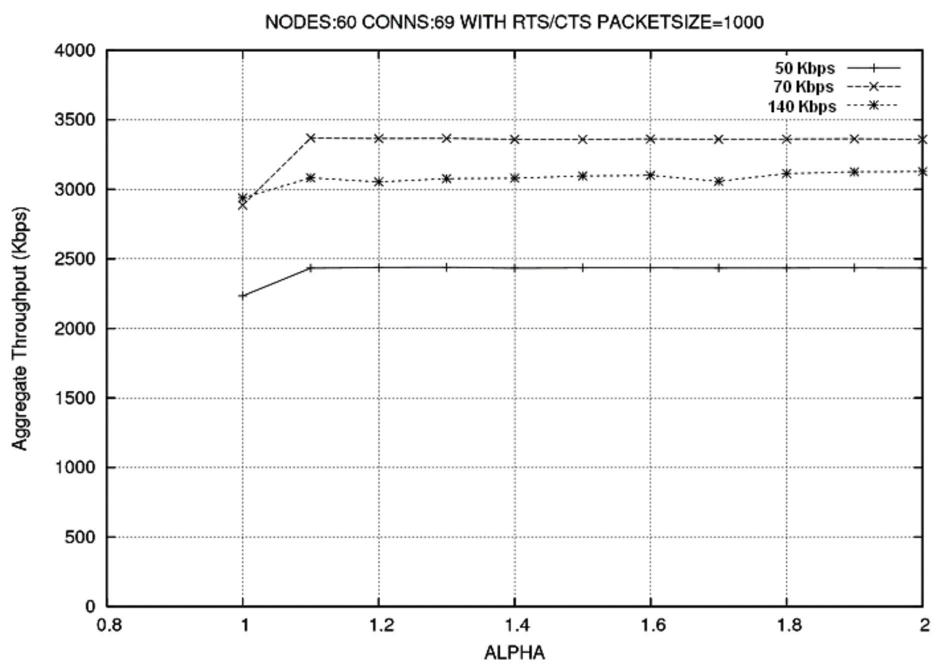


Figure 5.23 Random topology. ALPHA vs Aggregate Throughput with RTS/CTS

Chapter 6 Disscusion and Conclusions

6.1 Introduction

Power control limited the range of the carrier sense range by reused the space. In general, terminals in ad hoc wireless network have one radio or physical interface. The performance of the network is affected mainly by the interference due to the carrier sense range. In this range, the frames should be dropped at the link layer (at the receiver) because its signal strength is not strong enough to decode the message properly.

6.2 Impact of Power Control in the ISO layer

Power control is a complex problem that affects many layers of the ISO model. The goal of the physical layer is to transmit raw bits by using a connection. When the connection is wireless, the interference affects the transmission. In the past chapters, many simulations demonstrate the impact of the carrier sensing and transmission ranges. The transmitter power should be minimal when there is no other wireless connection present; otherwise, it is important to provide more power in order to overcome the interference (optimal transmission power). In real hardware, the SNR is a parameter that can be calculated at the physical layer and can be used to know the quality of the channel. Modification in the actual physical layer must take place. In the MAC and physical layer a power control mechanism is needed in order to provide discrete values; the majority of manufacturers include just five or six discrete values for the power control (1, 5, 20, 30, 50 and 100 mW) [3]. On the other hand, the inclusion of GPS in the network cards could improve the performance of the network. Nowadays GPS manufactured in Europe can work indoors or outdoors. Finally, the use of directional antennas could contribute to elevate the quality of the links since the interference is direct to just certain areas.

The Link layer controls the data rate between adjacent nodes. In short, it controls one hop in the wireless networks. The optimization of one hop is very important because it is going to limit the routes of the frames. There will be a tradeoff between power control and interference. The MAC layer and the network layer should work together because the network layer controls all the hops in the wireless network.

There are some observations about the simulation software. In order to obtain a simulation close to the real hardware some tasks must be done. The first task to do it is to characterize the interface. By default Ns-2 implements the 802.11a standard and it is necessary to setup the parameters to obtain the behavior of the 802.11b interface. Table 4.1 shows the values and the parameters. The following task is to calculate the suitable values to define the carrier sensing and transmission ranges by using parameters CSThresh and RX thresh. The CPThresh parameter is equal to ten and serves to decide that to do when there are collisions. The Pmin80211 module calculates the transmission power based on the model of propagation and the location of the nodes. The module passes those parameters to the layer MAC that is in charge to set up the transmission power of the DATA and RTS packages (if virtual carrier sensing mechanism is enabled). The head of frames has the values of the transmission power, in that fashion the receivers nodes can use that value in the transmission of the answers (ACK and CTS packets). The last task is compare the simulation values with experimental values (real hardware) in order to ensure that the simulation software is working properly.

6.3 Conclusions

Throughout this thesis, successive simulations have been made in networks that use interfaces 802.11b with or without power control. The conclusions are:

- The use of power control aids to improve the throughput. The interference cannot be eliminated however it can be reduced. The use of the power control reduces the effects of the transmission and to carrier sensing ranges.
- Carrier sensing is consider as noise to accurately compute other transmission's SNR. So functionality of RTS/CTS can be affected.
- Packet size does not affect the performance of the network that uses power control. When the power control is used, the interference range is limited which avoids that the interference in the network extends.
- ALPHA can be used to implement power control and can be adaptive, ALPHA is different for each network base on density of the network and load

Appendix A

A.1 6 nodes, 3 connections

CBR traffic with UDP. Packet size = 1000. Alpha =1

A.1.1 Case A with RTS/CTS

CBR (M)	Flow 0		Flow 1		Flow 2	
	Thp (Kbps)	E2E (secs)	Thp (Kbps)	E2E (secs)	Thp (Kbps)	E2E (secs)
0.1	97.90	836.75	97.75	837.99	97.37	841.27
0.5	485.76	168.63	488.18	167.79	489.42	167.37
0.9	871.92	93.95	879.73	93.11	876.29	93.48
1.3	1271.10	64.44	1270.98	64.45	1264.76	64.76
1.7	1652.77	49.54	1659.52	49.36	1656.92	49.43
2.1	1970.36	40.02	2039.55	40.16	2050.92	39.93
2.5	1468.84	33.72	2434.05	33.65	2439.80	33.57
2.9	1118.01	29.01	2831.30	28.93	2829.83	28.93
3.3	872.81	25.54	3214.89	25.46	3227.13	25.37
3.7	700.59	22.82	3600.87	22.74	3618.07	22.62
4.1	521.19	20.58	3988.26	20.52	4009.04	20.42
4.5	410.86	18.86	4288.87	18.79	4390.81	18.65
4.9	451.95	17.30	4252.40	17.22	4559.38	17.18
5.3	448.73	16.02	4270.20	15.94	4564.94	15.86
5.7	448.39	14.93	4260.49	14.83	4547.24	14.72
6.1	435.39	13.89	4274.07	13.81	4570.93	13.90
6.5	413.67	13.07	4296.78	12.99	4569.33	12.99
6.9	491.61	12.33	4213.15	12.24	4519.39	12.26
7.3	448.01	11.67	4250.81	11.60	4543.59	11.57
7.7	445.45	11.08	4258.63	11.02	4562.73	11.03

CBR (M)	Ave Thp (Kbps)	Agg. Thp (Kbps)	Total Pcks	Ok Pcks	Lost Pcks
0.1	97.67	293.02	31455	31455	0
0.5	487.79	1463.36	31455	31455	0
0.9	875.98	2627.94	31455	31455	0
1.3	1268.95	3806.83	31455	31454	1
1.7	1656.40	4969.21	31455	31450	5
2.1	2020.28	6060.83	31455	31061	394
2.5	2114.23	6342.69	31455	27307	4148
2.9	2259.71	6779.14	31453	25114	6339
3.3	2438.28	7314.84	31451	23808	7643
3.7	2639.84	7919.52	31455	23004	8451
4.1	2839.49	8518.48	31449	22327	9122
4.5	3030.18	9090.54	31431	21786	9645
4.9	3087.90	9263.73	31455	20401	11054
5.3	3094.62	9283.87	31450	18899	12551
5.7	3085.37	9256.12	31451	17512	13939
6.1	3093.46	9280.38	31454	16463	14991
6.5	3093.26	9279.78	31450	15432	16018
6.9	3074.71	9224.14	31430	14471	16959
7.3	3080.80	9242.41	31419	13710	17709
7.7	3088.94	9266.82	31436	13076	18360

A.1.2 Case A without RTS/CTS

CBR (M)	Flow 0		Flow 1		Flow 2	
	Thp (Kbps)	E2E (secs)	Thp (Kbps)	E2E (secs)	Thp (Kbps)	E2E (secs)
0.1	97.93	836.43	97.26	842.21	97.58	839.44
0.5	486.36	168.42	485.77	168.63	487.56	168.01
0.9	882.20	92.85	877.30	93.37	878.28	93.27
1.3	1270.90	64.45	1263.14	64.85	1268.45	64.58
1.7	1657.07	49.43	1662.02	49.29	1662.42	49.27
2.1	2044.44	40.01	2047.90	40.00	2046.32	40.03
2.5	1797.13	33.70	2440.10	33.57	2438.32	33.59
2.9	1166.56	29.01	2831.60	28.93	2828.06	28.96
3.3	781.45	25.43	3228.53	25.37	3228.31	25.37
3.7	551.61	22.79	3603.46	22.73	3607.50	22.71
4.1	360.85	20.55	4002.87	20.46	3998.78	20.48
4.5	232.88	18.69	4401.42	18.61	4386.17	18.68
4.9	156.54	17.27	4760.85	17.20	4787.59	17.11
5.3	113.90	15.91	5180.13	15.81	5159.50	15.88
5.7	47.88	14.85	5545.30	14.77	5564.15	14.72
6.1	25.78	13.94	5764.02	13.88	5749.51	13.84
6.5	28.64	13.10	5767.07	13.03	5758.13	12.98
6.9	31.21	12.26	5762.17	12.19	5770.28	12.28
7.3	32.20	11.65	5753.13	11.58	5771.12	11.57
7.7	33.92	11.05	5746.42	10.98	5764.91	10.98

CBR (M)	Ave Thp (Kbps)	Agg. Thp (Kbps)	Total Pcks	Ok Pcks	Lost Pcks
0.1	97.59	292.77	31455	31455	0
0.5	486.56	1459.68	31455	31455	0
0.9	879.26	2637.78	31455	31455	0
1.3	1267.49	3802.48	31455	31455	0
1.7	1660.50	4981.51	31455	31455	0
2.1	2046.21	6138.65	31455	31440	15
2.5	2225.17	6675.53	31455	28723	2732
2.9	2275.40	6826.21	31455	25300	6155
3.3	2412.76	7238.28	31445	23513	7932
3.7	2587.52	7762.57	31450	22578	8872
4.1	2787.50	8362.50	31455	21918	9537
4.5	3006.82	9020.46	31455	21526	9929
4.9	3234.98	9704.96	31441	21315	10126
5.3	3484.51	10453.53	31455	21201	10254
5.7	3719.11	11157.33	31443	21059	10384
6.1	3846.43	11539.31	31424	20469	10955
6.5	3851.28	11553.84	31445	19230	12215
6.9	3854.55	11563.66	31440	18110	13330
7.3	3852.15	11556.45	31438	17120	14318
7.7	3848.41	11545.25	31420	16229	15191

A.1.3 Case B with RTS/CTS

CBR (M)	Flow 0		Flow 1		Flow 2	
	Thp (Kbps)	E2E (secs)	Thp (Kbps)	E2E (secs)	Thp (Kbps)	E2E (secs)
0.1	97.90	836.75	97.75	837.99	97.37	841.27
0.5	485.76	168.63	488.18	167.79	489.42	167.37
0.9	871.92	93.95	879.73	93.11	876.29	93.48
1.3	1271.10	64.44	1270.98	64.45	1264.76	64.76
1.7	1652.77	49.54	1659.52	49.36	1656.92	49.43
2.1	1970.36	40.02	2039.55	40.16	2050.92	39.93
2.5	1498.87	33.67	2438.24	33.59	2425.71	33.77
2.9	1084.13	29.07	2822.21	29.02	2825.27	28.98
3.3	876.09	25.54	3216.11	25.43	3221.56	25.41
3.7	682.00	22.78	3607.38	22.70	3604.20	22.71
4.1	538.22	20.57	3993.91	20.45	4008.31	20.43
4.5	430.01	18.82	4285.54	18.75	4372.36	18.73
4.9	468.52	17.26	4245.67	17.18	4557.84	17.31
5.3	434.37	16.03	4277.99	15.94	4569.70	15.89
5.7	468.53	14.89	4242.57	14.81	4564.57	14.85
6.1	447.77	13.94	4265.08	13.85	4574.99	13.83
6.5	461.54	13.12	4232.36	13.04	4552.91	13.03
6.9	471.75	12.35	4249.86	12.26	4559.87	12.22
7.3	467.01	11.64	4233.07	11.55	4514.74	11.60
7.7	454.40	11.06	4258. 17	10.97	4561.81	11.03

CBR (M)	Ave Thp (Kbps)	Agg. Thp (Kbps)	Total Pcks	Ok Pcks	Lost Pcks
0.1	97.67	293.01	31455	31455	0
0.5	487.78	1463.35	31455	31455	0
0.9	875.97	2627.93	31455	31455	0
1.3	1268.94	3806.83	31455	31454	1
1.7	1656.40	4969.21	31455	31450	5
2.1	2020.27	6060.83	31455	31061	394
2.5	2120.94	6362.82	31448	27426	4022
2.9	2243.86	6731.60	31454	24998	6456
3.3	2437.92	7313.76	31455	23813	7642
3.7	2631.19	7893.57	31452	22947	8505
4.1	2846.81	8540.44	31455	22353	9102
4.5	3029.30	9087.90	31454	21800	9654
4.9	3090.67	9272.02	31448	20468	10980
5.3	3094.01	9282.05	31442	18914	12528
5.7	3091.88	9275.66	31438	17613	13825
6.1	3095.94	9287.83	31448	16461	14987
6.5	3082.27	9246.81	31434	15438	15996
6.9	3093.82	9281.48	31453	14544	16909
7.3	3071.60	9214.80	31434	13659	17775
7.7	3091.45	9274.37	31431	13061	18370

A.1.4 Case B without RTS/CTS

CBR (M)	Flow 0		Flow 1		Flow 2	
	Thp (Kbps)	E2E (secs)	Thp (Kbps)	E2E (secs)	Thp (Kbps)	E2E (secs)
0.1	97.93	836.43	97.26	842.21	97.58	839.44
0.5	486.36	168.42	485.77	168.63	487.56	168.01
0.9	882.20	92.85	877.30	93.37	878.28	93.27
1.3	1270.90	64.45	1263.14	64.85	1268.45	64.58
1.7	1657.07	49.43	1662.02	49.29	1662.42	49.27
2.1	2044.44	40.01	2047.90	40.00	2046.32	40.03
2.5	1747.58	33.60	2441.41	33.55	2438.48	33.59
2.9	1206.42	29.01	2829.06	28.95	2830.48	28.94
3.3	801.43	25.52	3216.77	25.46	3211.74	25.50
3.7	531.84	22.71	3620.45	22.62	3603.34	22.73
4.1	360.85	20.55	4002.87	20.46	3998.78	20.48
4.5	235.19	18.77	4381.20	18.69	4379.30	18.70
4.9	171.49	17.27	4764.56	17.19	4778.50	17.14
5.3	96.05	15.94	5158.90	15.88	5175.63	15.83
5.7	47.88	14.85	5545.30	14.77	5564.15	14.72
6.1	26.32	13.95	5753.87	13.89	5766.19	13.87
6.5	28.72	13.06	5753.57	12.99	5750.48	12.91
6.9	30.46	12.31	5762.98	12.24	5762.70	12.21
7.3	32.22	11.64	5754.16	11.57	5761.27	11.55
7.7	34.61	11.06	5749.19	10.99	5769.54	10.93

CBR (M)	Ave Thp (Kbps)	Agg. Thp (Kbps)	Total Pcks	Ok Pcks	Lost Pcks
0.1	97.59	292.77	31455	31455	0
0.5	486.56	1459.68	31455	31455	0
0.9	879.26	2637.78	31455	31455	0
1.3	1267.49	3802.48	31455	31455	0
1.7	1660.50	4981.51	31455	31455	0
2.1	2046.21	6138.65	31455	31440	15
2.5	2209.15	6627.47	31455	28486	2969
2.9	2288.65	6865.95	31445	25448	5997
3.3	2409.97	7229.93	31455	23587	7868
3.7	2585.20	7755.62	31455	22515	8940
4.1	2787.50	8362.50	31455	21918	9537
4.5	2998.56	8995.68	31439	21534	9905
4.9	3238.18	9714.54	31441	21348	10093
5.3	3476.86	10430.58	31434	21165	10269
5.7	3719.11	11157.33	31443	21059	10384
6.1	3848.79	11546.37	31453	20512	10941
6.5	3844.25	11532.76	31437	19115	12322
6.9	3852.04	11556.14	31451	18088	13363
7.3	3849.21	11547.65	31428	17090	14338
7.7	3851.11	11553.33	31443	16209	15234

A.1.5 Case C with RTS/CTS

CBR (M)	Flow 0		Flow 1		Flow 2	
	Thp (Kbps)	E2E (secs)	Thp (Kbps)	E2E (secs)	Thp (Kbps)	E2E (secs)
0.1	97.32	841.73	97.66	838.80	97.65	838.86
0.5	485.54	168.71	488.11	167.82	490.78	166.91
0.9	874.82	93.63	879.04	93.19	876.88	93.42
1.3	1270.49	64.47	1265.31	64.74	1263.75	64.81
1.7	1659.39	49.29	1659.06	49.32	1657.04	49.43
2.1	2028.26	39.91	2031.87	39.83	2039.49	40.16
2.5	2232.19	33.63	2211.16	33.61	2438.68	33.58
2.9	2277.45	29.11	2241.86	28.86	2822.96	29.01
3.3	2354.58	25.57	2195.64	25.41	3223.09	25.41
3.7	2289.80	22.80	2266.89	22.89	3610.02	22.68
4.1	2382.86	20.63	2165.14	20.64	3982.64	20.53
4.5	2266.29	18.83	2278.69	18.74	4374.06	18.72
4.9	2116.92	17.28	2440.61	17.38	4572.28	17.05
5.3	2394.04	15.95	2157.91	15.98	4580.29	15.94
5.7	2357.23	14.77	2201.34	14.86	4570.15	14.86
6.1	2270.56	13.94	2266.58	13.98	4546.66	13.79
6.5	2156.22	13.11	2388.88	13.10	4558.68	12.99
6.9	2338.47	12.26	2152.59	12.35	4501.49	12.28
7.3	2453.88	11.60	2056.43	11.67	4505.79	11.58
7.7	2487.78	11.10	2069.49	11.03	4561.69	10.97

CBR (M)	Ave Thp (Kbps)	Agg. Thp (Kbps)	Total Pcks	Ok Pcks	Lost Pcks
0.1	97.54	292.62	31455	31455	0
0.5	488.14	1464.42	31455	31455	0
0.9	876.91	2630.74	31455	31455	0
1.3	1266.51	3799.55	31455	31454	1
1.7	1658.49	4975.49	31455	31428	27
2.1	2033.20	6099.62	31455	31206	249
2.5	2294.01	6882.03	31455	29602	1853
2.9	2447.42	7342.27	31455	27251	4204
3.3	2591.10	7773.31	31454	25329	6125
3.7	2722.23	8166.71	31444	23806	7638
4.1	2843.54	8530.63	31451	22477	8974
4.5	2973.01	8919.03	31442	21409	10033
4.9	3043.26	9129.80	31446	20093	11353
5.3	3044.07	9132.23	31454	18650	12804
5.7	3042.90	9128.72	31419	17338	14081
6.1	3027.93	9083.79	31438	16135	15303
6.5	3034.59	9103.78	31425	15206	16219
6.9	2997.51	8992.55	31414	14148	17266
7.3	3005.36	9016.10	31434	13391	18043
7.7	3039.65	9118.96	31454	12863	18591

A.1.6 Case C with RTS/CTS

CBR (M)	Flow 0		Flow 1		Flow 2	
	Thp (Kbps)	E2E (secs)	Thp (Kbps)	E2E (secs)	Thp (Kbps)	E2E (secs)
0.1	97.53	839.91	97.23	842.45	97.94	836.34
0.5	487.75	167.94	491.59	166.63	487.95	167.87
0.9	877.06	93.40	877.07	93.39	878.64	93.23
1.3	1268.46	64.58	1274.56	64.27	1260.12	65.00
1.7	1655.92	49.47	1661.21	49.31	1656.83	49.44
2.1	2053.27	39.88	2042.96	40.10	2053.72	39.89
2.5	2421.56	33.72	2427.79	33.65	2438.04	33.60
2.9	2787.22	28.87	2769.75	29.01	2816.57	29.08
3.3	2833.93	25.48	2907.91	25.48	3213.58	25.49
3.7	2916.60	22.81	2900.82	22.83	3615.39	22.66
4.1	3060.28	20.59	2792.57	20.65	4011.92	20.42
4.5	2783.05	18.81	3074.18	18.76	4400.21	18.62
4.9	3039.62	17.20	2838.12	17.27	4783.73	17.12
5.3	2888.85	15.95	2978.80	15.88	5179.54	15.81
5.7	3108.90	14.85	2762.32	14.79	5551.69	14.75
6.1	2990.12	13.86	2863.71	13.84	5770.44	13.81
6.5	2856.67	13.05	3014.86	13.00	5752.82	13.00
6.9	2859.18	12.25	2995.57	12.29	5761.99	12.24
7.3	2879.46	11.55	2999.91	11.62	5742.34	11.60
7.7	2951.59	11.02	2918.78	10.97	5751.79	10.94

CBR (M)	Ave Thp (Kbps)	Agg. Thp (Kbps)	Total Pcks	Ok Pcks	Lost Pcks
0.1	97.56	292.70	31455	31455	0
0.5	489.09	1467.29	31455	31455	0
0.9	877.58	2632.76	31455	31455	0
1.3	1267.71	3803.14	31455	31455	0
1.7	1657.98	4973.96	31455	31455	0
2.1	2049.98	6149.94	31455	31452	3
2.5	2429.13	7287.39	31455	31392	63
2.9	2791.18	8373.54	31455	31072	383
3.3	2985.13	8955.41	31455	29213	2242
3.7	3144.26	9432.80	31455	27478	3977
4.1	3288.25	9864.7	31452	25933	5519
4.5	3419.14	10257.43	31453	24564	6889
4.9	3553.82	10661.47	31454	23452	8002
5.3	3682.39	11047.18	31449	22437	9012
5.7	3807.63	11422.91	31446	21625	9821
6.1	3874.75	11624.27	31437	20577	10860
6.5	3874.78	11624.35	31455	19363	12092
6.9	3872.24	11616.73	31444	18223	13221
7.3	3873.90	11621.70	31452	17247	14205
7.7	3874.05	11622.15	31444	16315	15129

A.2 25 nodes, 12 connections

CBR/UDP traffic. Packet size 1000.

A.2.1 With RTS/CTS, Alpha (1.0, 1.2, 1.6, 2.0, 2.5, 10.0)

Alpha	1.0	1.2	1.6	2.0	2.5	10
T F0 (Kbps)	1172.04	1380.70	1380.70	1337.50	1337.50	1064.76
T F1 (Kbps)	2429.56	2849.13	2849.13	2832.82	2832.82	1863.14
T F2 (Kbps)	1985.59	1609.08	1609.08	1688.07	1688.07	879.16
T F3 (Kbps)	3034.72	2951.98	2951.98	2956.99	2956.99	1635.74
T F4 (Kbps)	1525.01	1308.86	1308.86	1306.79	1306.79	1058.86
T F5 (Kbps)	2366.64	1828.24	1828.24	1809.13	1809.13	1334.35
T F6 (Kbps)	829.21	599.58	599.58	874.99	874.99	501.43
T F7 (Kbps)	1584.92	864.43	864.43	569.75	569.75	704.39
T F8 (Kbps)	735.46	557.11	557.11	560.48	560.48	496.86
T F9 (Kbps)	604.01	562.68	562.68	697.31	697.31	492.78
T.F10 (Kbps)	1662.67	1761.38	1761.38	1810.11	1810.11	1073.24
T.F11 (Kbps)	678.15	1285.84	1285.84	1302.74	1302.74	830.19
Dly. F0 (secs)	70.70	60.63	60.63	62.33	62.33	78.82
Dly. F1 (secs)	33.72	28.75	28.75	28.92	28.92	44.61
Dly. F2 (secs)	41.44	51.73	51.73	49.21	49.21	95.22
Dly. F3 (secs)	26.99	27.75	27.75	27.70	27.70	50.76
Dly. F4 (secs)	54.02	63.22	63.22	63.22	63.22	79.36
Dly. F5 (secs)	34.61	44.81	44.81	45.28	45.28	64.44
Dly. F6 (secs)	99.73	139.08	139.08	94.07	94.07	167.53
Dly. F7 (secs)	51.69	94.97	94.97	143.88	143.88	117.29
Dly. F8 (secs)	112.29	148.82	148.82	147.40	147.40	169.28
Dly. F9 (secs)	137.31	147.82	147.82	118.62	118.62	169.90
Dly. F10 (secs)	49.27	46.51	46.51	45.36	45.36	81.04
Dly. F11 (secs)	121.10	64.38	64.38	63.41	63.41	102.73
Ave. Thp (Kbps)	1550.66	1463.25	1463.25	1478.89	1478.89	994.57
Agg. Thp (Kbps)	18607.9	17559.0	17559.0	17746.6	17746.6	11934.9
Ave. Pck dly (msecs)	51.07	65.29	65.29	56.02	56.02	88.28
RxDist (m)	160.00	175.27	202.38	226.27	242.77	343.33

A.2.2 Without RTS/CTS Alpha (1.0, 1.2, 1.6, 2.0, 2.5, 10.0)

Alpha	1.0	1.2	1.6	2.0	2.5	10
T F0 (Kbps)	1547.54	1767.55	1767.55	1821.78	1421.25	1728.95
T F1 (Kbps)	3043.33	3697.32	3697.32	3584.33	2317.68	2549.16
T F2 (Kbps)	2582.82	1810.07	1810.07	2006.59	1350.05	1211.15
T F3 (Kbps)	3885.92	3583.56	3583.56	3647.81	2403.58	2360.61
T F4 (Kbps)	1799.15	1650.83	1650.83	1795.54	1248.90	1107.74
T F5 (Kbps)	3118.99	2347.07	2347.07	2629.82	1862.13	1951.32
T F6 (Kbps)	1057.68	750.67	750.67	726.92	656.20	590.50
T F7 (Kbps)	2066.70	857.40	857.40	1231.19	837.92	950.60
T F8 (Kbps)	912.34	771.94	771.94	865.03	662.12	591.00
T F9 (Kbps)	912.26	764.32	764.32	886.92	659.87	589.47
T F10 (Kbps)	2086.68	2486.21	2486.21	2425.01	1846.55	2190.11
T F11 (Kbps)	1206.34	1679.76	1679.76	1722.42	1318.16	658.67
Dly. F0 (secs)	53.58	47.13	47.13	46.30	58.75	47.87
Dly. F1 (secs)	26.92	22.16	22.16	22.85	35.35	32.14
Dly. F2 (secs)	31.88	46.06	46.06	41.81	61.56	68.73
Dly. F3 (secs)	21.08	22.86	22.86	22.46	34.08	34.71
Dly. F4 (secs)	46.22	49.84	49.84	45.85	66.62	75.74
Dly. F5 (secs)	26.26	34.90	34.90	31.15	43.99	42.19
Dly. F6 (secs)	78.27	111.56	111.56	112.80	127.05	141.82
Dly. F7 (secs)	39.64	95.64	95.64	66.62	98.04	86.34
Dly. F8 (secs)	90.78	108.32	108.32	95.31	125.89	141.64
Dly. F9 (secs)	91.46	109.09	109.09	93.16	126.60	141.68
Dly. F10 (secs)	39.37	32.95	32.95	33.78	44.36	37.42
Dly. F11 (secs)	68.13	49.00	49.00	47.93	62.67	124.46
Ave. Thp (Kbps)	2018.31	1847.22	1847.22	1945.28	1382.03	1373.27
Agg. Thp (Kbps)	24219.7	22166.6	22166.6	23343.3	16584.4	16479.2
Ave. Pck dly (msecs)	40.32	44.63	44.63	40.79	70.95	82.23
RxDist (m)	160.00	175.27	202.38	226.27	242.77	343.33

A.3. 60 nodes, 69 connections

A.3.1 60 nodes, 69 connections with RTS/CTS dialog

ALPHA	Average delay (msecs)	Aggregate Throughput (Kbps)	Average Throughput (Kbps)
1.0	138.9	49349.0	715.2
1.2	143.8	45445.6	658.6
1.4	153.0	39735.7	575.8
1.6	152.6	36227.5	525.03
1.8	157.2	36259.9	525.5
2.0	159.4	36377.8	527.21
2.5	167.2	31489.1	456.3
3.0	197.4	31421.8	455.3
5.0	215.2	28098.0	407.2
7.0	219.6	25817.2	374.1
10	242.1	25068.2	363.3
15	288.8	21086.0	305.5

A.3.2 60 nodes, 69 connections without RTS/CTS dialog

ALPHA	Average delay (msecs)	Aggregate Throughput (Kbps)	Average Throughput (Kbps)
1.0	95.8	63526.8	920.6
1.2	96.5	56836.0	823.7
1.4	100.2	45855.3	664.56
1.6	100.7	45153.3	654.4
1.8	109.3	47069.8	682.1
2.0	114.4	44803.6	649.3
2.5	122.3	38301.2	555.0
3.0	134.7	38741.4	561.4
5.0	160.2	35247.7	510.8
7.0	167.5	33119.6	479.9
10	164.5	37127.8	538.0
15	190.3	31281.1	453.3

Appendix B

B.1 Pmin80211.h

```
/* -*-  Mode:C++; c-basic-offset:8; tab-width:8; indent-tabs-mode:t -*-
 *
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 * SUCH DAMAGE.
 *
 * $Header: /cvsroot/nsnam/ns-2/mac/mac-802_11.cc,v 1.51 2006/01/30 21:27:51 mweigle Exp
$
 *
 * Ported from CMU/Monarch's code, nov'98 -Padma.
 * Contributions by:
 *   - Mike Holland
 *   - Sushmita
 */

#ifndef Pmin80211_H
#define Pmin80211_H

const int PMIN_MAX_NODE=100;
const int PMIN_NUM_PAR=4;
const int MAX_LINE=100;

class Pmin80211 : public TclObject {
public:
        /*initialize from one pmin file*/
        static int initialize(const char* const& filename);

        /*return the minimum power*/
        static double framePowerMin( int n1, int n2);

        /*return the rx range of a power tx.*/
        static double rangePowerMin( int n1, double pRange);

         /*return the cs range of a power tx.*/
        static double csPowerMin( int n1, double pRange);
```

```
        static int initialized_;  /*power table is loaded*/
        static int nodes_;
        static double alfa_;
        static int model_;
         static double RXThresh_;
         static double CSThresh_;
         static double Gt_;
         static double Gr_;
         static double freq_;
         static double L_;
         static double ht_;
         static double hr_;

        static double pmin_[PMIN_MAX_NODE][PMIN_NUM_PAR];

private:
        static void printTables();
        static double Friis(double P, double Gt, double Gr, double lambda, double L,
double d);
        static double TwoRay(double Pr, double Gt, double Gr, double ht, double hr, double
L,
                            double d, double lambda);
        static double distPowerMin(int src, int dst);
        static double RangeFriis(double Pt, double P, double Gt, double Gr, double lambda,
                               double L);
        static double RangeTwoRay(double P, double Pr, double Gt, double Gr, double ht,
                                double hr, double L, double lambda);
};

#endif
```

B.2 Pmin80211.CC

```
/* -
*-      Mode:C++; c-basic-offset:8; tab-width:8; indent-tabs-mode:t -*-
 *
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 *
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 * LIABILITY, OR TORT (INCLUDING NEGLIGENCE OR OTHERWISE) ARISING IN ANY WAY
 * OUT OF THE USE OF THIS SOFTWARE, EVEN IF ADVISED OF THE POSSIBILITY OF
 * SUCH DAMAGE.
 *
 * $Header: /cvsroot/nsnam/ns-2/mac/mac-802_11.cc,v 1.51 2006/01/30 21:27:51 mweigle Exp
$
```

```
 *
 * Ported from CMU/Monarch's code, nov'98 -Padma.
 * Contributions by:
 *   - Mike Holland
 *   - Sushmita
 */
#include <stdio.h>
#include <stdlib.h>
#include <math.h>
#include <string.h>

#include "config.h"
#include "Pmin80211.h"

#ifndef M_PI
#define M_PI 3.14159265359
#endif

#define SPEED_LIGHT 300000000    // to calculate lambda_

int    Pmin80211::initialized_=0;
int    Pmin80211::nodes_;
double Pmin80211::alfa_=1;
int    Pmin80211::model_=1;
double Pmin80211::RXThresh_;
double Pmin80211::CSThresh_;
double Pmin80211::Gt_;
double Pmin80211::Gr_;
double Pmin80211::freq_;
double Pmin80211::L_;
double Pmin80211::ht_;
double Pmin80211::hr_;

double Pmin80211::pmin_[PMIN_MAX_NODE][PMIN_NUM_PAR];


//-----------------------------------------
//       *-----------------------*
// node  | x | y | z | max power |
//       *-----------------------*
// model  1- friss    2- tworayground   3 - other

static class Pmin80211Class: public TclClass{
public:
	Pmin80211Class() : TclClass("Pmin80211") {}
	TclObject* create(int argc, const char * const * argv)
	{
		return (new Pmin80211());
	}

	virtual void bind();
	virtual int method(int argc, const char * const * argv);
} class_Pmin80211;

void Pmin80211Class::bind()
{
	TclClass::bind();
	 add_method("pmin_Alfa_");
	 add_method("pmin_LoadPminFile_");
	add_method("pmin_PropagationModel_");
	 add_method("pmin_RXThresh_");
	 add_method("pmin_CSThresh_");
	 add_method("pmin_Gt_");
	 add_method("pmin_Gr_");
	 add_method("pmin_freq_");
	 add_method("pmin_L_");
	 add_method("pmin_ht_");
	 add_method("pmin_hr_");
}

int Pmin80211Class::method(int ac, const char* const * av)
```

```
{
        Tcl& tcl = Tcl::instance();
        int argc = ac - 2;
        const char* const * argv = av+2;
        if(argc == 2)
        {
                if(strcmp(argv[1],"pmin_Alfa_")==0)
                {
                        tcl.resultf("%d",Pmin80211::alfa_);
                        return (TCL_OK);
                }else if(strcmp(argv[1],"pmin_PropagationModel_")==0)
                {
                        tcl.resultf("%d",Pmin80211::model_);
                        return (TCL_OK);
                }else if(strcmp(argv[1],"pmin_RXThresh_")==0)
                {
                        tcl.resultf("%f",Pmin80211::RXThresh_);
                        return (TCL_OK);
                }else if(strcmp(argv[1],"pmin_CSThresh_")==0)
                {
                        tcl.resultf("%f",Pmin80211::RXThresh_);
                        return (TCL_OK);
                }else if(strcmp(argv[1],"pmin_Gt_")==0)
                {
                        tcl.resultf("%f",Pmin80211::Gt_);
                        return (TCL_OK);
                }else if(strcmp(argv[1],"pmin_Gr_")==0)
                {
                        tcl.resultf("%f",Pmin80211::Gr_);
                        return (TCL_OK);
                }else if(strcmp(argv[1],"pmin_freq_")==0)
                {
                        tcl.resultf("%f",Pmin80211::freq_);
                        return (TCL_OK);
                }else if(strcmp(argv[1],"pmin_L_")==0)
                {
                        tcl.resultf("%f",Pmin80211::L_);
                        return (TCL_OK);
                }else if(strcmp(argv[1],"pmin_ht_")==0)
                {
                        tcl.resultf("%f",Pmin80211::ht_);
                        return (TCL_OK);
                }else if(strcmp(argv[1],"pmin_hr_")==0)
                {
                        tcl.resultf("%f",Pmin80211::hr_);
                        return (TCL_OK);
                }
        }else if(argc == 3 )
        {
                if(strcmp(argv[1],"pmin_Alfa_")==0)
                {
                        sscanf(argv[2],"%lf",&Pmin80211::alfa_);
                        //printf("Alfa : %lf \n",Pmin80211::alfa_);
                        return (TCL_OK);
                 }else if(strcmp(argv[1],"pmin_LoadPminFile_")==0)
                {
                        int rc;
                        rc = Pmin80211::initialize(argv[2]);
                        if(rc == TCL_OK) Pmin80211::initialized_=1;
                        return rc;
                }else if(strcmp(argv[1],"pmin_PropagationModel_")==0)
                {
                        if (!strcmp(argv[2],"FreeSpace")) {
                                Pmin80211::model_=1;
                        }else if (!strcmp(argv[2],"TwoRayGround")) {
                                Pmin80211::model_=2;
                        }else Pmin80211::model_=3;
                        return (TCL_OK);
                }else if(strcmp(argv[1],"pmin_RXThresh_")==0)
                {
                        sscanf(argv[2],"%lf",&Pmin80211::RXThresh_);
```

```
			return (TCL_OK);
		 }else if(strcmp(argv[1],"pmin_CSThresh_")==0)
		{
			sscanf(argv[2],"%lf",&Pmin80211::CSThresh_);
			return (TCL_OK);
		 }else if(strcmp(argv[1],"pmin_Gt_")==0)
		{
			sscanf(argv[2],"%lf",&Pmin80211::Gt_);
			return (TCL_OK);
		 }else if(strcmp(argv[1],"pmin_Gr_")==0)
		{
			sscanf(argv[2],"%lf",&Pmin80211::Gr_);
			return (TCL_OK);
		 }else if(strcmp(argv[1],"pmin_freq_")==0)
		{
			sscanf(argv[2],"%lf",&Pmin80211::freq_);
			return (TCL_OK);
		 }else if(strcmp(argv[1],"pmin_L_")==0)
		{
			sscanf(argv[2],"%lf",&Pmin80211::L_);
			return (TCL_OK);
		 }else if(strcmp(argv[1],"pmin_ht_")==0)
		{
			sscanf(argv[2],"%lf",&Pmin80211::ht_);
			return (TCL_OK);
		 }else if(strcmp(argv[1],"pmin_hr_")==0)
		{
			sscanf(argv[2],"%lf",&Pmin80211::hr_);
			return (TCL_OK);
		 }
	}
	return TclClass::method(ac,av);
}

int Pmin80211::initialize(const char* const& filename)
{
	FILE *fin;
	char line[MAX_LINE];
	int i,j,index,size;
	char num[25],*start;

	for(j=0;j<PMIN_MAX_NODE;j++)
		for(i=0;i<PMIN_NUM_PAR;i++)
			pmin_[j][i]=-1;

	fin = fopen(filename,"r");
	if(fin==NULL)
	{
		printf("%s can not be opened! Check the file name for pmin table. \n",
		filename);
		return(-1);
	}

	while(fgets(line,MAX_LINE,fin)!=NULL)
	{
		size = strchr(line,')')-strchr(line,'(')-1;
		start = strchr(line,'(');
		memset(num,'\0',25);
		strncpy(num,++start,size);
		index=atoi(num);		//index

		if(index>PMIN_MAX_NODE){
			printf("too many nodes! \n");
			return (-1);
		}

		memset(num,'\0',25);
		if((start=strstr(line,"X_"))!=NULL){
			strncpy(num,start+3,strlen(line)-(start-line));
			sscanf(num,"%lf",&pmin_[index][0]);
		}
```

```
		else if((start=strstr(line,"Y_"))!=NULL){
			strncpy(num,start+3,strlen(line)-(start-line));
			sscanf(num,"%lf",&pmin_[index][1]);
		}
		else if((start=strstr(line,"Z_"))!=NULL){
			strncpy(num,start+3,strlen(line)-(start-line));
			sscanf(num,"%lf",&pmin_[index][2]);
		}
		else {
			printf("error in inputfile! \n");
			return(-1);
		}
	}
	fclose(fin);
	Pmin80211::nodes_=index+1;
//	printTables();
//	printf("Pmin80211 is initialized successfully with %d nodes\n",index+1);
	initialized_ = 1;
	return TCL_OK;
}

double Pmin80211::Friis(double P, double Gt, double Gr, double lambda, double L, double
d)
{
	/*
	 * Friis free space propagation equation:
	 *
	 *       Pt * Gt * Gr * (lambda^2)         P * ((4 * pi * d)^2 * L)
	 *   P = -------------------------- >> Pt= -------------------------
	 *       (4 * pi * d)^2 * L                  Gt * Gr * (lambda^2)
	 */
	double M = (4 * M_PI * d) / lambda;
	return (P * (M * M) * L) / Gt * Gr;
}

double Pmin80211::TwoRay(double Pr, double Gt, double Gr, double ht,
			double hr, double L, double d, double lambda)
{	double P;
	 /*
	 *  if d < crossover_dist, use Friis free space model
	 *  if d >= crossover_dist, use two ray model
	 *
	 *  Two-ray ground reflection model.
	 *
	 *          Pt * Gt * Gr * (ht^2 * hr^2)             Pr * (d^4 * L)
	 *  Pr = -------------------------------- >> Pt = -------------------------
	 *           d^4 * L                              Gt * Gr * (ht^2 * hr^2)
	 *
	 * The original equation in Rappaport's book assumes L = 1.
	 * To be consistant with the free space equation, L is added here.
	 */

	double crossover_dist = (4 * M_PI * ht * hr) / lambda;

	if (d < crossover_dist)
		P = Friis(Pr, Gt, Gr, lambda, L, d);
	else
		P = Pr * (d * d * d * d * L) / (Gt * Gr * (hr * hr * ht * ht));

	return P;
}

void Pmin80211::printTables()
{
	int i,j;

	for(j=0;j<Pmin80211::nodes_;j++){
		for(i=0;i<PMIN_NUM_PAR;i++){
			printf("%lf ",pmin_[j][i]);
		}
		printf("\n");
```

```
        }
}

double Pmin80211::distPowerMin(int n1, int n2)
{
        double xt,yt,zt,dt;

        xt=pmin_[n1][0] - pmin_[n2][0];
        yt=pmin_[n1][1] - pmin_[n2][1];
        zt=pmin_[n1][2] - pmin_[n2][2];
        dt=sqrt((xt*xt)+(yt*yt)+(zt*zt));
        return dt;
}

double Pmin80211::RangeFriis(double Pt,double P, double Gt, double Gr, double lambda,
double L)
{
        /*
         * Friis free space propagation equation:
         *
         *       Pt * Gt * Gr * (lambda^2)           Pt * Gt * Gr * (lambda^2)   1/2
         *   P = -------------------------- >> d = (--------------------------)
         *       (4 * pi * d)^2 * L                   P * L * (4 * pi)^2
         */
        double N = Pt * Gt * Gr * lambda * lambda;
        double M = P * L * (4 * M_PI) * (4 * M_PI);
        return sqrt(N/M);
}

double Pmin80211::RangeTwoRay(double Pt, double P, double Gt, double Gr, double ht,
                        double hr, double L, double lambda)
{       double dist;
        /*
         *  if d < crossover_dist, use Friis free space model
         *  if d >= crossover_dist, use two ray model
         *
         *  Two-ray ground reflection model.
         *
         *      Pt * Gt * Gr * (ht^2 * hr^2)         Pt * Gt * Gr * (ht^2 * hr^2)  1/4
         *  P = ---------------------------- >> d = [----------------------------]
         *       d^4 * L                                          P * L
         *
         * The original equation in Rappaport's book assumes L = 1.
         * To be consistant with the free space equation, L is added here.
         */


        double N = Pt * Gt * Gr * (hr * hr * ht * ht);
        double M = P * L;
        dist = sqrt ( N / M );
        dist = sqrt ( dist );

        double crossover_dist = (4 * M_PI * ht * hr) / lambda;

        if (dist < crossover_dist){
                dist = RangeFriis(Pt, P, Gt, Gr, lambda, L);
        }
        return dist;
}

// For Tx and Rx
double Pmin80211::framePowerMin( int n1, int n2)
{
        double Pt, dist;
         double lambda_ = SPEED_LIGHT / Pmin80211::freq_;

        if((n1>=0 && n2>=0) && (n1 != n2)){// 1 on 1 transmission

                dist=distPowerMin(n1,n2);

                Pmin80211::ht_ += pmin_[n1][2];
```

```
                Pmin80211::hr_ += pmin_[n2][2];

                if(initialized_ == 0){
                        printf("Error! Pmin table was not inicializated \n");
                        return(-1);
                }

                if (model_==1) {
                        Pt = Friis(Pmin80211::RXThresh_, Pmin80211::Gt_, Pmin80211::Gr_,
                                     lambda_, Pmin80211::L_, dist);
                } else if (model_==2) {
                        Pt = TwoRay(Pmin80211::RXThresh_, Pmin80211::Gt_, Pmin80211::Gr_,
                          Pmin80211::ht_, Pmin80211::hr_, Pmin80211::L_, dist, lambda_);
                } else{
                        printf("Error! propagation model! \n");
                        return(-1);
                }
        }
//      printf("src:%d dst:%d dist:%.2f Pmin: %f rxThresh: %e ", n1,n2,dist,Pt,rxThresh_);
        return Pmin80211::alfa_*Pt;
}


/* return the range of a power tx. Which depends on RxThresh*/
double Pmin80211::rangePowerMin( int n1, double pRange)
{
        double dist;
         double lambda_ = SPEED_LIGHT / Pmin80211::freq_;

        Pmin80211::ht_ += pmin_[n1][2];

        if(initialized_ == 0){
                printf("Error! Pmin table was not inicializated \n");
                return(-1);
        }

        if (model_==1) {
                dist=RangeFriis(pRange,Pmin80211::RXThresh_,Pmin80211::Gt_,Pmin80211::Gr_,
                                   lambda_, Pmin80211::L_);
        } else if (model_==2) {

        dist=RangeTwoRay(pRange,Pmin80211::RXThresh_,Pmin80211::Gt_,Pmin80211::Gr_,
                                Pmin80211::ht_,Pmin80211::ht_,Pmin80211::L_, lambda_);
        } else{
                printf("Error! propagation model! \n");
                return(-1);
        }
//      printf("src:%d dst:%d dist:%.2f Pmin: %f rxThresh: %e ", n1,n2,dist,Pt,rxThresh_);
        return dist;
}

/* return the range of a power tx. Which depends on RxThresh*/
double Pmin80211::csPowerMin( int n1, double pRange)
{
        double dist;
         double lambda_ = SPEED_LIGHT / Pmin80211::freq_;

        Pmin80211::ht_ += pmin_[n1][2];

        if(initialized_ == 0){
                printf("Error! Pmin table was not inicializated \n");
                return(-1);
        }

        if (model_==1) {
                dist=RangeFriis(pRange,Pmin80211::CSThresh_,Pmin80211::Gt_,Pmin80211::Gr_,
                                   lambda_, Pmin80211::L_);
        } else if (model_==2) {

        dist=RangeTwoRay(pRange,Pmin80211::CSThresh_,Pmin80211::Gt_,Pmin80211::Gr_,
                                Pmin80211::ht_,Pmin80211::ht_,Pmin80211::L_, lambda_);
```

```
	} else{
		printf("Error! propagation model! \n");
		return(-1);
	}
	return dist;
}
```

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