Performance Analysis of TPC and DSC for WiFi Access Points in Realistic Dense Environment

A Project Report

submitted by

ANSIL S SHAJIL

in partial fulfilment of the requirements
for the award of the degree of

MASTER OF TECHNOLOGY

DEPARTMENT OF ELECTRICAL ENGINEERING
INDIAN INSTITUTE OF TECHNOLOGY MADRAS.

JUNE 2018

THESIS CERTIFICATE

This is to certify that the thesis titled **Performance Analysis of TPC and DSC for WiFi Access Points in Realistic Dense Environment**, submitted by **ANSIL S SHAJIL**, to the Indian Institute of Technology, Madras, for the award of the degree of **Master of Technology**, is a bonafide record of the research work done by him under our supervision. The contents of this thesis, in full or in parts, have not been submitted to any other Institute or University for the award of any degree or diploma.

Dr Venkatesh Ramaiyan
Professor
Dept. of Electrical Engineering
IIT-Madras, 600 036

Place: Chennai
Date: 18th June 2018

ACKNOWLEDGEMENTS

Foremost, I would like to express my deep sense of gratitude to my guide Dr. Venkatesh Ramaiyan for his erudite guidance, support, encouragement and generous help throughout the period of the project work. I am highly indebted to him for devoting his valuable time to help me execute this work in good time. I must not forget to mention that he had instant solution to every single problem I faced during the project work.

I am also extremely grateful to Kalpalatha S & Krishna Bharadwaraj , Project Associates, IIT Madras for helping succeed in doing simulations in NS3. I am also grateful to my family, friends and labmates for their support and suggestions throughout the work.

Last but not the least, I must not forget to thank Almighty for the wisdom and perseverance that He bestowed upon me during this project work, and indeed, throughout my life.

ABSTRACT

KEYWORDS: Transmit Power Control (TPC); Dynamic Sensitivity Control (DSC)

With the advent of smart-phones and other hand-held devices such as kindle e-readers in the last decade, there is a quantum leap in the number of devices that has to stay connected with internet. Coping up with this extravagant growth of the number of devices is one of the biggest hurdles in front of the 11 ax and future 802.11 standards. The WiFi Networks continue to get denser not only with increase in number of clients but also with the increase in number of Access Points. These dense network scenarios are termed as Overlapped Basic Service Set (OBSS) deployments. As the number of devices increase, the level of interference also increases. This will lead to severe degradation in network performance.

The most latest WiFi standard 802.11 ax is specifically designed for high dense scenarios like airport, shopping malls , stadiums, hotels, office etc. So research is being done focusing on improving the network performance by trying to achieve better spacial reuse, reduced interference and efficient methods of sharing resources. 11ax makes use of transmit power control, dynamic sensitivity control, BSS colouring and other features to achieve its usefulness in very dense scenarios. All these features work together to mitigate interference thereby improving the spatial reuse. In the first part of this work, focus is on transmit power control (TPC) in a realistic dense scenario of an office. The second part uses the same dense setup for studying the effect of dynamic sensitivity control (DSC) in the network performance.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

ABBREVIATIONS

CCA	Clear Channel Assessment
CSMA	Carrier Sensing Multiple Access
CST	Carrier Sensing Threshold
DSC	Dynamic Sensitivity Contol
MCS	Modulation Coding Scheme
NS-3	Network Simulator-3
RRI	Radio Resource Information
RSSI	Received Signal Strength Indicator
TPC	Transmit Power Control
UDP	User Datagram Protocol
Vht	Very High Throughput
YANS	Yet Another Network Simulator

CHAPTER 1

NS3

1.1 Introduction

NS-3 (Network Simulator-3) is a discrete-event network simulator for internet and other related systems. Discrete simulators assume any event happens at a specific instant of time & brings a change in the system. It is a free software licensed under GNU GPLv2 license and is mainly used for educational and research purposes. Development of the simulator started back in 2006 and was first released in June 2008. NS-3 contains a set of libraries written mostly in C++ and has a lot of inbuilt classes. Even though both NS-2 and NS-3 are written in C++, NS-3 is entirely different from NS-2 . The reason is that NS-2 uses tcl script whereas NS-3 uses the C++ script itself. NS-2 does not support the APIs of NS-3. The version used for this work is NS-3.27. The developers of the simulator frequently releases newer versions which will have more features added on from the previous versions. Since it is an open source, there are many contributors.

NS-3 provides support for wide variety of standards and protocols in data link layer (like LTE, WiFi, WiFiMAX, mesh etc), network layer (both IP and non IP based networks, OSLR, AODV routing protocols etc) and transport layer (TCP,UDP). The software has a plethora of channel models (Yans Wifi Channel was used for simulations in this work), pathloss models, delay models, mobility models for nodes, data rate adaptation etc. NS-3 takes into account all the needs of the simulation workflow from configuration of simulation parameters to trace collection and analysis. The simulator supports a real time scheduler which allows interacting with the real systems. For example, it allows user to send and receive NS-3 generated packets in real systems. NS-3 will serve to provide interconnection frameworks by adding links between the virtual machines. Waf build system is used in NS-3 to run the codes. Waf is a build automation tool which is designed for assisting automatic compilation and installation of computer software. Its written in python and its source code is open source software. All the codes in NS-3 are implemented in a C++ namespace called ns3. This allows the user to use the NS-3 classes without using ns3:: scope operator.

There is an option to view the simulations in an animated manner by using NetAnim which is there as part of NS-3. One can generate xml files of simulation. These files can be viewed as animation by using NetAnim. NetAnim is based on the Qt4 GUI toolkit. In the animation, user can see the node positions and also visualize the movement of packets across the network. Similarly ns3 can capture packets in pcap files. Wireshark can be used to read these files. Pcap files give information about the packet type (data, beacon, association request, ACK etc), time instance, traffic protocol, packet length, sender address, receiver address, RSSI, data rate, channel frequency etc.

1.2 NS3 Implementation of WiFi

The WiFi Module in NS-3 allows the user to setup Medium Access Control (MAC) implementation based on various 802.11 b/g/n/ac/ax specifications and allows the user to have a packet level abstraction for different PHY models and channel models.

NS-3's WiFi module can be broadly classified into 3 sublayers.

PHY Layer : The classes associated with this layer deals with reception and transmission of packets across the wireless medium. It allows the user to set various parameters such as the transmission power used or the carrier sensing threshold used. The channel classes associated with PHY can be used to set the propagation loss model or the propagation delay model. Channel interference is also modelled in the WiFi PHY layer.

MAC Low : MAC layer can be divided into 2 : *MAC Low & MAC High*. The MAC LOW layer concentrates on medium access control protocols like DCF, EDCA, RTS/CTS, data and ACK transmissions. The queueing, fragmentation, aggregation of packets are also dealt in this layer.

MAC High : MAC high deals with the functionalities that deal with management of the WiFi Network such as beacon transmissions, client association etc. NS3 has three MAC high models currently: ns3::ApWifiMac and ns3::StaWifiMac for the infrastructure WLAN and ns3::AdhocWifiMac for the adhoc network. ApWifiMac models the functions of an access point like generating beacons, setting beacon intervals, association, authentication and is responsible for receiving, processing and forwarding packets to higher/lower layers. Similarly the StaWifiMac deals with the functionalities of a station in a infrastructure WLAN. This includes managing probe requests, associations, beacon missed timeouts etc. AdHocWifiMac implements functionlaities which are necessary for ad hoc wlan networks. All these three classes have a common parental class called ns3::RegularWifiMac that implements Quality of Service (QoS) feaures an can support high throughput (HT) and very high throughput (VHT) wireless.

The WifiNetDevice models a wireless network interface controller based on the IEEE 802.11 standard.

NS-3 provides models for the following aspects of 802.11:

- It has the basic 802.11 DCF with infrastructure and adhoc modes.
- It supports 802.11a, 802.11b, 802.11g and 802.11n (both 2.4 and 5 GHz bands) physical layers.
- MSDU aggregation and MPDU aggregation for packets.
- QoS-based EDC
- It has different propagation loss models as well as propagation delay models.
- It has various rate adaptation models like Constant Rate WiFi Manager, Minstrel, PARF, ARF, Onoe, robust rate adaptation etc.

NS3 has quite a lot of modules which aid the user in setting up the user in setting the network system he wants to study. Some of the major ones :

- PHY & Data Link layer : models for LTE, WiFi, Ethernet
- Network Layer : IP & Non-IP based networking, routing protocols
- Transport Layer : Different versions of UDP & TCP
- Models for application, mobility & channel models.

These modules contain a lot of classes and objects. The main objects which should be used for all simulations are

Nodes : It is analogous to a motherboard with input output interfaces.

NetDevice : This refers to the Network Interface Card in devices which aids in communication between the nodes. One can use WifiNetDevice, CsmaNetDevice, PointToPointNetDevice etc depending on the system.

Channel : Physical connection between the netdevices. For example in a wired network, one can use CSMA Channel and in a wireless network, WiFi channel can be used .

Application : This is an object that creates and receives packets. It is installed on the nodes. We can change the parameters in the application to alter the data rate, packet size etc. The user can use variation of TCP and UDP applications.

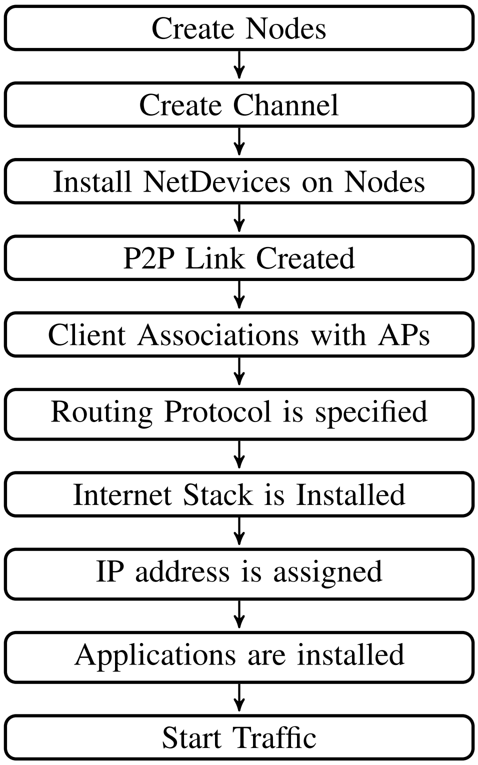


Figure 1.1: Steps in configuring a network using NS3

Once the applications are set in the nodes, global function Simulator::Run is used to start the simulation. When this function is called, the system will look at the scheduled events and execute them sequentially. After all the scheduled events (such as the start sending packets from the source) are executed, the function returns back. The simulation will then be completed. Then we will have to destroy the objects created such as nodes, netdevices etc. Another global function Simulator::Destroy takes care of this task.

1.3 RRI Module

For making measurements of the wireless a new class called Rri Module was used. ns3::RriModule class is inherited from ns3::RegularWifiMac. Implementation of Rri module is done in MAC high and it resides with ns3::ApWifiMac and ns3::StaWifiMac. The main two functions in Rri Module are Receive() and Scan().

Receive() : Like the promiscuous mode in NS-3, the function receive takes care of reception of all data and control packets. It will collect information regarding the packets such as its SNR, BSSID, MAC ID etc. The SNR can be used to calculate the RSSI of the packet signal since the noise is a constant value. This RSSI information obtained by the Rri Module is used in the simulations for computing the converged transmit power.

Scan() : This function can be used for dynamic channel selection. For the simulations in TPC and DSC, constant channel number 36 was used.

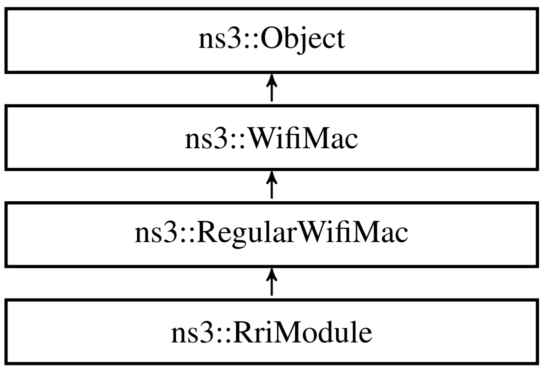


Figure 1.2: Class Inheritance for the RRI Module

CHAPTER 2

Simulation Setup

2.1 Building Model

The objective was to study the effect of TPC and DSC in a more realistic dense environment. A multi-storey building with room dimensions 10x10x3 was used for the simulations. The building has three floors and each of these floors has 10 rooms aligned in a single row. So it has a total of 30 rooms across the three floors. This building was set up using the building module in ns3. In ns3, a building is represented as a rectangular parallelepiped. Walls in the building are assumed to be parallel to x, y and the z axis. The 802.11 ax task group had a list of scenarios for doing simulations (S. (2014)). This multi storey building scenario is one among those. NS3 building model gives freedom to the user to specify the dimensions of the building, number of floors, number of rooms in the X direction, number of rooms in the Y dimension, type of walls like concrete or wood etc. The type of building was chosen to be office. One can choose residential or commercial building types as well. The difference between the office, residential and commercial building types lies in the small variations in floor penetration loss. Access Points were fixedly placed at the middle of the specified rooms. Stations were also randomly positioned inside a region in each room. The location of APs and STAs in the rooms have been diagrammatically shown in figure 2.1a and figure 2.1b respectively.

Room dimension	10m x 10m x 3m
Floors	3
Building Type	Office
Wall Type	Concrete with Windows
Rooms in X direction	10
Rooms in Y direction	1

Table 2.1: Building Model Parameters

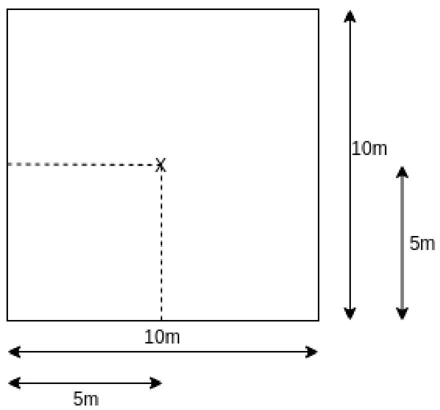
2.2 Deployment of Nodes

The number of clients have been fixed that is one client per room. The clients are randomly deployed in each room. 30 clients are there in total. Total number of APs is increased from 3 to 30 .The APs are deployed in a symmetric manner around the building as in figure 2.2. The client in each room is positioned randomly. Clients will associate with AP which it sees with best RSSI. RSSI was calculated based on the AP transmit power and the propagation loss model equation. All the APs are operating in the same channel so a lot of collisions will occur due to co-channel interference. Channel number 36 is used which is a 20 MHz channel in 5 GHz bandwidth. The building model will improve the spatial reuse with the help of internal walls and floor which increases the pathloss of WiFi signals thereby reducing the interference.

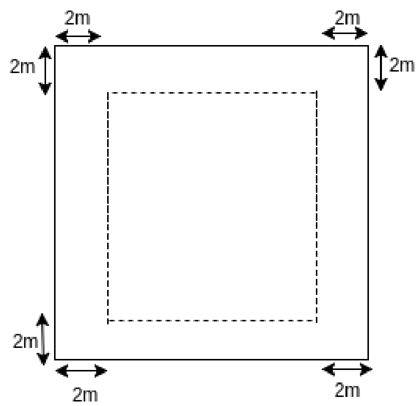
2.3 MobilityBuildingInfo

The position of nodes are defined in the x, y and z coordinates. This NS-3 class helps in incorporating this coordinate information to determine

- whether the node is indoor or outdoor
- if indoor : to determine the room and floor where the node is located



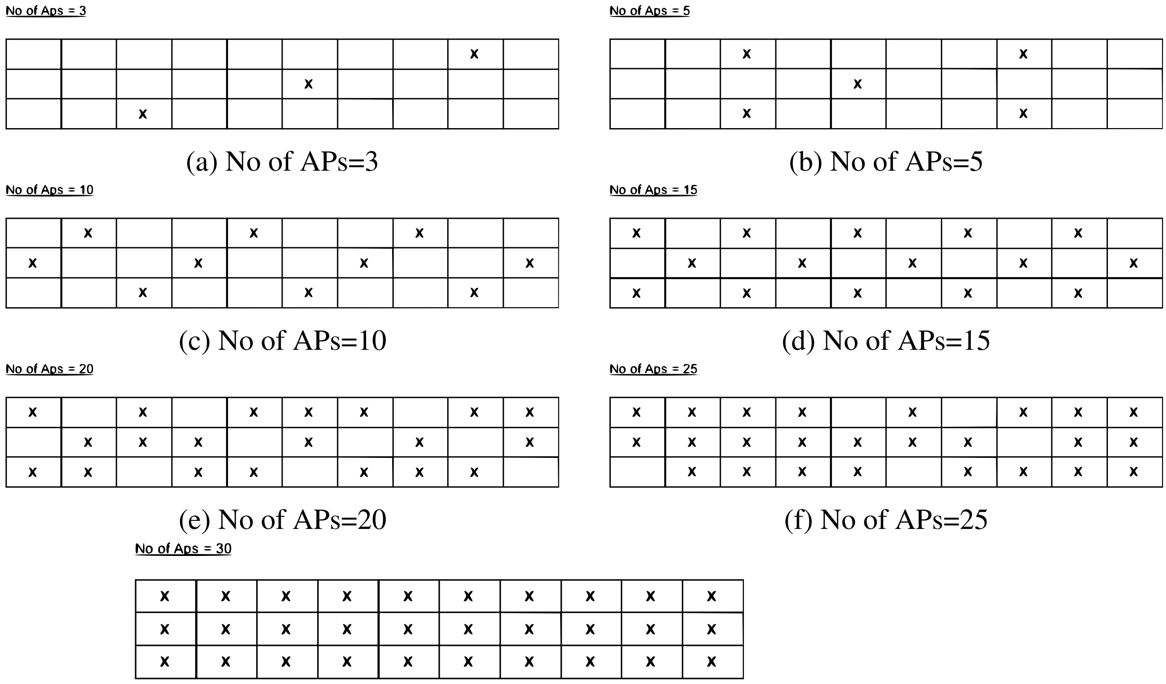
(a) 2D Top View of location of Access Point inside a room. They are placed at a height of 1 metre from the floor level. Unlike the client position, APs' positions are fixed.



(b) 2D Top View of location of client in a room. Clients are deployed in a random manner in the area enclosed by the dashed lines. They are at height of 1 metre from the floor level.

Figure 2.1: Access Point & Client position inside a given room

The AP deployments are given below .



(a) No of APs=3

(b) No of APs=5

(c) No of APs=10

(d) No of APs=15

(e) No of APs=20

(f) No of APs=25

(g) No of APs=30

Figure 2.2: The rooms which has Access Points for different AP densities

2.4 Hybrid Buildings Propagation Loss Model

NS3 has different pathloss models for different indoor and outdoor scenarios. It has a pathloss model called the Hybrid Building Model which combines different pathloss models to calculate pathloss. In the simulations, 5GHz frequency was used. The pathloss models present in it are

1. Okumura Hata Propagation Loss Model (Hata (1981))
2. Itu R1411 Los Propagation Loss Model (Series (2015)) and Itu R1411 Nlos Over Rooftop Propagation Loss Model (I1411) (Series (2015))
3. Itu R1238 Propagation Loss Model (Series (2012))
4. The pathloss elements of the Buildings Propagation Loss Model (External Wall Loss, Height Gain, Internal Wall Loss)

Depending on the environment (suburban, urban ,open areas) , location of nodes (whether the receiver-transmitter combination is indoor-indoor, indoor-outdoor, outdoor-

outdoor, or outdoor-indoor), height of the antennae etc, the hybrid path-loss combines some of the above models for computing the pathloss between the two nodes.

As the nodes used in the simulation are inside the building the Hybrid Building Model will combine ItuR1238 Propagation Loss Model and Building propagation loss model. The parameters used in the Hybrid Buildings Propagation Loss Model are listed below.

Frequency	5 GHz
Environment	Urban
City Size	Small
ShadowSigmaOutdoor	7.0 dB
ShadowSigmaIndoor	0.0 dB
ShadowSigmaExtWalls	8.0 dB
InternalWallLoss	5.0 dB

Table 2.2: Hybrid Building Model Parameters

2.4.1 Itu R1238 Propagation Loss Model

The ITU Radiocommunication Sector (ITU-R) is one of the divisions of International Telecommunication Union which is responsible for radio communication. Itu R1238 Propagation Loss Model (Series (2012)) gives the equation to determine the pathloss inside a room or a closed area inside a building. This is one of the widely used indoor propagation loss model.
The path-loss equation is given by

$$L_{total} = 20 \log_{10} f + N \log_{10} d + L_f(n) - 28[dB]$$

$$N = \begin{cases} 28\ dB \text{ for Residential} \\ 30\ dB \text{ for Office} \\ 22\ dB \text{ for Commercial} \end{cases}$$

$$L_f = \begin{cases} 4n\ dB \text{ for Residential} \\ 15 + 4(n-1)\ dB \text{ for Office} \\ 6 + 3(n-1)\ dB \text{ for Commercial} \end{cases}$$

n : number of floors between the AP and clients

f : frequency [MHz]

d : distance [meters]

2.4.2 Internal Wall Loss

This factor is derived from the Building Pathloss Model. It takes into account wall penetration loss when the waves traverse from one room to another. It depends on the material of wall i.e. concrete or wood. Internal wall loss is given by

$$L_{IWL} = L_{siw}\ (|x_1 - x_2| + |y_1 - y_2|)\ [dB]$$

$|x_1 - x_2|$: the Manhattan room difference in the x-axis

$|y_1 - y_2|$: the Manhattan room difference in the y-axis

L_{siw} refers to the single internal wall loss factor. In the simulations done, the internal loss factor is a constant of 5dB.

2.4.3 External Wall Loss

This value specifies the pathloss due to communication from indoor to outdoor and vice versa. The value depends on the material of the wall and is taken from the COST231 model. Since our simulations contain only indoor nodes, this factor is insignificant.

2.4.4 Shadowing Model

In the building propagation loss model, shadowing is modelled as a log-normal distribution. The standard deviation of the distribution is a function of relative position of the nodes. The mean of the distribution is always taken as 0 dB. There are 3 different cases for variance.

- outdoor $X_O \sim (\mu_O, \sigma_O^2)$
- indoor $X_I \sim (\mu_I, \sigma_I^2)$
- external walls penetration $X_W \sim (\mu_W, \sigma_W^2)$

If the node pair is indoor-outdoor then shadowing of outdoor as well shadowing due to wall penetration also should be taken into consideration. As these two factors are independent of each other, the combined variance will be

$$X_{IO} \sim (\mu_{IO}, \sigma_{IO}^2)$$

where $\sigma_{IO} = \sqrt{\sigma_O^2 + \sigma_W^2}$
As of now, the nodes are indoor and the indoor shadowing is set to zero making shadowing ineffective. In the future simulations, we are planning to introduce indoor shadowing factor also into consideration.

2.5 AP Association

Each client in the building will listen to each AP's beacon it can hear. Then the client will try to associate with the AP it sees with the maximum value of RSSI. In the simulation each RSSI of each AP heard at each client's end is calculated with the help of the pathloss equation. As said before, since the nodes are indoor the pathloss equation is just the combination of Itu R1238 Propagation Loss Model and the Internal wall loss.

For each client i & each Access Point j, pathloss between the both is given by

$$PL_i[j] = \begin{cases} 20\ \log_{10} 5000\ +\ 30\ \log_{10} d_{i,j}\ + 5 * rd_{ij}\ -\ 28 & \\ \qquad \text{for the same floor} & \\ 20\ \log_{10} 5000\ +\ 30\ \log_{10} d_{i,j}\ + 5 * rd_{ij}\ + 15 + 4 * (fd_{i,j} - 1)\ -\ 28 & \\ \qquad \text{for different floors} & \end{cases}$$

$d_{i,j}$: the euclidean distance between client i and AP j .

$rd_{i,j}$: the Manhattan room distance between client i and AP j .

$fd_{i,j}$: the floor difference between client i and AP j .

The RSSI of AP j seen by the client i is given by

$$RSSI_i[j] = Tx\_power[j] - PL_i[j]$$

$Tx\_power[j]$: the transmit power of AP j.
Client i will choose to associate with AP j for which $RSSI_i[j]$ is maximum among all the APs.

2.6 Physical Layer

2.6.1 Yans WiFi Channel

The channel used for all the simulations is the yans WiFi channel in ns3. This channel model is based on Lacage and Henderson (2006)'s Yet Another Network Simulator. This is the only model of class WiFiPhy in NS3.

Initial AP power	23.0 dBm
STA power	14.0 dBm
CCA Threshold	-85.0 dBm
Channel	Yans WiFi Channel
Channel Number	36
WiFi Phy Standard	802.11 ac
Transmitter Gain	0 dB
Receiver Gain	0 dB
Short Guard Interval	True (Enabled)

Table 2.3: PHY Parameters

2.7 Mobility

APs	Constant Position Mobility Model
Clients	Constant Position Mobility Model

Table 2.4: Mobility Parameters

2.7.1 Waypoint Mobility Model

In almost all of our simulations, the clients are static. Even though their location inside the room is random, their position won't change during the simulation. In few of our simulations, we had to use a mobility model which is not static. Waypoint model is a mobility model which defines how the mobile nodes move during the simulation time. NS3 allows the user to set specific locations in terms of x, y & z-coordinates at specific time instances. For that time instance , the node will be in that specified location. The time instances must be given in the ascending order. The simulator then calculates the velocity in the x-axis , y-axis & the z-axis. This is a constant velocity vector between two time instances specified by the user. So for a time instance which is between two time instances specified by the user, the simulator will calculate the position using the velocity information calculated. This model is used for simulations to obtain the coverage CDFs, best RSSI seen by the clients and for counting the hand-offs. In all of these simulations, the waypoint model was modelled in such a manner that they traverse all the rooms sequentially.

2.8 Data Link Layer

MAC	VHT WiFi Mac
Rate Manager	Constant Rate WiFi Manager
VhtMCS Index	Value will be adaptive depending on the distance between AP and the client.

Table 2.5: Data Link Layer Parameters

2.8.1 Rate Adaptation

Modulation Coding Scheme (MCS) index refers to an integer value which specifies the no of spatial streams, the modulation scheme and the coding rate used. In 802.11 networks, this feature was first included in the 802.11 n standard. For instance, an MCS value of 8 would correspond to 1 spatial stream and BPSK modulation with a coding rate of $\frac{1}{2}$. For the specific bandwidth (20MHz or 40 MHz) and the guard interval (400 ns (short) or 800 ns), it specifies the maximum data rate that can be supported. Rate adaptation refers to the variation in transmission rate in data as well as control packets in a wireless system to give the best possible network performance for a given channel condition. 802.11 defines a number of modulation and coding schemes (MCS) that can be used at the PHY layer. A higher MCS value corresponds to a higher data rate and a lower MCS value means a lower data rate. But when the packet success rate is taken into consideration, a lower MCS value is the better performer. That means if we have a poor channel, its better to have a lower MCS. Wireless channels are affected by a lot of factors like path-loss, fading, interference etc. If two nodes are nearby, the pathloss component would be a lower value than that when nodes are far apart. Hence a higher MCS value would be used in the first scenario than in the second. Rate adaptation will be the one that balances the trade off between a better throughput and a lower bit error rate. The PHY which is used in simulation is 802.11 ac which is only defined in 5GHz. It supports Vht (Very High Throughput) MCS. The value of the same ranges from 0 to 8. The simulations are done with short guard interval and in 20 Mhz channel with a single spatial stream. The VhtMCS table for this specification in 11ac is given below.

Vht MCS	Modulation and Coding	Data Rate (Mbps)
0	BPSK $\frac{1}{2}$	7.2
1	QPSK $\frac{1}{2}$	14.4
2	QPSK $\frac{3}{4}$	21.7
3	16-QAM $\frac{1}{2}$	28.9
4	16-QAM $\frac{3}{4}$	43.3
5	64-QAM $\frac{2}{3}$	57.8
6	64-QAM $\frac{3}{4}$	65.0
7	64-QAM $\frac{5}{6}$	72.2
8	256-QAM $\frac{3}{4}$	86.7

Table 2.6: Vht MCS Table

For the simulations in the multi storey building model, an adaptive but constant MCS value is chosen. For choosing the best MCS for a given RSSI, an experiment was conducted with one AP and one client. The location of the AP is fixed and in a loop, the client's position was changed in small steps (0.1 metre increment). For each distance the RSSI value and the data throughput was noted. This experiment was repeated for all VhtMCS values from 0 to 8. The throughput vs RSSI curve was plotted for each VhtMCS value. An AP's MCS adaptation should take of all the clients associated with it. To satisfy this criteria, the worst AP RSSI heard by its client is chosen for picking the MCS index. The best MCS is picked from the plot for the RSSI such that the point doesn't lie in that part of the curve where its is falling. If it is in the falling part of some MCS index, we will have to choose the next best MCS index for the given RSSI value.

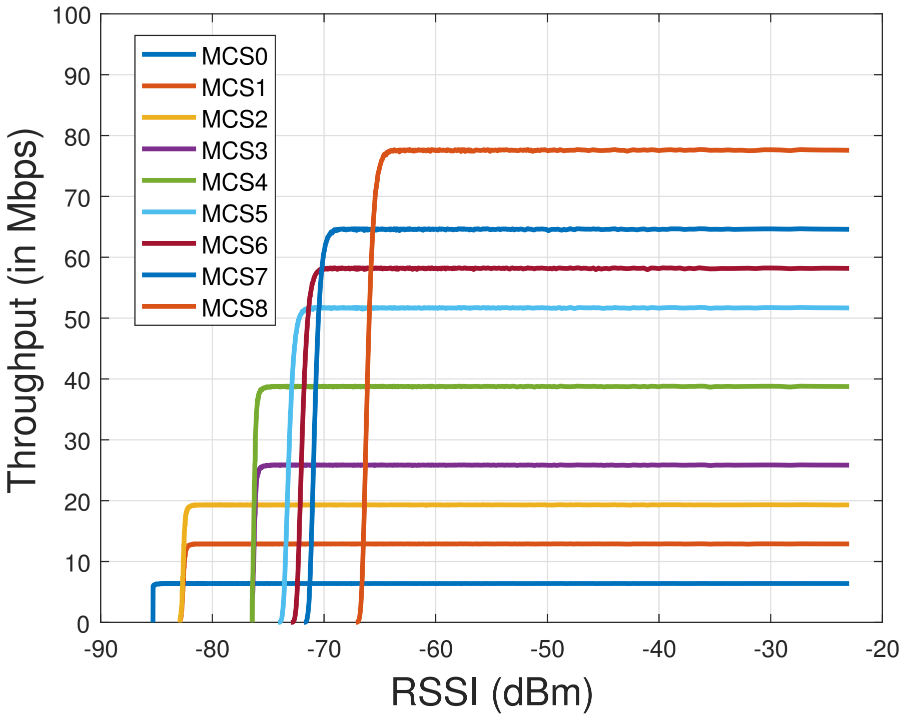


Figure 2.3: Throughput versus Received Signal Strength for different values of VhtMcs. One AP and one client were considered. One UDP downlink transfer was used.

2.9 WiFi Mac

2.9.1 AP WiFi Mac

Beacon Interval	100ms
Beacon Jitter	True (Enabled)
QoS Supported	True (Enabled)

Table 2.7: AP WiFi Mac Parameters

2.9.2 STA WiFi Mac

Active Probing	False (Disabled)
QoS Supported	True (Enabled)

Table 2.8: STA WiFi Mac Parameters

2.10 Transport Layer

The application used for both downlink and uplink traffic was User Datagram Protocol (UDP). The traffic was generated using the OnOffHelper. It has alternate On & Off states. No data is transfered in the Off state. During the On state, constant bit rate data is generated. Data rate and maximum packet size can be specified in the helper. The specifications are given below

Maximum Data Rate	100 Mbps
On Time	1000 seconds
Off Time	0 seconds
Maximum Packet Size	Infinite

Table 2.9: OnOff Helper Parameters

2.11 Time instances

Traffic Starting Time	A random value between 20 & 25 seconds for each node
Traffic Ending Time	35 seconds

Table 2.10: Traffic Timings

CHAPTER 3

Transmit Power Control

3.1 Introduction

In most Wi-Fi networks, the Access Points (APs) transmit at a very high transmit power. This creates high interference to other APs which are operating in the same channel which is termed as co-channel interference or to APs which are operating in some other channel termed as adjacent channel interference. Increased interference means lower values of SINR at the receiving end. If the SINR is below a certain threshold, the packet will be dropped. So higher interference leads to more packet loss and hence decrease in spatial reuse due to reduced throughput. Hence transmit power control (TPC) methods play a pivotal role in managing interference and thereby the overall network performance. In WiFi, the number of non-overlapping channels in 2.4 GHz is 3 and that in 5GHz is 24. This channel has to be shared by multiple APs and STAs. A client in a network would connect to the AP with which it sees the best SNR among all its APs. By reducing the transmit power to a level which can still support successful communication between the client and the AP, the other nodes will experience lesser interference. With a low transmit power, lesser is the spatial interval needed to reuse the channel without interference. So by reducing the interference, TPC improves the channel reuse and increase the overall capacity in the network. TPC also has an added advantage of saving energy and would better the battery life if the APs are mobile.

3.2 Prior Works

Akella and Steenkiste (2007) talks about an algorithm called Power-controlled Estimated Rate Fallback(PERF) algorithm where the AP adapts to a transmit power value where it can support all its client at its best maximum rate. But this is a greedy algorithm and hence would be not optimal from the view of the overall network.

Monks and Hwu (2001) put forward a power controlled multiple access system (PCMA). In this each receiving node calculates the amount of noise it can withstand. This node then advertises this noise tolerance level in a busy tone. The transmitting nodes will listen to this. Based on the noise tolerance, transmitting nodes will decide which transmit power should be used. Then an RPTS-APTS handshake is done between the receiver and transmitter to determine the minimum transmitting power so that the transmission is successful.

Sheth and Han (2005) proposed SHUSH algorithm for power control. Unlike PCMA, SHUSH uses an optimal power for transmission until there is an interferer. In this, an interfered node will have higher priority to transfer than the other nodes. The intereferered node will have the RSSI of the interferer. And if it can access the transmitting power of the interfering node, the optimal power to SHUSH the interferer can be found out.

Muqattash and Krunz (2005) proposed POWMAC for Mobile Adhoc NETworks or Manets. In this system the MAC allows simultaneous transmissions if the interference constraints are met. Each node i maintains a Power Controlled List which keeps data regarding every other active node u in the system. The data includes address of every other node u, estimated channel gain between u and i, maximum tolerable interference (MTI) of node u (that is the maximum amount of interference u can tolerate from i without having u's reception affected), start and end time of node u's transmission (mentioned in u's control packet). Unlike in the conventional WiFi MAC, POWMAC doesn't use RTS/CTS to silence the other nodes, they are used to exchange MTI at each node so that multiple concurrent transmissions can occur.

Sheth and Han (2002*b*) came up with a mobility adaptive TPC algorithm where the optimal transmit power was calculated by taking the weighted average of RSSI values over different time intervals. They also tried implementing the RSSI based TPC algorithm 802.11 b cards (Sheth and Han (2002*a*)). In their later work (Sheth and Han (2003)), concept of selective radio activation was introduced. Radios will go into sleep mode for certain period of time after a burst of data. The time period of sleep is calculated from the inter-arrival times of packets.

Grilo and Nunes (2003) proposed a link adaptive TPC where the sender node chooses the transmit mode-transmit power pair which maximizes the throughput. Shrivastava

(2007) studied the limitations of TPC algorithms in indoor environment. They argued that only a few (2-3) power levels can make significant changes in RSSI values. An algorithm to come up with useful set of power level values was also proposed in the paper.

Mhatre and Baccelli (2007) argued that both transmit power and CCA should be tuned simultaneously. They used annealed Gibbs sampler to find the optimal transmit power and the optimal CCA value. In Qiao (2003*a*) and Qiao (2003*b*), authors proposed joint rate adaptation and transmit power.

3.3 TPC A Algorithm

We studied a distributed transmit power control algorithm which is very similar to Cisco (2016)'s algorithm. The main goal of the algorithm is to maximize the coverage and also mitigate the co-channel interference. Since controlling the client power is not possible by the AP, the algorithm focuses on AP power control to achieve the aim. Initially all the APs will be bursting at the maximum transmit power that is 23 dBm. The client's transmit power is chosen a fixed value of 14 dBm for all. APs will broadcast its current transmit power information in its beacon. The receiving APs can use this information and the receiving signal's RSSI to calculate the pathloss between the two APs. This path-loss is assumed to symmetric (effect of shadowing is ignored). Hence we can use this pathloss value to calculate the RSSI of its own transmissions at another AP's end. Minimum AP transmit power is constrained to be above 0 dBm.

There are two thresholds being used in this algorithm.

3.3.1 Loudness Threshold

Loudness Threshold is a constant threshold value set by the user. In the simulations value of -85 dBm was used. The reason for choosing this value is because of the fact -85 dBm was used as the CCA threshold. Every AP can continue to see at most 'K' neighbors with RSSI above this predefined Loudness Threshold. For the simulations , three neighbours ($K = 3$) have been considered.

3.3.2 Visibility Threshold

If an AP, when operating at maximum Tx power, is visible to another AP at RSSI above the Loudness threshold, it should continue to be visible with RSSI above a predefined Visibility Threshold. Loudness threshold is always greater than visibility threshold. A very low value was used as the Visibility Threshold for the simulations.

Step 0

Initially all the Access Points will be transmitting at the maximum power level i.e., 23 dBm. The two thresholds and K value are set. The beacons will contain information regarding the current transmit power of an AP.

Step 1

Each AP listens to its neighbouring AP transmissions and will calculate the average RSSI values seen from those APs (due to data packets, beacons and other control packets). The average is taken over 10 samples in 5 minutes. The AP will also get the information regarding the neighbouring AP transmit power from the beacon.

Step 2

Let the RSSI of AP j observed at AP i be $RSSI_i(j)$ and the current transmit power of AP j be $Tx\_cur(j)$. The pathloss (PL) between APs i and j

$$PL(i,j) = Tx\_cur(j) - RSSI_i(j)$$

Since the pathloss is symmetric

$$PL(i,j) = PL(j,i)$$

Hence the estimated RSSI of AP i at AP j is

$$RSSI_j(i) = Tx\_cur(i) - PL(i,j))$$

Step 3

After computing the estimated RSSI heard by the neighbouring APs, a sorted RSSI table is created at each AP. The table contains the neighbouring APs in the decreasing order of RSSI heard by them. Only those neighbouring which hears this AP above the Loudness Threshold will get to be on this table. There is an updation in this list every few seconds. This time interval for updating is called as Neighbour Table Update Interval or NTU interval.

Step 4

At the end of the Update period, each AP identifies the neighbours which are above the loudness threshold. The number of such neighbours are taken to be N. Considering coverage hole detection and mitigation, if $N < K$ and $Tx\_cur(i) <= Tx\_max(i)$, then

$$Tx\_new(i) = Tx\_max(i)$$

For interference reduction, if $N \geq K$, then the power is decremented to meet the loudness criteria

$$\Delta_L = RSSI(K) - L\_thresh$$

where $RSSI(K)$ is the K^{th} entry in the sorted RSSI table. $RSSI(K)$ will give the estimated RSSI of AP i heard by the K^{th} neighbour. For maintaining visibility map, the maximum allowed decrement to satisfy the visibility criteria is

$$\Delta_V = RSSI(N) - V\_thresh$$

where $RSSI(N)$ is the N^{th} entry in the sorted RSSI table. $RSSI(N)$ will give the estimated RSSI of AP i heard by the N^{th} neighbour.

If $N = K$, then $\Delta_V = \Delta_L$. Power decrement is done by a factor of

$$\Delta = min(\Delta_V, \Delta L)$$

If $\Delta \geq TPC\_Hyst$, the new transmit power is

$$Tx\_new(i) = Tx\_cur(i) - \Delta_{TPC}$$

where Δ_{TPC} is the TPC step size. If $\Delta < TPC\_Hyst$, the transmit power is unchanged:

$$Tx\_new(i) = Tx\_cur(i)$$

3.4 Best Equal Transmit Power

In this simple algorithm, all the access points in the network will choose a common transmit power that will maximize the aggregate downlink throughput of the system. This is used for comparing purpose with the TPC A Algorithm.

3.5 Simulation Setup

The APs and clients are present in a three storey building. The details of the deployment and other network parameters are the same as that discussed in Chapter 3. The AP density is varied from 3 to 30. The traffic used in all simulations is UDP.

K	3
Loudness Threshold	-85 dBm
CCA Threshold	-85 dBm
Maximum AP Power	23 dBm
Minimum AP Power	2 dBm
Δ_{TPC}	3dB

Table 3.1: TPC A Parameters

3.6 Performance Evaluation

The performance measures used for studying are throughput, coverage and the number of hand-offs. Throughput refers to the amount of data successfully transmitted in one second. The unit used in the simulation is Mbps. In figure 3.1, the aggregate network downlink throughput (traffic from APs to clients) is seen with increase in network density. A comparison between the no TPC case, best equal power and TPC A algorithm has been done. TPC seems to be more effective as the number of APs increased. With a smaller density of APs, the TPC didnt have much impact on the performance. This is due to the fact the number of APs were not sufficient enough to get most of the clients connected. When the density increased, the throughput improved even in the case were there is no power control. The throughput without TPC saturates at some point even when AP density is increased. But with the TPC algorithm, we were able to see better performance in terms of improved aggregate throughput. The throughput is improving with increase in AP density at higher densities also. As the density of APs increase from 3 to 30, we can observe that the curve of the TPC algorithm reaches very near to the best equal power curve. One would infer that the TPC is very effective in a high dense AP scenario, not so much in a low dense scenario.

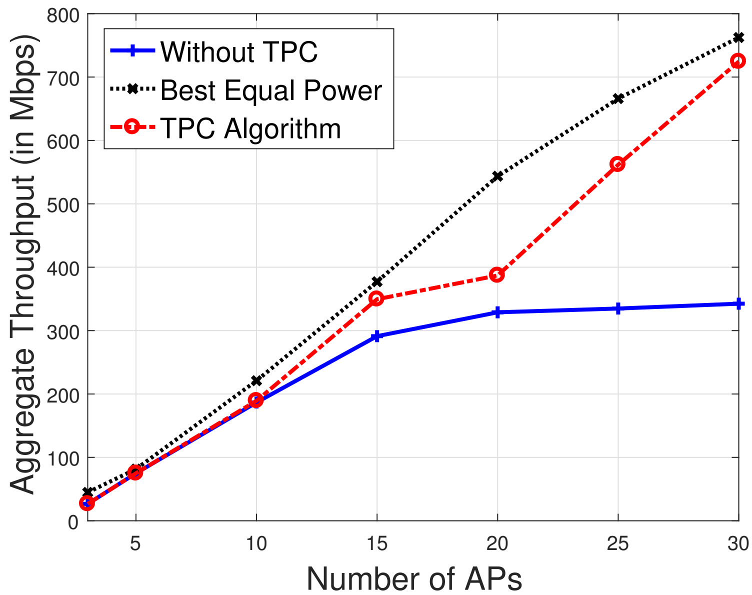


Figure 3.1: Aggregate Throughput versus the AP density in the WLAN without any TPC (bursting at 23 dBm), with best equal transmit power & with TPC A algorithm. One client per room is considered and each client has one UDP downlink transfer.

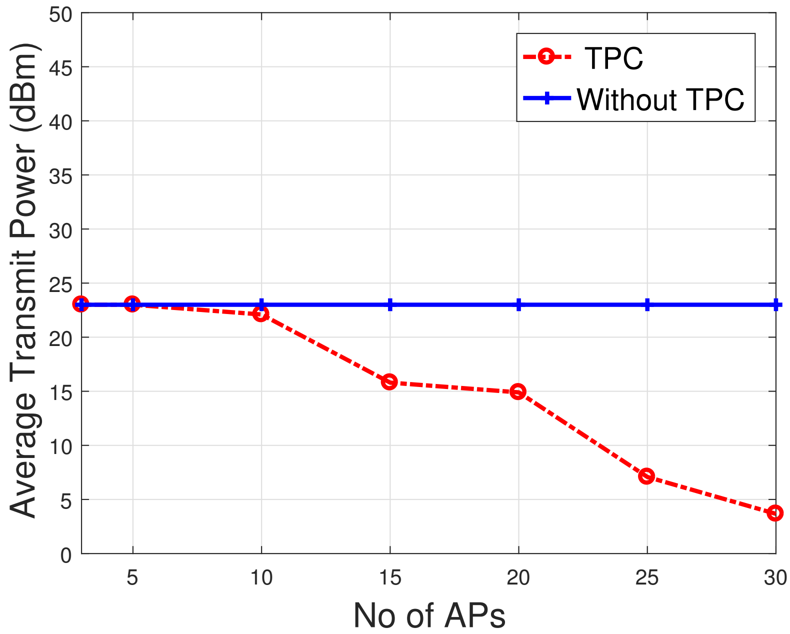


Figure 3.2: Average AP Transmit power as the AP density increases for No TPC (bursting at 23 dBm) and TPC A algorithm.

In figure 3.2, the average transmit power is plotted with respect to the increasing AP density. We can see that the average transmit power reduced with increase in node density. Then the study was conducted to test whether TPC is effective in case of uplink scenario. From figure 3.3, we were able to say transmit power control is not effective in the uplink scenario. It may be noted that the uplink aggregate throughput without TPC is higher than the aggregate downlink throughput without TPC. The reason is that the clients are transmitting at 14 dBm whereas the Access Points are at 23 dBm. Lower power levels of clients is giving better spatial reuse in the uplink scenario than in downlink scenario.

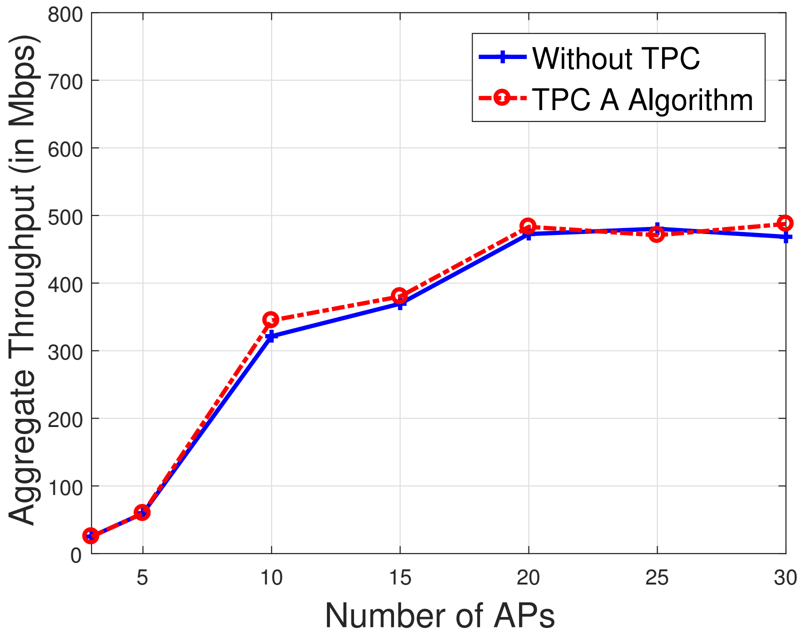


Figure 3.3: Aggregate Throughput versus AP density in the WLAN without any TPC (bursting at 23 dBm) and with TPC A algorithm. One UDP uplink transfer per client is considered.

In figure 3.4, the performance of TPC when other network APs were present was evaluated. These other network APs were said to burst at the maximum 23 dBm transmit power. The transmit power of the in-network was set by using the TPC algorithm without taking the other network APs into consideration. The scenario with 30 APs was used to study. The number of in-network APs changed from 0, 3, 5, 10, 15, 20, 25 to 30. The position of the in-network APs was the same as mentioned in the Simulation Setup. The other network APs were placed in the rest of the 30 rooms. It has been observed that the downlink throughput of in-networks (thereby the total throughput) is less than in the case where we only considered in-network APs. One would infer that TPC-A algorithm is less effective when there is interference from other network APs.

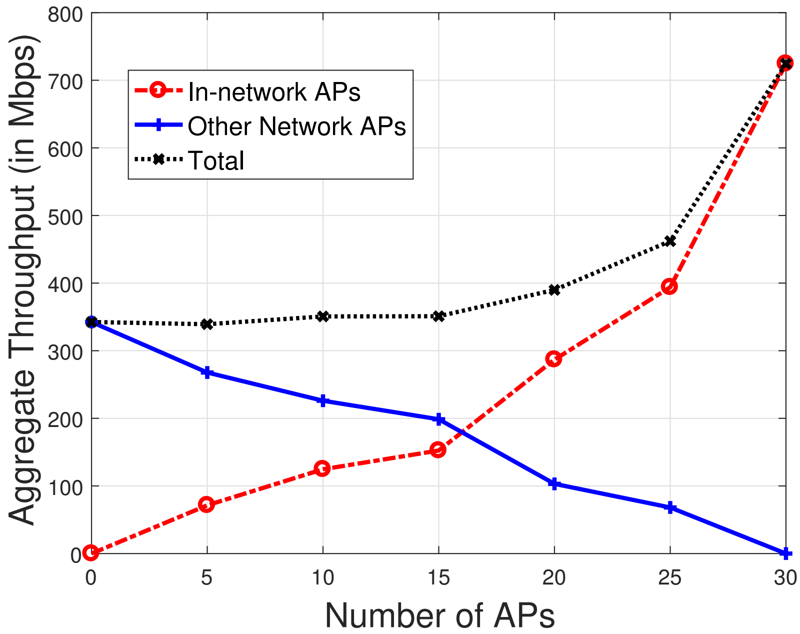


Figure 3.4: Aggregate throughput of x in-network and 30-x other network Access Points . The in-network APs use the TPC A algorithm to find the transmit power. Other network power is taken as 23 dBm. One client per room was deployed. One UDP downlink traffic per client was considered.

In figure 3.5, CDF of number of APs seen in different parts of buildings are plotted. With TPC, one would observe that the number of APs seen is reduced with TPC. This in turn means that the number of interferers are less with TPC. The figure 3.6 shows the coverage with & without TPC. The main drawback would be the reduced coverage with TPC. The number of handoffs is plotted in figure 3.7. With increase in threshold, the number of handoffs is more. The increased overhead is another negative impact of TPC.

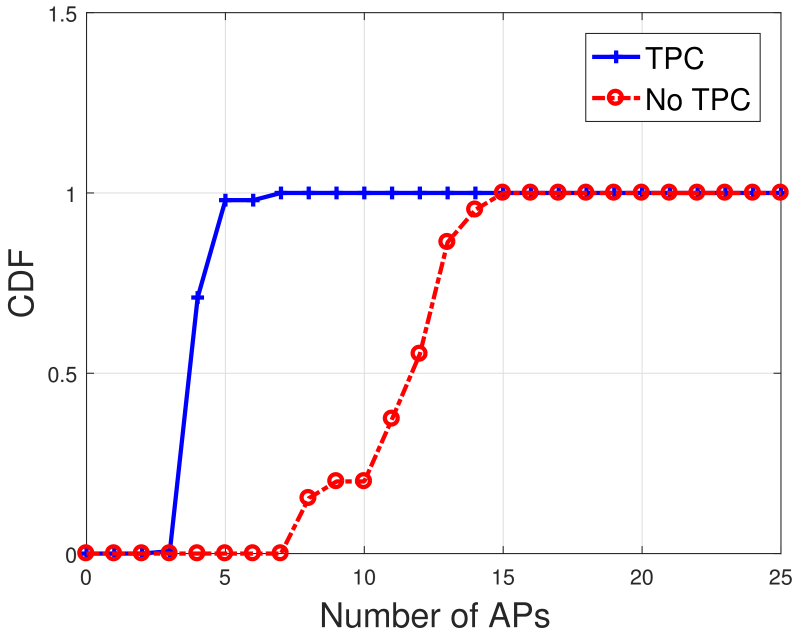


Figure 3.5: CDF of expected number of Access Points visible above the loudness threshold (-85 dBm). 30 APs were deployed in the simulation.

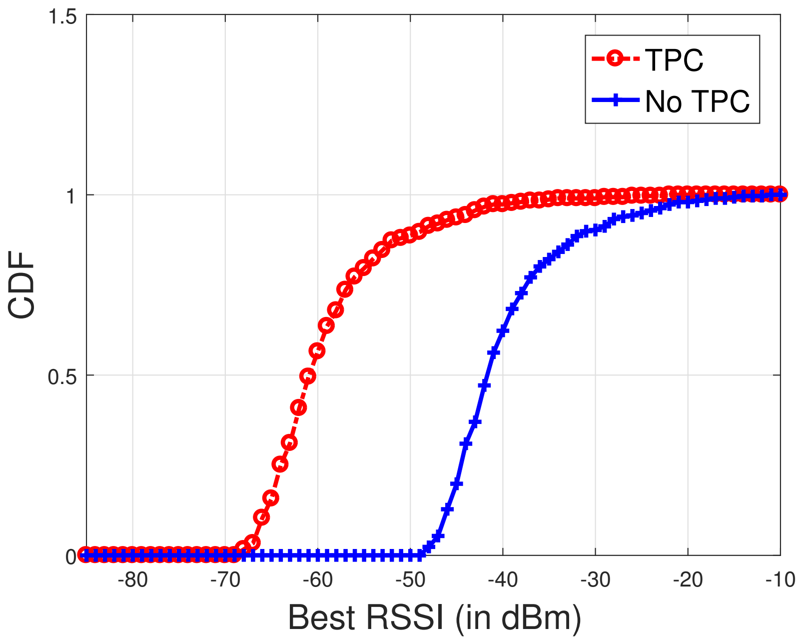


Figure 3.6: CDF of the best RSSI, received signal strength in the network region which was used in the figure .

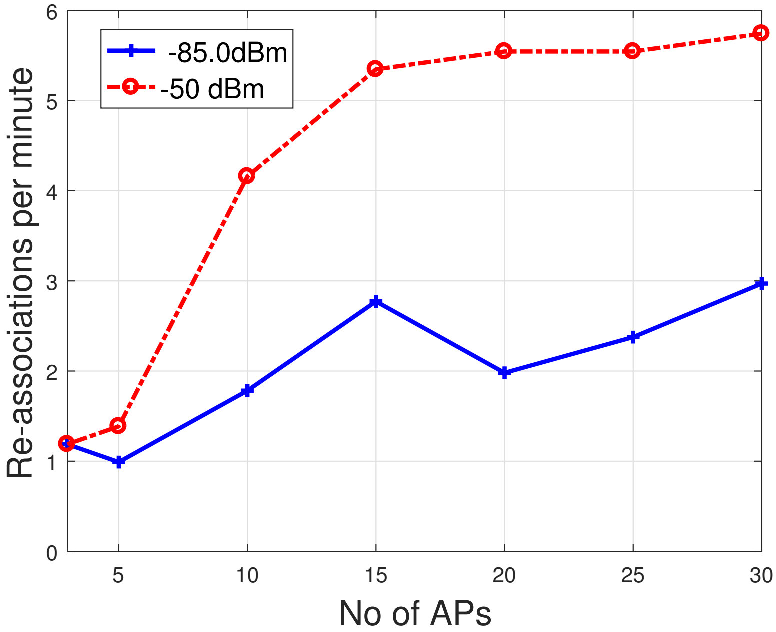


Figure 3.7: Average number of re-associations per minute for different AP densities. The client is moving at 1m/s in the x-direction. Once it reaches the end of one floor, it moves to next floor at 1m/s and then again moves in the x-direction as previously.

In the previous plots, the client power was set at a constant value of 14 dBm. The next objective was to study whether client power control can assist AP's TPC. For this simulation, uplink traffic was used. The power of the client was to be the minimum of 14 dBm and the power of the AP to which the client is associated with. With the increase in AP density, the client power adaptation was observed to be effective. In figure 3.8 lower densities, the AP's converged transmit power is more than 14 dBm, hence the client power will be choosing 14 dBm. This is the reason for not observing any improvement in throughput for low AP densities. For downlink traffic in figure 3.9, client support didn't have much effect.

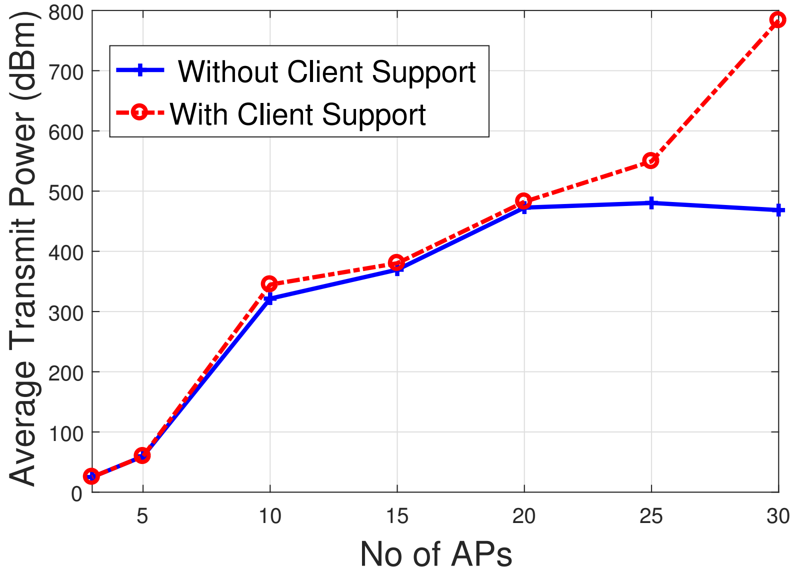


Figure 3.8: Aggregate Throughput versus the number of Access Points in the WLAN without any client power adaptation & with client power adaptation. One client per room is deployed. One UDP uplink transfer per client is considered.

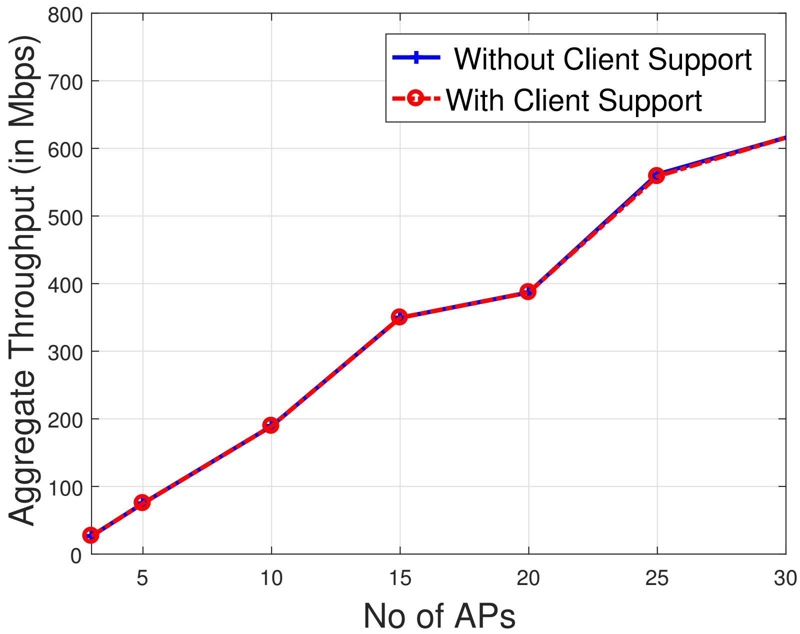


Figure 3.9: Aggregate Throughput versus the number of Access Points in the WLAN without any client power adaptation & with client power adaptation. One client per room is deployed. One UDP downlink transfer per client is considered.

A study was conducted in figure 3.10 to observe the throughput variation seen when a different loudness threshold. The value of the threshold was set at -75 dBm and the downlink aggregate throughput was compared with the loudness threshold value of -85 dBm which is used for all the other simulations.

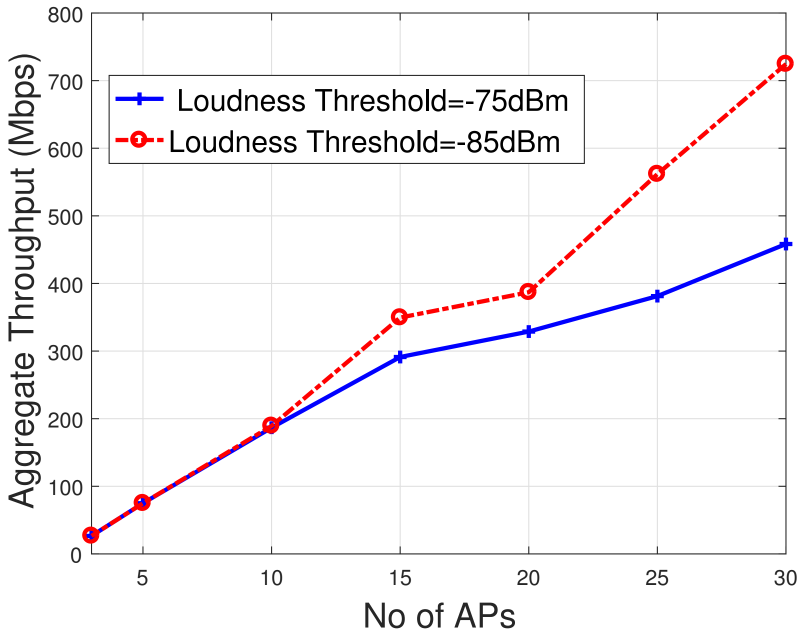


Figure 3.10: Aggregate Throughput versus the number of Access Points in the WLAN with TPC A Algorithm: loudness threshold at -75 dBm & loudness threshold at -85 dBm. One client per room and one UDP downlink traffic per client is considered.

All the above simulations were concentrating on the aggregate throughput of the system. Next we are looking at another important aspect in a WiFi network; fairness. The aggregate throughput won't be equally shared between the clients. If that happens, then its the best case scenario. The worst one would be the one where a single client gets a high throughput and rest all of them have zero throughput. To evaluate the fairness, a metric called Jain's Fairness Index was used. Consider a network with n clients and let x_i be the throughput of i-th client. Then the Jain's Fairness index is given by

$$\mathcal{J}(x_1, x_2, \ldots, x_n) = \frac{(\sum_{i=1}^{n} x_i)^2}{n \cdot \sum_{i=1}^{n} {x_i}^2}$$

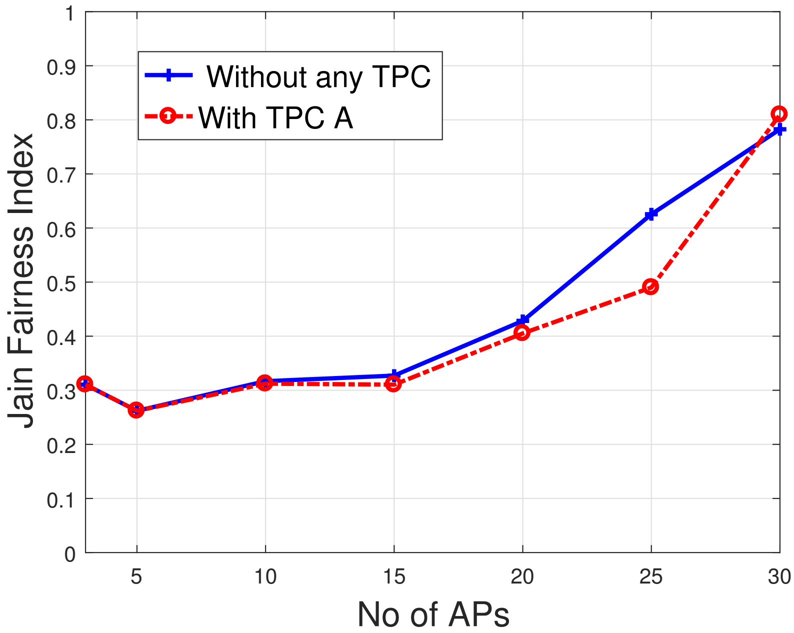


Figure 3.11: Client Fairness versus the number of Access Points in the WLAN without any TPC and with TPC A. One client per room is deployed and one downlink UDP transfer per client.

The values will range from $\frac{1}{n}$ to 1 (which is the best case scenario where the resources are shared equally). In figure 3.11, we looked at the fairness of clients with & without TPC. Fairness was not improved with the introduction of TPC.

CHAPTER 4

Dynamic Sensitivity Control

4.1 Introduction

The IEEE 802.11 standard has two modes of performing carrier sensing: the Distributed Coordination Function (DCF) (Association (2012)) and the Point Coordinated Function(PCF). DCF is the widely used method due to its simplicity and distributed implementation. For channel access, DCF uses Carrier Sensing Multiple Access with Collision Avoidance (CSMA/CA). This allows multiple nodes to access the wireless medium for communicating. Theoretically all nodes will have equal chance of gaining access. Each node which wishes to transmit will listen to the channel. The listening node will sample the energy of the medium to check if it is busy or idle. The sampled energy level is compared with a threshold. If the energy value is greater than the threshold, then the medium is considered busy and the listening node will defer from transmitting. If it is below the threshold, the listening node will transmit. This threshold is called Physical Carrier Sensing Threshold (PCST). In NS3, one can set the CCAThreshold for the medium. The default value is set to -85 dBm. So a channel will be sensed idle by a transmitting node i when

$$\sum_{k \epsilon int} P_r(d_{ik}) \leq CST$$

where $P_r(d_{ik})$ is the power received from another concurrent transmitter k, d_{ik} refers to the distance between the nodes i & k and interferers to the active interfering nodes. We can dynamically vary this Carrier Sensing Threshold to improve the performance. This method can be termed as Dynamic Sensitivity Control (DSC).

There is one more sensing method called Virtual Carrier Sensing (VCS). In this method if node A wants to transmit to node B, it will send a RequestToSend (RTS) frame to node B. Then node B responds with a ClearToSend (CTS) frame. Suppose another node C also wants to transmit. It will also receive the RTS frame from A (or CTS from B). Node C will set a Network Allocation Vector time that is the time C will consider the medium as busy. This time is calculated from the value it receives from the RTS/CTS frame. Node C won't transmit anything until the NAV timer expired. This is how VCS works.

In PCS if the channel is sensed as IDLE for a DCF Inter Frame Spacing (DIFS) period, the node will start its transmission immediately. If the channel is sensed as BUSY, the node will constantly listen to the channel until it is sensed IDLE for a DIFS period. Then it transmits.

4.2 Carrier Sensing Range

There are three different distance ranges associated with packet transmission in a 802.11 system. First one, the transmission range corresponds to the range over which a node can successfully receive a packet. Then there is interference range; the distance over which any new transmission would interfere with the packet reception. The carrier sensing range is defined as the distance range within which a node can hear an ongoing transmission with high probability by using the physical carrier sensing mechanism. Hearing just means it can sense the transmission and not necessarily being able to decode the packet. In 802.11, the transmission range is smaller than the carrier sensing range as well as the interfering range. Consider a two node scenario. Suppose node A is transmitting to node B. Transmission power is assumed to be constant for all nodes and value is taken as P_t. AB denotes the euclidean distance between the nodes A and B. The carrier sensing range R_s can be considered as circular area around the transmitter given by

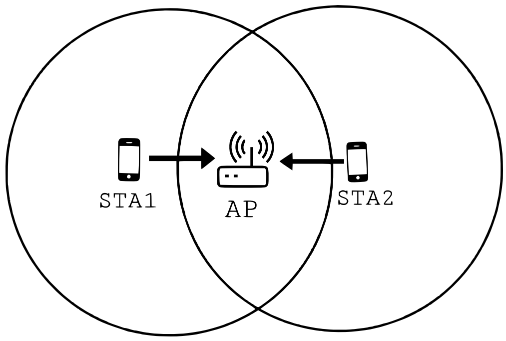
$$R_s = d_0(\frac{P_0}{CST})^{\frac{1}{\gamma}}$$

where P_0 is the RSSI seen at the reference distance d_0 and γ is the pathloss exponent. This is obtained with assumption that all the nodes are having a common transmit power and the pathloss is log distance. So the problem of controlling CST essentially boils down to controlling the radius R_s.

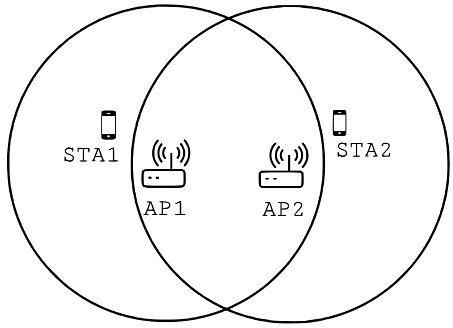
4.3 Hidden Node & Exposed Node Problem

For an ideal carrier sensing, two criteria must be satisfied. The first one is that it should be able to prevent simultaneous transmissions by interfering nodes. Second one is to allow simultaneous transmissions of non interfering nodes. The failure to meet these criteria leads to two types of problem nodes. One is called the hidden node problem and the other is known as the exposed node problem. Both of them will lead to reduced aggregate throughput of the system. Hidden node problem happens when a node which is outside the sensing range can interfere with another node's transmission. An example is when two stations want to communicate with the AP. Due to the long distance between them, they cannot sense each others transmissions. Thus neither of them will back-off. So the stations will transmit packets to the AP. This results in collision of data packets in the AP end. The receivers can decode the data packets which has the best SNR of the collided packets. This phenomenon is termed as Capture Effect in (A. Kochut and Agrawala (2004)). If one transmitter consistently has a stronger received signal strength at the AP, it will lead to connectivity problems and fairness issues.

On the other hand, exposed node happens when a node is unnecessarily refrained from transmitting even when the node's interference is not sufficient to cause collisions. An example of exposed node problem is when we have two APs which are far apart but their clients are closer to each other. If Client1 is transmitting to AP1, Client2 will definitely hear this ongoing transmission. This leads to Client2 unnecessarily deferring from its own transmission even though the transmission won't result in interference. An increase in CST value will decrease the number of exposed nodes thereby mitigating the exposed node problem. But increasing CST could also lead to the increase in hidden nodes. So an optimal CST value would be the one that balances the number of exposed nodes and the number of hidden nodes for the network scenario. The network scenario we have studied is a dense network and hence the gist of finding the CST would be more focusing on reduction of exposed node problem rather than the hidden node problem. With a low value of CST, the chances of packet collisions decreases thereby increasing the packet success rate. But a low CST has a drawback of reduced spatial reuse. So CST performs the job of maintaining the trade off between spacial reuse and chances of packet collisions in the system. One of the reasons the aggregate throughput saturates with increase in the AP density is the increase in the number of exposed nodes.



(a) Illustration of hidden node problem. The two stations not hearing each other; Stations will transmit data to the AP resulting in collisions. The circle around represents the carrier sensing region around that node.



(b) Illustration of exposed node problem. The APs defer from their transmission hearing each other. The circle around represents the carrier sensing region around that node.

Figure 4.1: Hidden Node & Exposed Node Problem

Hidden nodes mainly cause unfairness related issues and throughput instabilities(Jiang and Liew. (2008)).

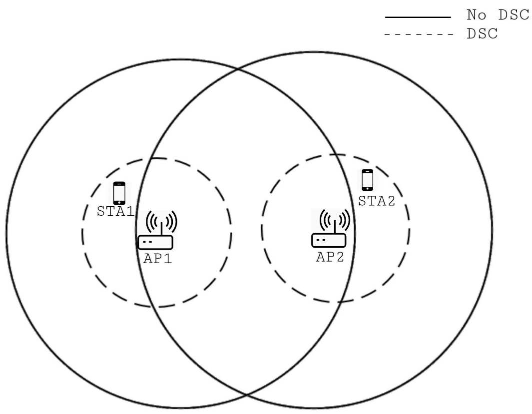


Figure 4.2: Illustration of how DSC can reduce the number of exposed nodes. The dashed circle represent the CSR after using DSC and the normal circle represents range without using DSC.

4.4 Carrier Sensing Constraints

Consider a scenario with 3 nodes: A, B & C. A is transmitting to node B and C is the strongest interferer of node B. The Signal to Interference Ratio (SIR) should be greater than a threshold to successfully receive the signal from A. Let SIR_t be that threshold. Assume that both nodes A & C are transmitting the same time. P_t is the common transmit power for all the nodes. Assuming two ray model, the power received from A is

$$P_{AB} = \frac{P_t}{d_{AB}^{\gamma}}$$

Similarly the interfering node C 's power at B's end is, $P_{CB} = \frac{P_t}{d_{CB}^{\gamma}}$

For successful reception of the packet,

$$SIR = \frac{P_{AB}}{P_{CB}} \geq SIR_t$$

Rearranging, the distance at which the interfering node should be to allow successful reception is

$$d_{CB} = SIR_t^{\frac{1}{\alpha}} \times d_{AB}$$

Since $d_{CA} \leq d_{AB} + d_{CB}$, the carrier sensing threshold can be set at

$$CSR_A = d_{AB} + d_{CB}$$

The carrier sensing range of A should take into account the interference range of B. Transmissions outside CSR_A should not cause any collisions at B. Therefore to calculate the proper CST_A, the power received from C at A should be considered.

$$P_{CA} \geq \frac{P_t}{(d_{AB} + d_{CB})^{\alpha}}$$

Dividing both numerator and denominator by d_{AB} and using $P_{AB} = \frac{P_t}{d_{AB}^{\alpha}}$ we get

$$P_{CA} \geq \frac{P_{AB}}{(SIR_t^{\frac{1}{\alpha}} + 1)^{\alpha}}$$

Therefore CST is given by

$$CST_A = \frac{P_{AB}}{(SIR_t^{\frac{1}{\alpha}} + 1)^{\alpha}}$$

4.5 Prior Works

Acholem and Harvey. (2010) propose a linear mapping between CST and the nodal density in a multihop system. With increase in nodal density, the amount of interference increases. Therefore CST should also increase. The aggregate throughput improved by 30%.

Deng and Varshney. (2004) proposed a reward function which is dependent on channel throughput and the total amount of data transmitted.

$$\eta = N_s - cN_d$$

where N_s is the total channel throughput and N_d is the total data transmitted. For different values of c, one can vary CST to find the optimal value of CST that maximizes the reward function. This work was on adhoc WiFi networks. It was noted that the CST value increased with respect to c.

Thorpe and Murphy. (2011) talk about using radio resource management to find the optimal CST value for the network. Each node will record the time the channel is busy due to transmissions of other nodes in the CS range, time the channel is busy due to the node's own transmissions and the rate of re-transmissions of the node. Each AP maintains a list of all the connected stations. Its called the Station Activity List and contains the transmission time for each station. Each node maintains a Neighbour List which contains all the nodes in the reception region. Both the lists are compared to identify the number of hidden and exposed nodes. If the hidden nodes are more, the CST is decremented. If exposed nodes are more then there is an increment in the value of CST. This work is defined on a single AP system, that means all the APs work as a single entity.

Zhu (2004) proposes an analytical model to estimate the CST for a given network topology, reception power and data rate was proposed. The value is derived based on the condition that the interference power and noise sensed by its receiver cannot exceed the power level for which the packet may be dropped. So

$$P_C = \frac{P_D}{S_0}$$

where P_C is the carrier sensing threshold, P_D is the receiving power and S_0 is the SINR threshold.

Zhai and Fang. (2006) takes into account the MAC overheads for calculating the optimal CST value. They showed that it has better performance than the optimal calculated without taking MAC overhead into consideration. In an analytical Markov Model was used to derive the optimal CST value for ad hoc networks. The impact of PCS on multi-rate and multi-hop wireless ad hoc networks was studied in Zhai and Fang. (2006).

Zhu (2007) put forward a heuristic CST tuning algorithm based on QoS. For the notion of fairness a global CST is chosen for all the nodes. CST value depends on the time the channel is busy, the time for which the user is busy due to transmission due to transmissions from the users within the carrier sensing range, the time taken for successful transmission of the user itself, and the number of users in the reception range. It achieved upto 50% improvement in total throughput compared to traditional 802.11 mechanism.

802.11 ax task group proposed a DSC algorithm in Smith (2013). It was studied in Afaqui (2015). The algorithm only focuses on stations and not on APs. CST value is calculated by decreasing a margin from the average RSSI of the beacons from the client's corresponding AP. This value of CST is then confined within a lower and upper limit. The value of margin is experimentally chosen by taking factors like total throughput, jain fairness index and fer into consideration. The same authors went on to propose a DSC algorithm for the APs also in Afaqui (2016). In this algorithm, the APs listen to the beacons from the other APs and also data and control packets from the associated clients. Each AP keeps a note of the RSSI from the clients and the other AP. From those RSSI values, the minimum RSSI of the clients and the maximum RSSI of other APs are taken into consideration for calculating the CST. Minimum RSSI of clients is taken into consideration so that the farthest client is accounted for. Other APs' maximum RSSI is taken so that the carrier sensing almost avoids the other APs.

4.6 Two AP Experiments

From the previous analysis it was noted if the interferer is relatively closer then CST may not be a good option. Simulations were done with 2 Access Points & 2 clients to prove this analysis. Two APs are placed 10 metres apart in a straight line. The respective clients were kept directly above the APs. The distance between the AP and the client were varied. This is like changing the distance d_{AB} in the analysis. The distance d_{CB} however remains a constant 5 metres & SIR_t is also a constant.

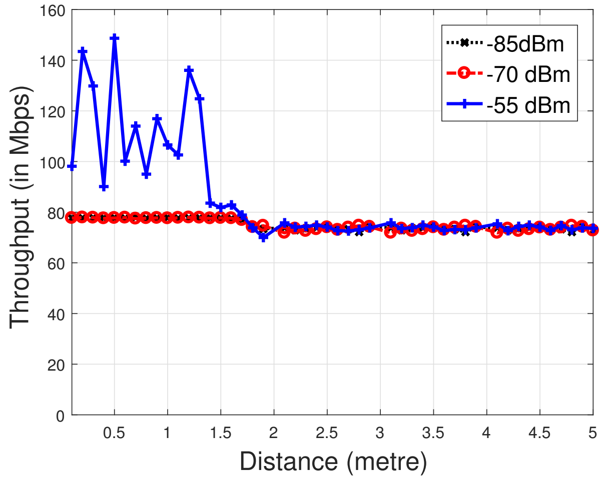


Figure 4.3: Aggregate Throughput of the two clients when the distance from the APs are varied for CST values of -85 dBm, -70 dBm & -55 dBm

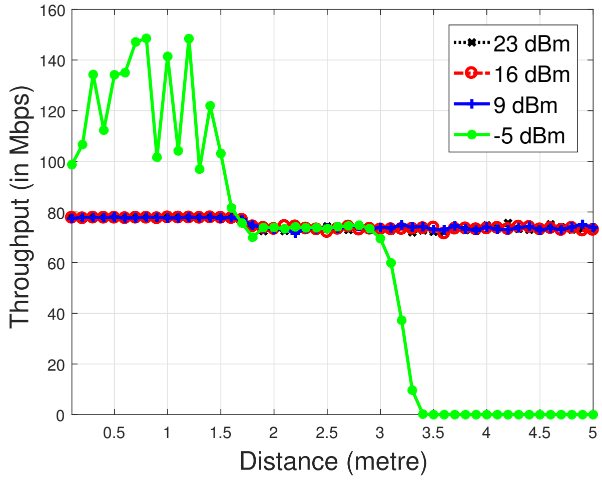


Figure 4.4: Aggregate Throughput of the two clients when the distance from the APs are varied for transmit power values of 23 dBm, 16 dBm , 9dBm & -5 dBm

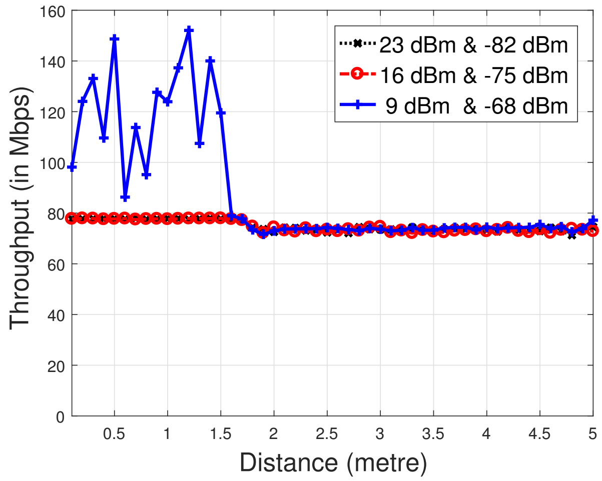


Figure 4.5: Aggregate Throughput of the two clients when the distance from the APs are varied for transmit power-CST pair values of 23 dBm & -82 dBm, 16 dBm & -75 dBm and 9 dBm & -68 dBm

From the analysis in the previous section, we saw that the relative distance of the interferer will have an impact on how DSC can be effective. From the two AP experiments also, we can see that increasing CST becomes ineffective as the distance between the transmitter and the receiver increases. That in turn means only the nearer clients will be benefited because of DSC. The farther clients wont have any improvement in throughput. This might introduce fairness issues in the system.

4.7 Curve between CST and Tx Power

The below graph is obtained from 802.11ax task group's 802.11ax draft 2.0. They recommend to choose a CST- Transmit power pair which lies below the curve. The logic behind the curve is that if one has set the CST as a high value then it will ignore the far away transmissions. Therefore for one's transmission, the power level should be a low level so that interference is not caused. In the simulations, first we choose CST_{curve} for the AP transmit power from the curve. We can't use this value directly as the CST threshold since there can be a client of the AP which may be heard below the CST threshold. The AP in this case will ignore the client's uplink transmission and will start downlink traffic. This can potentially lead to severe collisions. To tackle this, CST_{final} is chosen as the minimum of CST_{curve} & the worst RSSI of the clients associated with that AP. This CST value is then lower bounded by -85 dBm.

For an AP i,

Step 1

$$CST_{curve}[i] = \mathbf{f}(tx\_pw[i])$$

where **f** is the mapping from transmit power to CST

$tx\_pw[i]$ is the transmit power of AP i

Step 2

$$CST_{final}[i] = Min(\textbf{\textit{minRSSI}}[i] + guard, CST_{curve}[i])$$

where *minRSSI*[i] is the minimum of all the RSSI values of AP i clients heard at AP i's end.

guard is a constant value of -5 dBm

Step 3

$$CST_{final}[i] = Max(-85.0, CST_{final}[i])$$

Step 4

Repeat all these steps for all AP i.

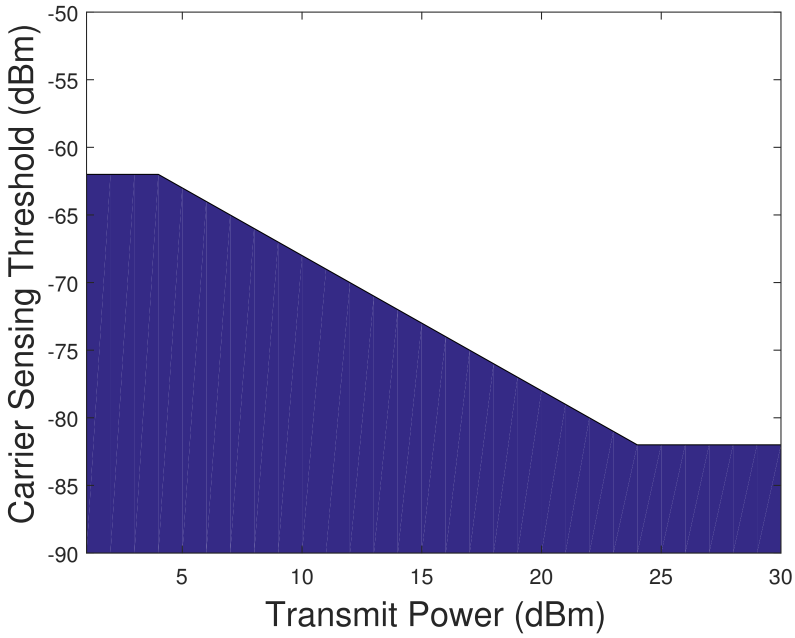


Figure 4.6: The shaded region specifies the operating region for each AP transmit power.

We are varying the transmit power from 23 dBm to 2 dBm in steps of 2 dBm, consequently the CST gets tuned. The pair of transmit power & carrier sensing threshold which gives the best downlink throughput is taken as the operating point for the given WLAN.

4.8 Simulation Setup

The APs and clients are present in a three storey building. The details of the deployment and other network parameters are the same as that discussed in Chapter 3. The AP density is varied from 3 to 30. The traffic used in all simulations is UDP.

Client Power	-14 dBm
Maximum AP Power	23 dBm
Minimum AP Power	2 dBm
Maximum CCA Threshold	-62 dBm
Minimum CCA Threshold	-85 dBm

Table 4.1: DSC Simulation Setup

4.9 Performance Evaluation

The simulations used the simulation setup which was described earlier. The total no of clients are still fixed at 30 and the AP density varied from 3 to 30. The traffic application used is UDP.

In figure 4.7, the value of Access Points' transmit power and CCA Threshold were varied together and best throughput obtained was plotted. This plot is compared with the No TPC and best equal power plots which were previously discussed in figure 3.1. An improvement in throughput was seen when the AP density compared to just the best equal power scenario. Only the access points' transmit power and CST values are varied. For the clients, their transmit power was fixed at 14 dBm and CCA threshold at -85 dBm (same values which were used in simulating TPC).

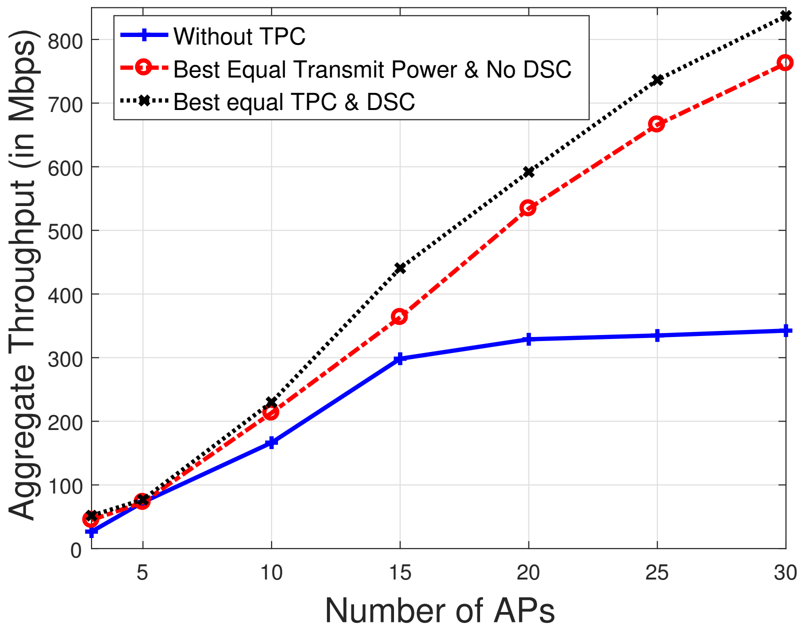


Figure 4.7: Aggregate Throughput versus the AP Density for No TPC (bursting at 23 dBm), Best Equal TPC & Best Equal TPC-DSC pair. One client is deployed in each room and one UDP downlink per client is considered.

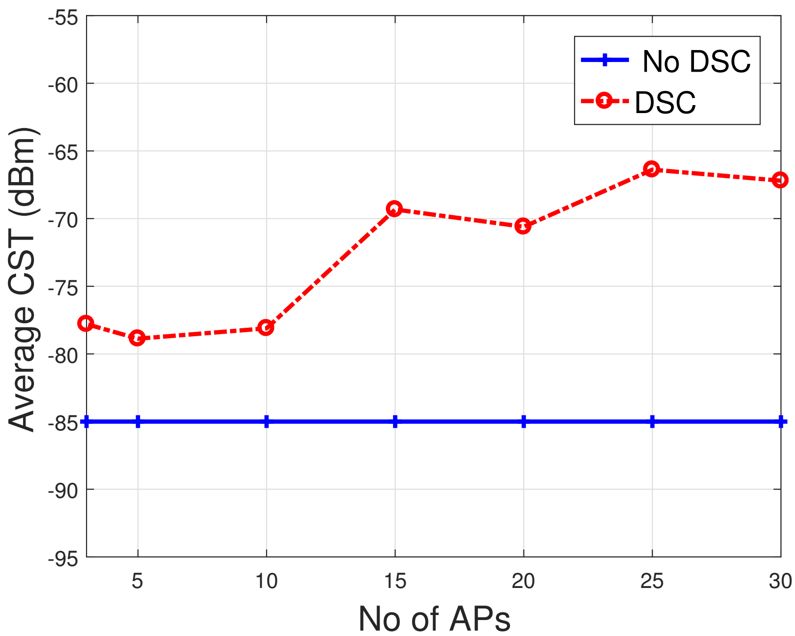


Figure 4.8: Average CST values of APs for with and without DSC. The setup is the same as that in figure 4.7.

The figures 4.9 & 4.10 study the impact of AP & client fairness with the introduction of DSC. As expected the fairness degraded due to the fact that the clients which are nearer to the Access Point will be benefited than those which are farther away from the APs.

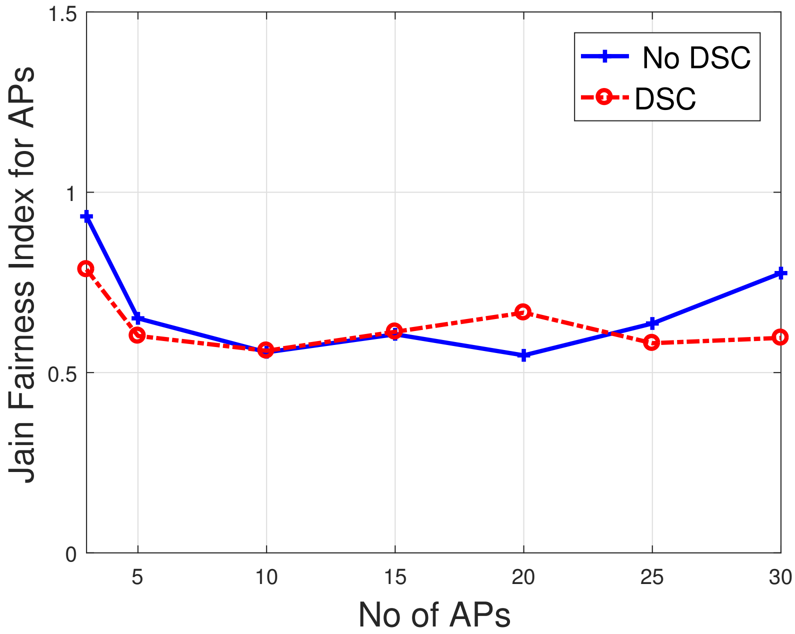


Figure 4.9: Fairness among APs for the UDP downlink traffic discussed versus the varying AP density.

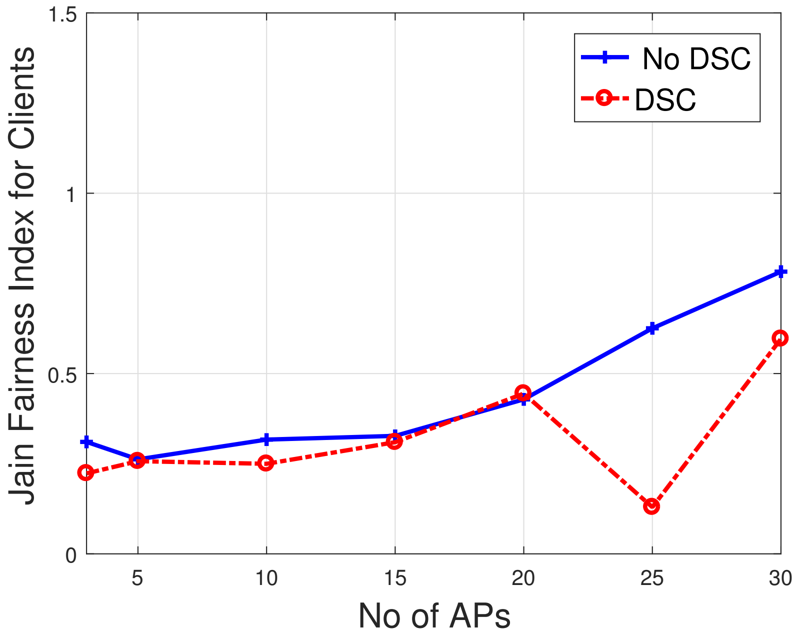


Figure 4.10: Fairness among clients for the UDP downlink traffic discussed versus the varying AP density.

The figure 4.11 plot tries to study the effect of the best equal CST- Transmit power pair when the data traffic is from clients to the APs (uplink). The DSC-TPC pair which gave the best throughput was chosen for AP parameters and the client transmit power fixed at 14 dBm and its CST at -85 dBm. As expected the adaptation of transmit power and CCA threshold for APs didn't have any impact on the network performance when the traffic is uplink.

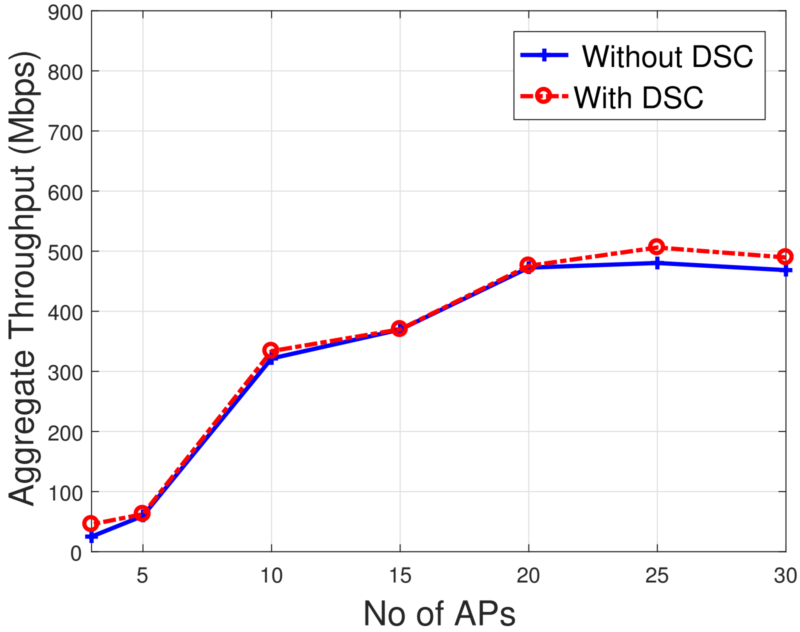


Figure 4.11: Aggregate Throughput versus the AP Density for No TPC (bursting at 23 dBm), Best Equal TPC & Best Equal TPC-DSC pair. One client is deployed in each room and one UDP uplink per client is considered.

The figure 4.12 studies the effect of client support when the traffic is uplink. The APs already have the DSC algorithm implemented on it. Now for client support, we use the same algorithm on the client side. The minimum of the value from the curve & the RSSI of the AP to which it is associated is taken as the CST value for the client. A good improvement in throughput was seen with DSC in the client side.

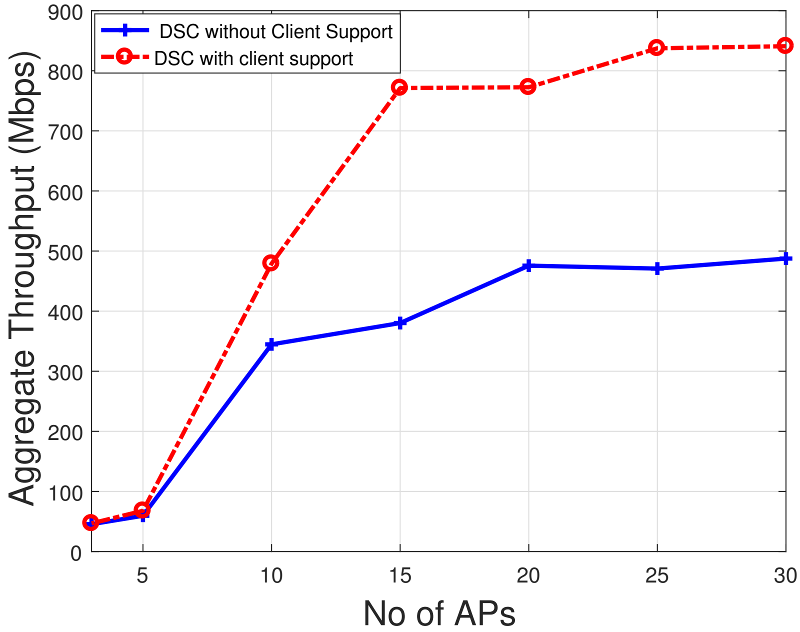


Figure 4.12: Aggregate Throughput versus the AP Density in the WLAN with Client DSC support & without client DSC support. One client per nodes i deployed and one UDP uplink transfer is considered.

CHAPTER 5

Conclusions & Future work

Transmit Power Control for Access Points seemed to improve the network performance in some scenarios. From the simulations, it was effective when the traffic is downlink. But with uplink traffic, it was seen to be ineffective. With the presence of other network interferers also, TPC's effect was diminished. The coverage in terms of best RSSI has been reduced. But this negative impact was compensated by the number of interferers seen. The increase in overheads due to handoffs with TPC is another drawback. Client support was effective in uplink traffic and not in downlink scenario. So for a conversation traffic, DSC in APs along with client support would be very effective.

Dynamic Sensitivity Control improved the throughput but fairness seemed to decrease. With client support, the uplink traffic had a good improvement. Like in TPC, for a conversation traffic, DSC in both AP & client side would improve the overall performance. Current focus is to do more simulations to study the effect of DSC.

The simulations done so far didn't consider the effect of shadowing along with the pathloss component. In future we would include the shadowing factor also. Multiple clients which are mobile inside the building would also make the setup more realistic. Implementing Minstrel rate adaptation is another aspect we will be looking to implement in our future work.

REFERENCES

1. **A. Kochut, A. S., A. Vasan** and **A. Agrawala** (2004). Sniffing out the correct physical layer capture model in 802.11b, in network protocols. *ICNP 2004. Proceedings of the 12th IEEE International Conference on Oct 2004.*

2. **Acholem, O.** and **B. Harvey.** (2010). Throughput performance in multihop networks using adaptive carrier sensing threshold. *IEEE SoutheastCon 2010 (SoutheastCon), Proceedings of the. IEEE.*

3. **Afaqui, e. a., M. Shahwaiz** (2015). Evaluation of dynamic sensitivity control algorithm for ieee 802.11 ax. *Wireless Communications and Networking Conference (WCNC), 2015 IEEE.*

4. **Afaqui, e. a., M. Shahwaiz** (2016). Dynamic sensitivity control of access points for ieee 802.11 ax. *Communications (ICC), 2016 IEEE International Conference on. IEEE.*

5. **Akella, J. G. S. S., A.** and **P. Steenkiste** (2007). Self-management in chaotic wireless deployments. *Wireless Networks.*

6. **Association, I. S.** (2012). Ieee standard for information technology– telecommunications and information exchange between systems local and metropolitan area networks–specific requirements part 11: Wireless lan medium access control (mac) and physical layer (phy) specifications. *ANSI/IEEE Std. 802.11-2012.*

7. **Cisco** (2016). Radio resource management white paper. *Chapter:Transmit Power Control (TPC) Algorithm, Technical Reference.*

8. **Deng, B. L., Jing** and **P. K. Varshney.** (2004). Tuning the carrier sensing range of ieee 802.11 mac. *Global Telecommunications Conference, 2004. GLOBECOM'04. IEEE.*

9. **Grilo, A.** and **M. Nunes** (2003). Link-adaptation and transmit power control for unicast and multicast in ieee 802.11 a/h/e wlans. *In Local Computer Networks, 2003. LCN'03. Proceedings. 28th Annual IEEE International Conference on IEEE.*

10. **Hata, M.** (1981). Empirical formula for propagation loss in land mobile radio services. *IEEE Transactions on Vehicular Technology*, **29**.

11. **Jiang, L. B.** and **S. C. Liew.** (2008). Improving throughput and fairness by reducing exposed and hidden nodes in 802.11 networks. *IEEE Transactions on Mobile Computing 7.1.*

12. **Lacage, M.** and **T. R. Henderson** (2006). Yet another network simulator. *In WNS2 06: Proceeding from the 2006 Workshop on ns-2: the IP network simulator, New York, NY, USA.*

13. **Mhatre, K. P., Vivek P** and **F. Baccelli** (2007). Interference mitigation through power control in high density 802.11 wlans. *In INFOCOM 2007. 26th IEEE International Conference on Computer Communications. IEEE.*

14. **Monks, B. V., J.P.** and **W. Hwu** (2001). A power controlled multiple access protocol for wireless packet networks. *In INFOCOM 2001. Twentieth Annual Joint Conference of the IEEE Computer and Communications Societies. Proceedings. IEEE.*

15. **Muqattash, A.** and **M. Krunz** (2005). Powmac: a single-channel power-control protocol for throughput enhancement in wireless ad hoc networks. *IEEE Journal on Selected Areas in Communications.*

16. **NS-3** (Network Simulator-3). URL `http://www.nsnam.org/`.

17. **Qiao, e. a., Daji** (2003*a*). Adaptive transmit power control in ieee 802.11 a wireless lans. *Vehicular Technology Conference, 2003. VTC 2003-Spring. The 57th IEEE Semi-annual..*

18. **Qiao, e. a., Daji** (2003*b*). Miser: an optimal low-energy transmission strategy for ieee 802.11 a/h. *Proceedings of the 9th annual international conference on Mobile computing and networking. ACM.*

19. **S., M.** (2014). 802.11 tgax simulation scenarios. *IEEE 802.11ax, IEEE 802.11-14/0980r6.*

20. **Series, P.** (2012). Propagation data and prediction methods for the planning of indoor radiocommunication systems and radio local area networks in the frequency range 900 mhz to 100 ghz. *Recommendation ITU-R.*

21. **Series, P.** (2015). Propagation data and prediction methods for the planning of short-range outdoor radiocommunication systems and radio local area networks in the frequency range 300 mhz to 100 ghz. *ITU, Tech. Rep. ITU-R.*

22. **Sheth, A.** and **R. Han** (2002*a*). An implementation of transmit power control in 802.11 b wireless networks. *Department of Computer Science University of Colorado, CU-CS-934-02.*

23. **Sheth, A.** and **R. Han** (2002*b*). A mobility-aware adaptive power control algorithm for wireless lans a short paper. *IEEE CAS Low Power Workshop.*

24. **Sheth, A.** and **R. Han** (2003). Adaptive power control and selective radio activation for low-power infrastructure-mode 802.11 lans. *In Distributed Computing Systems Workshops, 2003. Proceedings. 23rd International Conference on IEEE.*

25. **Sheth, A.** and **R. Han** (2005). Shush: Reactive transmit power control for wireless mac protocols. *In Wireless Internet, 2005. Proceedings. First International Conference.*

26. **Shrivastava, e. a., Vivek** (2007). Understanding the limitations of transmit power control for indoor wlans. *Proceedings of the 7th ACM SIGCOMM conference on Internet measurement. ACM.*

27. **Smith, G.** (2013). Dynamic sensitivity control-v2. *IEEE 802.11ax, IEEE 802.11-13/1012r4.*

28. **Thorpe, S. M., Christina** and **L. Murphy.** (2011). Ieee802. 11k enabled adaptive carrier sense management mechanism (kapcs2). *Integrated Network Management (IM), 2011 IFIP/IEEE International Symposium on. IEEE.*

29. **Zhai, H.** and **Y. Fang.** (2006). Physical carrier sensing and spatial reuse in multirate and multihop wireless ad hoc networks. *INFOCOM 2006. 25th IEEE International Conference on Computer Communications. Proceedings. IEEE*.

30. **Zhu, e. a., Jing** (2004). Adapting physical carrier sensing to maximize spatial reuse in 802.11 mesh networks. *Wireless Communications and Mobile Computing 4.8*.

31. **Zhu, e. a., Yanfeng** (2007). Qos-aware adaptive physical carrier sensing for wireless networks. *Wireless Communications and Networking Conference, 2007. WCNC 2007. IEEE*.