Modelling physical and mac layer strategies for IEEE802.11ad

RN Lingeswarao Kandregula

A Thesis Submitted to
Indian Institute of Technology Hyderabad
In Partial Fulfillment of the Requirements for
The Degree of Master of Technology

भारतीय प्रौद्योगिकी संस्थान हैदराबाद
Indian Institute of Technology Hyderabad

Department of Elecctrical Engineering

February 2016

Declaration

I declare that this written submission represents my ideas in my own words, and where ideas or words of others have been included, I have adequately cited and referenced the original sources. I also declare that I have adhered to all principles of academic honesty and integrity and have not misrepresented or fabricated or falsified any idea/data/fact/source in my submission. I understand that any violation of the above will be a cause for disciplinary action by the Institute and can also evoke penal action from the sources that have thus not been properly cited, or from whom proper permission has not been taken when needed.

KRN

(Signature)

RN Lingeswarao Kandregula

(Student Name)

EE13M10004.

(Roll No.)

Approval Sheet

This Thesis entitled Modelling physical and mac layer strategies for IEEE802.11ad by RN Lingeswarao Kandregula is approved for the degree of Master of Technology from IIT Hyderabad

29/2/16

(Dr. Sumohana Channapayya) Examiner
Dept. of Electrical Engineering
IITH

29/2/16

(Dr. Abhinav Kumar) Examiner
Dept. of Electrical Engineering
IITH

(Dr G.V.V. Sharma) Adviser
Dept. of Electrical Engineering
IITH

Acknowledgements

I would like to thank Dr. G.V.V. sharma and Dr. Abhinav Kumar for their constant help and support during this thesis work. They always gave me valuable comments during this work. I also wanted to show my gratitude to my institute given sisters Ms. Rayapati Sushma and Ms. Yogitha Ramamoorthy for their affection and moral support during my whole M.Tech program. Finally, I would like to thank my family who have been always there for me. Without them, this work had not been possible. And thanks to all people who, as much as they possibly could, have supported and guided me through this thesis.

Dedication

I dedicate this thesis to my family without them i wouldn't be here.

Abstract

In this thesis a simulation model for IEEE802.11ad single carrier physical model (PHY) is developed. In order to test the model different modulation schemes and LDPC code rates are considered. The considered modulation schemes includes QPSK,16-QAM and 64-QAM where as the code rates involved are 1/2, 3/4, 5/8 and 13/16. The decoder used for hard decision is bit flipping algorithm(BF) where as for soft decision is sum product algorithm(SPA). On comparing with the results obtained from hard and soft decision decoders, it is concluded that soft decoder performs better at low SNRs when compared to the hard decoder. In addition to the above we carried out the performance analysis for directional cooperative MAC protocol for IEEE802.11ad under imperfect channels and finite buffer case for contention based access periods in uplink. In order to calculate the system throughput a 3-D markov chain model is used by considering the directional hidden terminal problem. The throughput is depicted by plotting the plots between varying beam sectors fixing number of stations and between varying stations and fixing number of beam sectors.

Contents

Chapter 1

Introduction to 802.11ad

802.11ad is a wifi standard operating at 60 GHz frequency band, which is unlicensed and abundant. Like 2.4 and 5 GHz bands, it has four channels each having 2GHz bandwidth. Unlike 2.4 and 5 GHz bands, the signal degrades significantly due to oxygen absorption and atmospheric attenuation. The IEEE 802.11ad standard defines a directional communication scheme that uses beamforming to cope up with increased attenuation by using the high-gain and less-interference properties of Directional antennas. Beamforming also optimizes the power at the receiver. This standard is backward compatible with 2.4 and 5GHz bands. Typical applications for IEEE802.11ad are Wireless Display, Distribution of HDTV content, Wireless PC connection to transmit huge files quickly and Automatic sync applications.

According to Friis free space equation,additional attenuation of 22 dB compared to the 5 GHz band at a typical IEEE 802.11ad range of 10 m.

1.0.1 802.11ad Physical layer

It can also be called as ”Directional Multi-Gigabit (DMG) PHY”. The standard defines three different PHY layers depending on different applications namely control PHY, Single Carrier(SC) PHY and Orthogonal Frequency Division Multiplexing Phy(OFDM). The control PHY is designed for low signal-to-noise ratio operation. The single carrier (SC) PHY enables power-efficient and low-complexity transceiver implementation by employing LDPC encoder. The low-power SC PHY uses Reed-Solomon encoder instead of LDPC encoder to reduce the processing power. The OFDM PHY provides high performance in frequency selective fading channels to achieve maximum data rates. [1] All three have the same packet structure with Golay sequence as the preamble and uses same rate 3/4 LDPC structure for channel encoding. [2]

The control PHY uses basic modulation and coding scheme (MCS) 0 for management frames. The SC PHY uses MCS 1-12, low-power SC PHY uses MCS 25-31. To provide inter-operability between any two devices, MCS 1-4 are mandatory for all devices. In our thesis we use these MCS schemes. The OFDM PHY uses MCS 13-24, it is more complex and requires more power for processing compared to remaining two. In our thesis, we mainly focus on SC PHY and is discussed in chapter 2.

1.0.2 channels

This 802.11ad standard consists of 4 channels each having a bandwidth of 2.16 GHz. These bands are regulated differently in various countries. Channel-2 is available in all regions and is therefore used as the default channel. Channel-1 operates between 58.32 and 60.48 GHz , Channel-2 between 60.48 and 62.64 ,Channel-3 from 62.64 to 64.80 and Channel-4 from 64.80 to 65.96 GHz.

1.0.3 MAC layer

The standard supports contention based access periods(CBAP) and scheduled service periods(SP). Polling based service is used for scheduled service periods and CBAPs follow IEEE 802.11 enhanced distributed channel access (EDCA),which is similar to 802.11 DCF. To improve the performance of systems, relaying is enabled. For SPs, the standard defines two relaying strategies namely link forwarding and link switching. In our thesis we assume that the sector level sweep is already done, which means that the best transmit sector between transmitter and receiver is established. chapter 3 focuses on this.

Directional Communication

Directional communication uses beamforming to mitigate the effects of attenuation at 60GHz frequency. Beamforming indirectly refers to directional signal towards the intended user. The standard defines virtual antenna sectors that divides the antenna azimuth into several sectors. These sectors are implemented either by antenna weight vectors for a phased antenna array or by multiple directional antennas. Both cases ensure that the antenna height is less compared to 2.4 and 5 GHz band antennas. The Fig. 1.1 is redrawn from [2]. The Fig. 1.1 is an example for two nodes operating

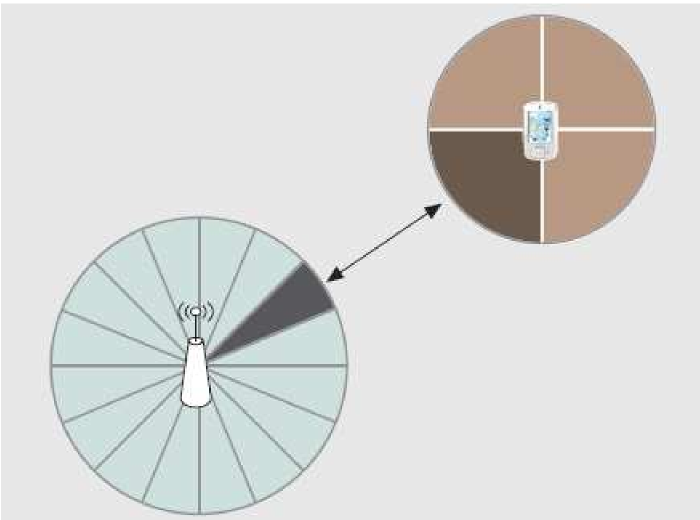

Figure 1.1: Example for Virtual antenna sectors

under virtual IEEE 802.11ad sectors. The thick sections of each node are in line of sight with respect each other and called best transmit sector with respect to other station.

Chapter 2

Modeling of Physical layer

In this chapter we analyze the performance of physical layer by taking a variant of SC PHY layer. The Fig. 2.1 gives an overview of all the blocks present in it.

First we take a stream of raw data bits(0's and 1's) and then we encode according to different code rates mentioned in the standard (i.e., 1/2, 3/4, 5/9, 13/16). We modulate these LDPC encoded bits with respect to corresponding modulation. Later, we add the channel which is AWGN. At the receiver we use either soft or hard decoder to get the actual data bits. If we consider hard decoder, first we need to demodulate the bits according to corresponding modulation and then we apply LDPC hard decoder. For soft decoder, the output of the soft decoder itself is the required actual raw data. We compare the resulted data bits with the raw data to find bit error rate(BER).

2.0.4 LDPC Encoder

LDPC codes discovered by Gallager in 1962 .An LDPC code is defined as null-space of parity check matrix. As the name suggests it has a parity matrix whose density is low. Here density means number of ones in each row or column. There are two kinds namely regular and irregular LDPC codes. In regular LDPC codes, the no.of ones in each row/column are less compared to the number of rows/columns in the matrix. In case of irregular codes, the no.of ones may vary.

For different code rates, the parity matrix will vary and the common code word size is 672 bits. For each code rate, H matrix is partitioned into square submatrices. These square submatrices are nothing but cyclic-permutations of identity matrix where the index is mentioned and null matrix.

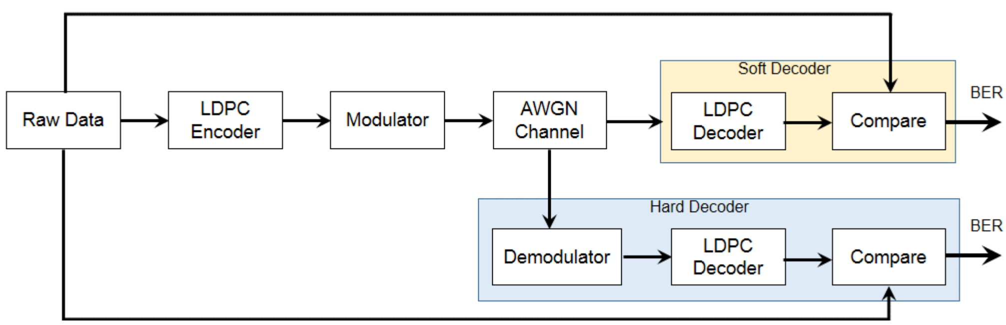

Figure 2.1: PHY block diagram

A location is indicated by an integer i denotes the cyclic-permutation of identity matrix by shifting the columns cyclically to the right by i elements. The parity matrices for all the code rates are taken from the standard [1].

An example for Z=3 is given by,

$$P_0 = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \quad P_1 = \begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ 1 & 0 & 0 \end{bmatrix} P_2 = \begin{bmatrix} 0 & 0 & 1 \\ 1 & 0 & 0 \\ 0 & 1 & 0 \end{bmatrix}$$

For rate 1/2 LDPC code, the H matrix is given by, where each index is having cyclic permutations of identity matrix of size 42x42 and H is 336x672.

$$\begin{pmatrix}
40 & & 38 & & 13 & & 5 & & 18 & & & & & & & \\
34 & & 35 & & 27 & & & 30 & 2 & 1 & & & & & & \\
 & 36 & & 31 & & 7 & & 34 & & 10 & 41 & & & & & \\
 & 27 & & 18 & & 12 & 20 & & & & 15 & 6 & & & & \\
35 & & 41 & & 40 & & 39 & & 28 & & & 3 & 28 & & & \\
29 & & 0 & & & 22 & & 4 & & 28 & & 27 & & 23 & & \\
 & 31 & & 23 & & 21 & & 20 & & & 12 & & & 0 & 13 & \\
 & 22 & & 34 & 31 & 14 & & 4 & & & & 13 & & 22 & & 24
\end{pmatrix}$$

For rate 5/8 LDPC code, the H matrix is given by

$$\begin{pmatrix}
20 & 36 & 34 & 31 & 20 & 7 & 41 & 34 & & 10 & 41 & & & & & \\
30 & 27 & & 18 & & 12 & 20 & 14 & 2 & 25 & 15 & 6 & & & & \\
35 & & 41 & & 40 & & 39 & & 28 & & & 3 & 28 & & & \\
29 & & 0 & & & 22 & & 4 & & 28 & & 27 & 24 & 23 & & \\
 & 31 & & 23 & & 21 & & 20 & & 9 & 12 & & & 0 & 13 & \\
 & 22 & & 34 & 31 & & 14 & & 4 & & & & & & 22 & 24
\end{pmatrix}$$

For rate 3/4 LDPC code, the H matrix is given by

$$\begin{pmatrix}
35 & 19 & 41 & 22 & 40 & 41 & 39 & 6 & 28 & 18 & 17 & 3 & 28 & & & \\
29 & 30 & 0 & 8 & 33 & 22 & 17 & 4 & 27 & 28 & 20 & 27 & 24 & 23 & & \\
37 & 31 & 18 & 23 & 11 & 21 & 6 & 20 & 32 & 9 & 12 & 29 & & 0 & 13 & \\
25 & 22 & 4 & 34 & 31 & 3 & 14 & 15 & 4 & & 14 & 18 & 13 & 13 & 22 & 24
\end{pmatrix}$$

For rate 13/16 LDPC code, the H matrix is given by

$$\begin{pmatrix}
29 & 30 & 0 & 8 & 33 & 22 & 17 & 4 & 27 & 28 & 20 & 27 & 24 & 23 & & \\
37 & 31 & 18 & 23 & 11 & 21 & 6 & 20 & 32 & 9 & 12 & 29 & 10 & 0 & 13 & \\
25 & 22 & 4 & 34 & 31 & 3 & 14 & 15 & 4 & 2 & 14 & 18 & 13 & 13 & 22 & 24
\end{pmatrix}$$

2.0.5 Modulator and AWGN Channel

This block modulates the LDPC coded bits into corresponding modulation scheme. Here we are considering BPSK, QPSK, 16-QAM and 64-QAM modulation schemes. The input to this block are 672 bits considering any rate encoder. The output of this block depends on modulation scheme. For

BPSK, the input and output bits are same. For QPSK, it makes half and for 16-QAM output is one fourth of the input bits and for 64-QAM, it makes one sixth.

Here we are also normalizing the symbol energy for each constellation. After calculating this normalized factor, we multiply each symbol by this to get the entire energy to be unity. For QPSK, the factor is $\frac{1}{\sqrt(2)}$. For 16-QAM it is $\sqrt(0.1)$ and for 64-QAM, the value is $\frac{1}{\sqrt(42)}$.

The channel is just an additive white gaussian noise channel and the factor we are varying is signal to noise ratio(SNR). For different SNRs, the channel effect is different. Better the SNR, better to decode so that the received signal contains less errors.

2.0.6 LDPC Decoder

Here we are having two kinds of decoders for decoding. They are Hard decision decoding and soft decision decoding. Hard decision decoder deals with the bit stream. This bit stream is obtained after demodulating the received signal. We consider bit flipping algorithm for hard decision decoding. Soft decision decoder takes probabilities or received signal strength as inputs and produce the data bits. For soft decision decoding we use sum product algorithm.

Bit Flipping Decoder

For Hard decision decoding, bit flipping algorithm is considered. This algorithm takes the demodulated bits from the demodulator. The steps involved in this algorithm are

1. Compute the syndrome $r * H^T$
2. If the syndrome vector is zero, the code word is without errors.
3. For each bit , compute the unsatisfied parity checks.
4. Flip the set of bits for which unsatisfied checks are more.
5. Compute the syndrome again, if it satisfies stop. otherwise repeat upto certain no. of times and declare as decode failure.

Sum Product Algorithm

The soft decision decoder used is sum product algorithm. It takes the received vector at the receiver and processes to get the codeword. It involves following steps. In the algorithm vertical nodes indicate columns of the parity matrix whereas the check nodes are the row elements of the parity matrix.

1. Initialization step to compute probabilities of received vector based on the noise distribution. AWGN is used to compute them. Initialize the measures which are going from check node to variable node and variable node to check node for both 0 and 1.
2. Horizontal step to calculate the responses from variable nodes to check nodes.
3. Vertical step to calculate the probabilities of bit 0 and bit 1. Depends on which one is bigger we choose that as the decoded bit.

BER Calculation

After retrieving the code word we will take the first few bits of 672 bits based on the code rate as data bits. After getting these data bits we compare them with raw data and count the number of errors obtained for the corresponding signal to noise ratio values. The results are given in the results section.

2.0.7 Results

The figures from 2.2 to 2.5 indicates the BER curves for all the four rates by taking hard bit flip algorithm for different SNR values. The figures from 2.6 to 2.9 indicates the BER curves for all the four rates by taking sum product algorithm for different SNR values.

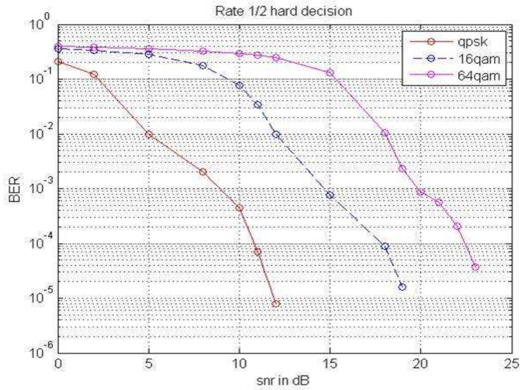

Figure 2.2: Rate 1/2 Hard

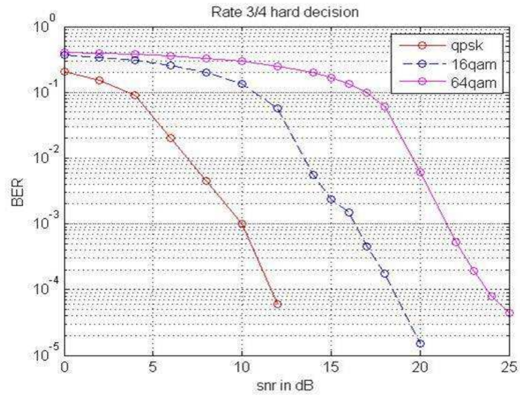

Figure 2.3: Rate 3/4 Hard

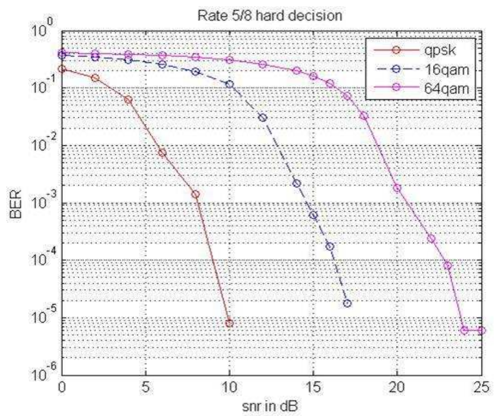

Figure 2.4: Rate 5/8 Hard

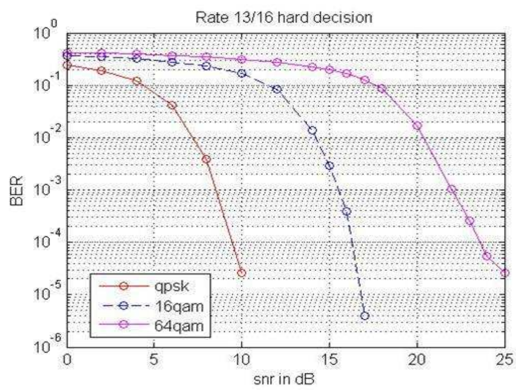

Figure 2.5: Rate 13/16 Hard

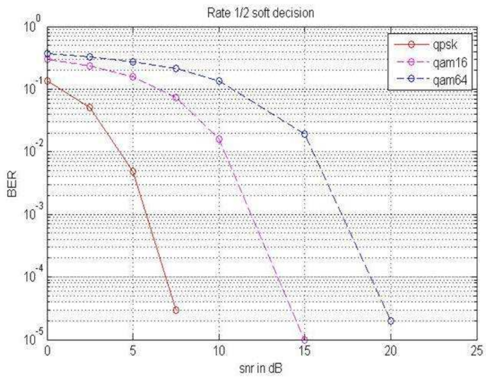

Figure 2.6: Rate 1/2 Soft

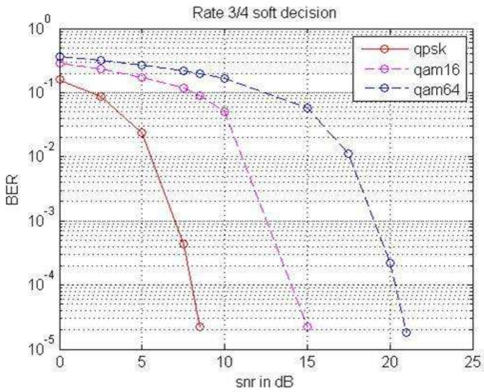

Figure 2.7: Rate 3/4 Soft

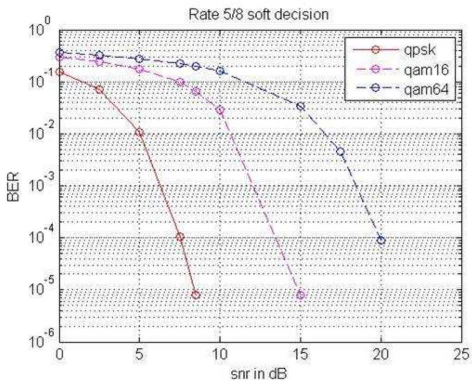

Figure 2.8: Rate 5/8 Soft

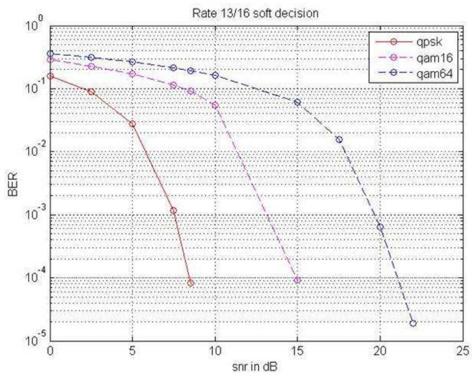

Figure 2.9: Rate 13/16 Soft

Chapter 3

MAC layer modeling

In this chapter we model the MAC protocol for directional cooperative MAC under imperfect channel conditions for a finite buffer. The system model is same as that of the one in [3].

3.0.8 system model

The system model considered is shown Fig. 3.1. A personal basic service set(PBSS) is situated at the center and all other stations are uniformly distributed in the radius of 10m. We assume that beamforming process is already done, which means that the best transmit sector between any two stations as shown in 1.1 is already established. The channel access from normal users to the access point is chosen in this thesis. We also assume that the signal strength in minor lobes of radiation pattern are neglected. The system model shown in Fig. 3.1 is redrawn from [3].

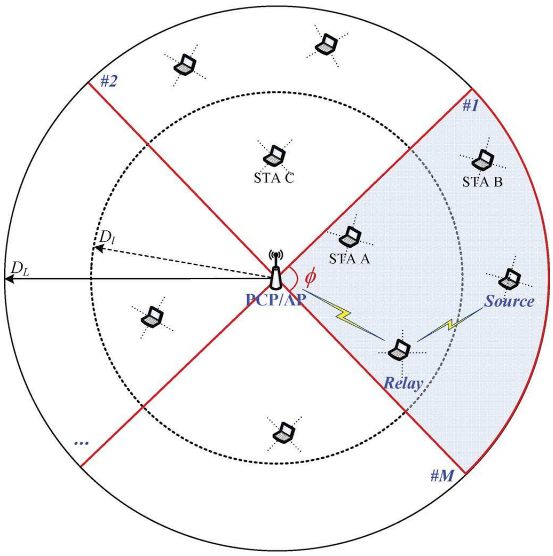

Figure 3.1: System model

3.0.9 IEEE 802.11ad MAC

IEEE 802.11ad MAC uses enhanced distribution channel access(EDCA) which is almost similar to distributed coordination function for 802.11 systems. This access uses four way handshaking mechanism which involves RTS, CTS, Data and ACK and an exponential backoff scheme to coordinate the channel access [5]. A sender which has packet to send initializes its backoff timer with a randomly selected value from the initial contention window size. Each time the sender senses the channel idle, it decrements this count by one and stuck at the particular value if the channel is busy. The procedure is resumed from the value where it has stuck when the channel is sensed idle and for busy cases. The channel sensing time is known as distributes inter frame space in this case. Whenever this value becomes zero, sender sends an RTS to the receiver. During this process all other stations will defer their transmission and suspends their backoff window. Upon receiving RTS from the sender, receiver will send DMG CTS to the sender. If RTS transmission is failed, the sender repeats the above exponential backoff process. Now, the contention window size is doubled and the process is same. If W_0 is the intial contention window size, then the value for the i^{th} stage is given as $2^i W_0$. This doubling of contention window size is stopped when it reaches maximum contention window size W_{max}. After that W_{max} is used for the stages upto a maximum retry limit. Even after the maximum retry limit stage the channel is not idle, it drops the packet. After receiving DMG CTS from the receiver, the sender starts transmitting the data packet to the receiver. Upon receiving data from sender, receiver sends an ACK saying that the transmission is successful.

3.0.10 Metric for choosing relay

We will choose a station as relay when the path through relay performs better in terms of data rate than the direct link. A metric W is used to choose a relay and is given by

$$W = \frac{R_c^{-1}}{R_a^{-1} + R_b^{-1}} \tag{3.1}$$

Where R_c is the data rate for the direct link, R_a is the data rate between source station and relay station and R_b is the data rate for between relay and access point direct link. This metric is same as the one used in [3]. After calculating these metrics for all the other stations with respect to source station, we will choose the some station as relay for which this metric is maximum compared to all other stations metrics.

3.0.11 Directional cooperative MAC

It defines two access modes for channel access, namely basic access and relay mode. The timing diagrams for both basic access scheme and relay based access mode are redrawn from [3]. The basic access scheme is used when no relay station is present for source station and relay based access mode is used when a source has a relay to transmit.

The basic access scheme is same as that of the one explained in IEEE802.11ad MAC. Any station which has packet to send first goes into backoff process and sends an RTS whenever the backoff counter becomes zero. The AP waits for a short period of time known as short inter frame space to send the DMG CTS. After receiving DMG CTS, the sender transmits its data to the AP.

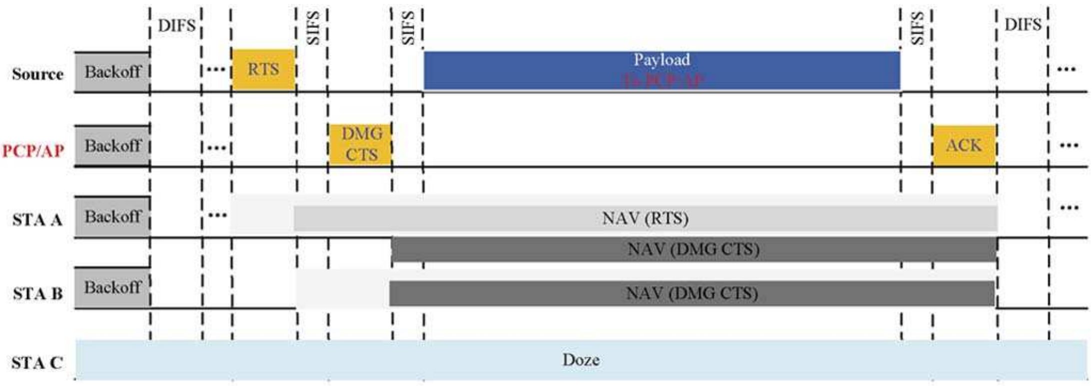

Figure 3.2: Basic Access mode

here

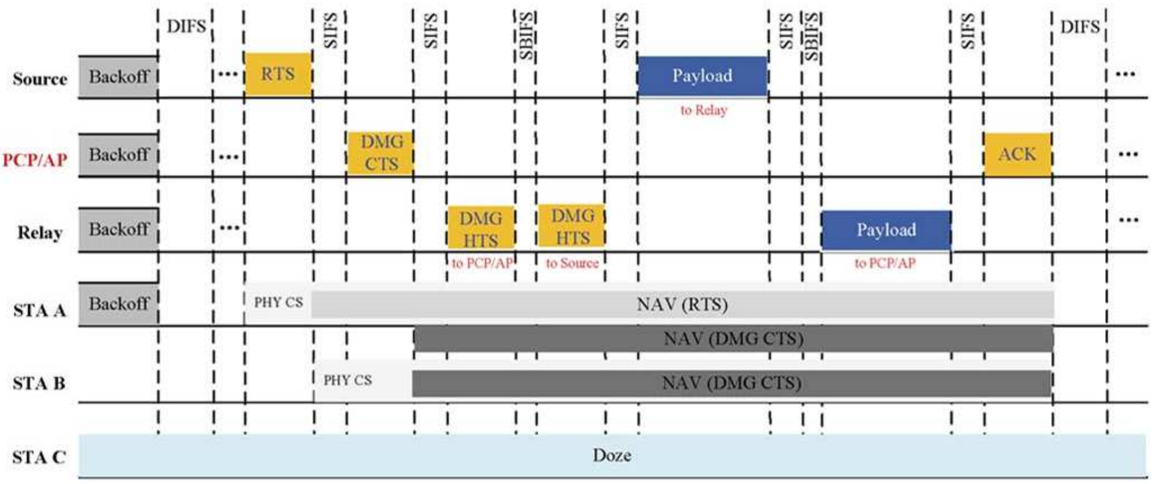

Figure 3.3: Relay based access mode

Upon successful data transmission, the AP responses with an acknowledgement(ACK). Next, the station which has its backoff counter becomes zero and enters into transmission mode.

In case of relay based access mode, the relay uses an help to send packet between both source and access point. Referring to Fig. 3.3, upto DMG CTS from the access point is same for both access schemes. The relay also hears the DMG CTS packet and it prepares an HTS packet for both source and AP. It sends HTS packet to AP and waits for short period known as short beamforming inter frame space(SBIFS) to send it to the source station. This SBIFS is used at the relay to switching the antenna properties of the relay to accommodate the directional communication. When the AP and source station knows about the relay, the source station first sends the data to relay station and waits for SBIFS time to change direction towards AP. In the next slot it sends the data to Access point. After successfully receiving the data at the AP, AP sends an ACK to the source station.

3.0.12 Directional Hidden Terminal Problem

As shown in Fig. 3.4, we divide the whole sector into four regions based on their interference effect with the source station. The stations in Region I are hidden terminal nodes to source station because they do not know about the transmission happening between source station and AP. And also the source station does not know about transmissions of stations located in Region I. Similarly stations in Region II are hidden node terminals to source station but the source station is not an hidden terminal node for the stations in Region II. For region III, source station is hidden terminal, which means that stations in Region I and III are interfering stations for source station. Stations in Region IV are not hidden node terminals. So, the stations in Region II and Region IV are interfering stations to source station.

Based on the radiation pattern of the source station, the equations for ellipses are calculated. With the available given coordinates of the stations in sector, we can simply substitute their coordinates into these ellipse equations and line equations of the sector originating from the source station. When the values given are greater than zero for every equation, it means that they are outside upper side of that region. Likewise we will calculate the regions of all other stations with respect to source station. The Fig. 3.4 is the same model used in [3].

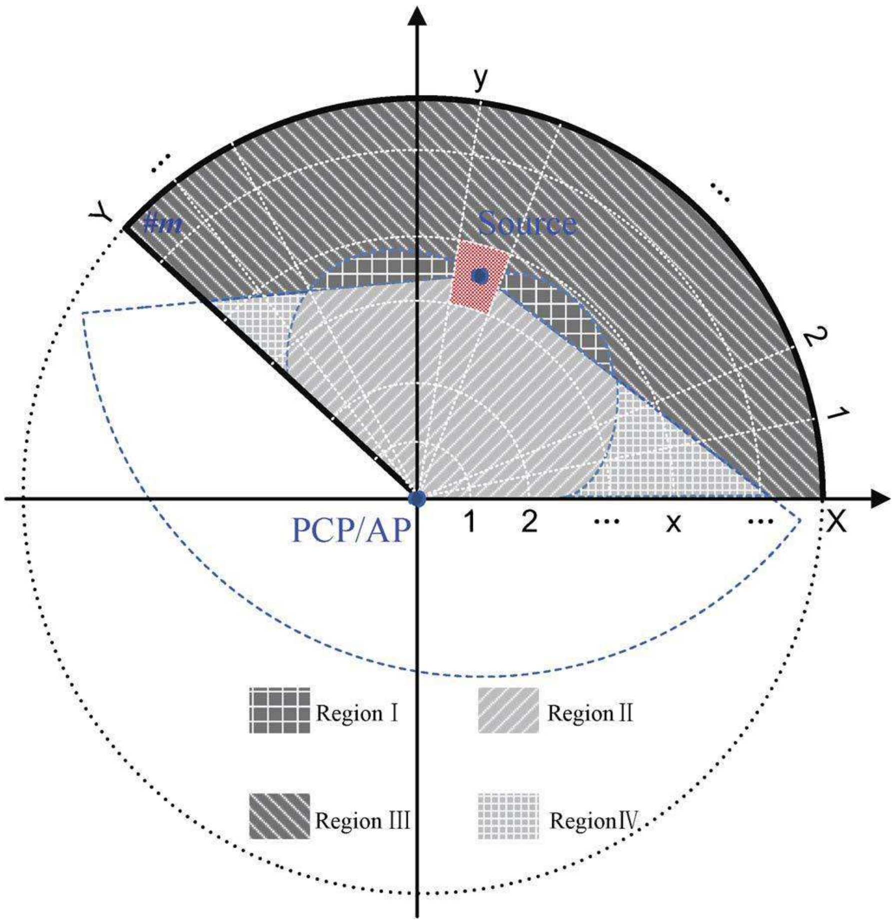

Figure 3.4: Directional Hidden Terminal Problem

3.0.13 Markov Chain Model for Packet Transmission Probability

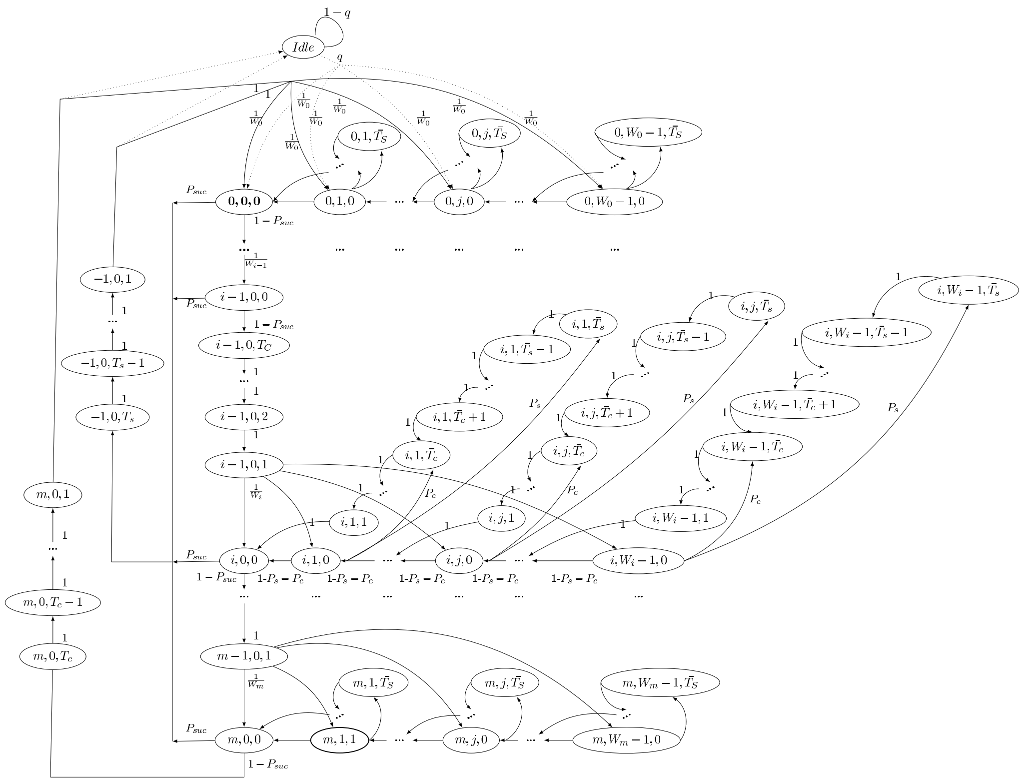

Figure 3.5: flowgraph

A station having a packet to transmits continuously and monitors the channel availability. If the channel is sensed idle for a period of time equal to a distributed interframe space (DIFS), the station transmits. Otherwise, if the channel is sensed busy, the station persists to monitor the channel until it is measured idle for a DIFS. At this point, the station generates a random backoff interval before transmitting (this is the collision avoidance feature), to minimize the probability of collision with packets being transmitted by other stations ‘[5].

At each packet transmission, the backoff time is uniformly chosen in the range $(0, W_i - 1)$. The value is called contention window, and depends on the number of transmissions failed for the packet. At the first transmission attempt,W_i is set equal to a value called minimum contention window W_0. After each unsuccessful transmission, W_i is doubled, up to a maximum value[5].

Here, $W_{max} = 2^d W_0$ is a constant value; thus, we have $W_i = max(2W_i - 1, W_{max})$, $i[1, m]$, where W_0 is the initial backoff window size, and m is the maximum retry limit for dropping a packet [3].

The non-null one-step transition probabilities shown in Fig.3.5 are given by

$$P(i, j, \bar{T}_s | i, j, 0) = P_s, i\epsilon[0, m] \; and \; j\epsilon[1, W_i - 1] \tag{3.2}$$

The equation (3.2) accounts for the fact that, hearing other stations success with a probability P_s.

$$P(i, j, \bar{T}_c | i, j, 0) = P_c, i\epsilon[0, m] \; and \; j\epsilon[1, W_i - 1] \tag{3.3}$$

The above equation (3.3) accounts for the fact that, hearing two or more of other stations are colloiding and their transmission with probability P_c.

$$P(i, j, k - 1 | i, j, k) = 1, i\epsilon[0, m] \;, j\epsilon[1, W_i - 1] \; and \; k\epsilon[2, \bar{T}_s] \tag{3.4}$$

The equation (3.4) accounts for the fact that, after hearing other stations success or collision, it enters a backoff of residual time, the residual backoff time is decremented.

$$P(i, j - 1, 0 | i, j, 1) = 1, i\epsilon[0, m] \; and \; j\epsilon[1, W_i - 1] \tag{3.5}$$

In equation 3.5, Once the residual backoff timer k becomes zero, it decrements the backoff counter j by one.

$$P(i, j - 1, 0 | i, j, 0) = 1 - P_s - P_c, i\epsilon[0, m] \; and \; j\epsilon[1, W_i - 1] \tag{3.6}$$

The equation 3.6 accounts for decrementing backoff counter by taking both success and collision from other stations into consideration.

$$P(i, 0, T_c | i, 0, 0) = 1 - P_{suc}, i\epsilon[0, m] \tag{3.7}$$

The above equation (3.7) tells that U_1's transmission collides with other transmissions.

$$P(-1, 0, T_s | i, 0, 0) = P_{suc}, \; i\epsilon[0, m] \tag{3.8}$$

Equation 3.8 shows that U_1's packet is successfully transmitted with probability P_{suc} given that U_1's backoff timer reaches 0.

$$P(-1, 0, k - 1 | -1, 0, k) = 1, \; k\epsilon[2, T_s] \tag{3.9}$$

In equation 3.9, when a packet transmitted successfully from U_1', it enters a residual backoff stage to decrement upto zero from T_s.

$$P(i, 0, k - 1 | i, 0, k) = 1, i\epsilon[0, m] \; and \; k\epsilon[2, T_c] \tag{3.10}$$

In equation 3.10, when a packet collision occurs at U_1', it enters a residual backoff stage to decrement upto zero from T_c.

$$P(i, j, 0 | i - 1, 0, 1) = \frac{1}{W_i}, i\epsilon[1, m] \; and \; j\epsilon[0, W_i - 1] \tag{3.11}$$

In equation 3.11, when the channel is not idle, U_1' doubles the backoff window size to retransmit and enters any of the states.

NOTE that equations from (3.6) to (3.11) are similar to the equations in [3].

After maximum backoff stage, the station re-enters into initial backoff stage if at least one packet is available in the buffer. Otherwise, it enters into Idle state.

NOTE::Equations (3.8) and (3.9) are similar to the ones in [3].

$$P(0,j,0|-1,0,1) = \frac{q}{W_0},\ j\epsilon[0, W_0-1] \tag{3.12}$$

Equation (3.12) indicates that atleast one packet is available in the buffer after the successful transmission.

$$P(0,j,0|m,0,1) = \frac{q}{W_0},\ j\epsilon[0, W_0-1] \tag{3.13}$$

Equation (3.13) indicates that atleast one packet is available in the buffer after the maximum backoff stage is reached.

$$P(0,j,0|-1,-1,-1) = \frac{q}{W_0},\ j\epsilon[0, W_0-1] \tag{3.14}$$

Equation (3.14) gives the probability of choosing any of the states in initial backoff stage from the idle state.

$$P(-1,-1,-1|-1,-1,-1) = 1-q \tag{3.15}$$

Equation (3.15) gives the probability of staying in the Idle(-1,-1,-1) state until it gets the packet to transmit.

Equation (3.14) gives the probability of choosing any of the states in initial backoff stage from the idle state.

$$P(-1,-1,-1|-1,0,1) = (1-q),\ i\epsilon[0,m] \tag{3.16}$$

Equations (3.16) indicates the transition to Idle(-1,-1,-1) state after the successful transmission.

$$P(-1,-1,-1|m,0,1) = (1-q),\ i\epsilon[0,m] \tag{3.17}$$

Equations (3.17) indicates the transition to Idle(-1,-1,-1) state after maximum backoff stage is reached.

$$Let\ b_{i,j,k} = \lim_{x\to\infty} P(s(t)=i, b(t)=j, v(t)=k)\ be\ the\ steady-state\ probability.$$

First, we note the following relations,

$$b_{i,0,0} = (1-P_{suc})^i b_{0,0,0},\ i\epsilon[0,m] \tag{3.18}$$

The stationary probability to be in Idle(-1,-1,-1) state can be evaluated as follows

$$b_{-1,-1,-1} = (1-q)P_{suc}\sum_{i=0}^{m} b_{i,0,0} + (1-q).b_{-1,-1,-1} \tag{3.19}$$

Upon simplifying...

$$b_{-1,-1,-1} = \frac{(1-q)}{q}P_{suc}\sum_{i=0}^{m} b_{i,0,0} \tag{3.20}$$

The other stationary probabilities for any $j\epsilon[1, W_i - 1]$ follow by resorting to state diagram:

$$b_{i,j,k} = P_s b_{i,j,0}, i\epsilon[0, m], j\epsilon[1, W_i - 1] \; and \; k\epsilon[\bar{T}_c + 1, \bar{T}_s] \tag{3.21}$$

$$b_{i,j,k} = (P_s + P_c) b_{i,j,0}, i\epsilon[0, m], j\epsilon[1, W_i - 1] \; and \; k\epsilon[1, \bar{T}_c] \tag{3.22}$$

$$b_{-1,0,k} = \sum_{i=0}^{m} P_{suc} b_{i,0,0}, k\epsilon[1, T_s] \tag{3.23}$$

$$b_{i,0,k} = (1 - P_{suc}) b_{i,0,0}, i\epsilon[0, m], k\epsilon[1, T_c] \tag{3.24}$$

$$b_{i,j,0} = \frac{W_i - j}{W_i} b_{i,0,0} + q b_I, i\epsilon[0, m] \; and \; j\epsilon[1, W_i - 1] \tag{3.25}$$

NOTE::Equations (3.21) to (3.24) are same as that of in [3]. Equations (3.25) is affected by Idle(-1,-1,-1) state.

Employing normalization condition,We have:

$$1 = \sum_{k=1}^{T_s} b_{-1,0,k} + \sum_{i=0}^{m} \sum_{k=0}^{T_c} b_{i,0,k} + \sum_{i=1}^{m} \sum_{j=1}^{W_i - 1} \sum_{k=0}^{\bar{T}_s} b_{i,j,k} + \sum_{j=1}^{W_i - 1} \sum_{k=0}^{\bar{T}_s} q b_{-1,-1,-1} + b_{-1,-1,-1}, \tag{3.26}$$

$$\begin{gathered} \sum_{k=1}^{T_s} b_{-1,0,k} = \sum_{k=1}^{T_s} \sum_{i=0}^{m} P_{suc} b_{i,0,0} \\ \text{which becomes,} \sum_{k=1}^{T_s} b_{-1,0,k} = P_{suc} T_s \sum_{i=0}^{m} b_{i,0,0} \end{gathered} \tag{3.27}$$

$$\begin{gathered} \sum_{i=0}^{m} \sum_{k=0}^{T_c} b_{i,0,k} = \sum_{i=0}^{m} \sum_{k=1}^{T_c} ((1 - P_{suc}) b_{i,0,0} + b_{i,0,0}) \\ \text{which becomes,} \sum_{k=1}^{T_s} b_{i,0,k} = (1 - P_{suc}) T_c \sum_{i=0}^{m} b_{i,0,0} + \sum_{i=0}^{m} b_{i,0,0} \end{gathered} \tag{3.28}$$

$$\sum_{i=0}^{m} \sum_{j=1}^{W_i - 1} \sum_{k=0}^{\bar{T}_s} b_{i,j,k} = \sum_{i=0}^{m} \sum_{j=1}^{W_i - 1} \sum_{k=1}^{\bar{T}_c} (P_s + P_c) b_{i,j,0} + \sum_{i=0}^{m} \sum_{j=1}^{W_i - 1} \sum_{\bar{T}_c + 1}^{\bar{T}_s} P_s b_{i,j,0} + \sum_{i=0}^{m} \sum_{j=1}^{W_i - 1} b_{i,j,0} \tag{3.29}$$

$$\sum_{i=0}^{m} \sum_{j=1}^{W_i - 1} \sum_{k=0}^{\bar{T}_s} b_{i,j,k} = \sum_{i=0}^{m} \sum_{j=1}^{W_i - 1} (P_s \bar{T}_c + P_c \bar{T}_c + P_s (\bar{T}_s - \bar{T}_c) b_{i,j,0} + \sum_{i=0}^{m} \sum_{j=1}^{W_i - 1} b_{i,j,0} \tag{3.30}$$

$$\sum_{i=0}^{m} \sum_{j=1}^{W_i - 1} \sum_{k=0}^{\bar{T}_s} b_{i,j,k} = \sum_{i=0}^{m} \sum_{j=1}^{W_i - 1} (P_c \bar{T}_c + P_s \bar{T}_s + 1) b_{i,j,0} \tag{3.31}$$

Substituting (3.25) in 3.31, we get

$$\sum_{i=0}^{m}\sum_{j=1}^{W_i-1}\sum_{k=0}^{\bar{T}_s} b_{i,j,k} = (P_c\bar{T}_c + P_s\bar{T}_s + 1)\sum_{i=0}^{m}\sum_{j=1}^{W_i-1}(\frac{W_i-1}{2}b_{i,0,0} + (W_i-1)qb_{-1,-1,-1}) \tag{3.32}$$

Substituting (3.20) in 3.32, we get

$$\sum_{i=0}^{m}\sum_{j=1}^{W_i-1}\sum_{k=0}^{\bar{T}_s} b_{i,j,k} = \frac{W_i-1}{2}\sum_{i=0}^{m}(P_c\bar{T}_c + P_s\bar{T}_s + 1 + 2(1-q)P_{suc})b_{i,0,0} \tag{3.33}$$

$$1 = \sum_{i=0}^{m} b_{i,0,0}(P_{suc}T_s+1+(1-P_{suc})T_c+\frac{1-q}{q}P_{suc}+\frac{(W_i-1)}{2}(P_s\bar{T}_s+2(1-q)P_{suc}\bar{T}_s+P_c\bar{T}_c+1)) \tag{3.34}$$

$$1 = \sum_{i=0}^{m} b_{i,0,0}(P_{suc}T_s + 1 + (1-P_{suc})T_c + \frac{1-q}{q}P_{suc}) + (P_s\bar{T}_s + 2(1-q)P_{suc}\bar{T}_s + P_c\bar{T}_c + 1)\times$$

$$\left\{\sum_{i=0}^{d}\frac{W_i}{2}b_{i,0,0} + \sum_{i=d+1}^{m}\frac{W_i}{2}b_{i,0,0} - \frac{1}{2}\sum_{i=0}^{m}b_{i,0,0}\right\} \tag{3.35}$$

substituting (3.18) into (3.0.13), we have

$$1 = \sum_{i=0}^{m} b_{i,0,0}(P_{suc}T_s + 1 + (1-P_{suc})T_c + \frac{1-q}{q}P_{suc}) + (P_s\bar{T}_s + 2(1-q)P_{suc}\bar{T}_s + P_c\bar{T}_c + 1)\times$$

$$\left\{\sum_{i=0}^{d}2^iW_0(1-P_{suc})^ib_{0,0,0} + \sum_{i=d+1}^{m}2^dW_0(1-P_{suc})^ib_{0,0,0} - \frac{1}{2}\sum_{i=0}^{m}(1-P_{suc})^ib_{0,0,0}\right\} \tag{3.36}$$

Upon simplifying..

$$\begin{aligned} b_{0,0,0} = &\left\{ \frac{1-(1-P_{suc})^{H+1}}{P_{suc}} \times [P_{suc}(T_s-T_c) + T_c + 1 + \frac{1-q}{q}P_{suc}] \right. \\ &+ \langle P_c\bar{T}_c + (P_s + 2P_{suc} - 2qP_{suc})\bar{T}_s + 1\rangle \\ &\left. \times\left\{W_0[2^d(1-P_{suc})^{d+1}\ \frac{1-(1-P_{suc})^{H-d}}{P_{suc}} + \frac{1-[2(1-P_{suc})]^{d+1}}{2P_{suc}-1}] - \frac{1-(1-P_{suc})^{H+1}}{2P_{suc}}\right\}\right\}^{-1} \end{aligned} \tag{3.37}$$

we have

$$\tau = \sum_{i=0}^{m} b_{i,0,0} = \frac{1-(1-P_{suc})^{H+1}}{P_{suc}}b_{0,0,0} \tag{3.38}$$

The above equation is for packet transmission probability τ at U_1 for each time slot, occuring when U_1's backoff timer reaches zero considering the finite buffer which means at the time transmission the station is not having the packets to send every time. P_s in Equation. 3.37 is the sender station hearing success from other stations and is given by

$$P_s = \sum_{u=2}^{n} \tau_u P_{suc,u} \tag{3.39}$$

P_c in Equation. 3.37 is the sender station hearing collision from other stations and is given by,

$$P_c = 1 - P_s - \prod_{u=2}^{n} (1 - \tau_u) \tag{3.40}$$

T_c is the packet collision duration and is given by,

$$T_c = RTS + SIFS + CTS + DIFS \tag{3.41}$$

T_s is the packet successful transmission duration and is different for different modes,

$$\begin{aligned} T_s{}^{basic} &= RTS + 3SIFS + CTS + DATA^{basic} + ACK + DIFS \\ T_s{}^{coop} &= RTS + 5SIFS + CTS + 2HTS + 2SBIFS + DATA^{coop} + ACK + DIFS \end{aligned} \tag{3.42}$$

$$\begin{aligned} DATA^{basic} &= (H_{PHY} + H_{MAC} + E[P])/(R_{c,1}\sigma) \\ DATA^{coop} &= (H_{PHY} + H_{MAC} + E[P]) \times (1/R_{a,1} + 1/R_{b,1})/\sigma \end{aligned} \tag{3.43}$$

$\bar{T}_s$ and T_c are the average success duration and collision duration.

$$\bar{T}_c = 1.5RTS + DIFS \tag{3.44}$$

3.0.14 Packet Transmission Process Under D-CoopMAC Protocol

The packet successful transmission probability P_{suc1} is same as that of P_{suc} in [1].

$$P_{suc} = P_{e1} * p_{e2} * p_{e3} \tag{3.45}$$

where p_{e1} is the probability of None of the other STAs U_us (u = 2, . . . , n) located in Region I, II, III, or IV intend to transmit its RTS exactly at the same time slot t0 with U_1s RTS and is given by

$$p_{e1} = \prod_{u=2}^{n} (1 - \tau_u) \tag{3.46}$$

where p_{e2} is the probability of None of the U_us located in the Region I or II start RTS within the period of $[t0 - Tv, t0)$, where $Tv = RTS + SIFS$ and is given by

$$p_{e2} = \prod_{u \epsilon N_{I,U_1} or N_{II,U_1}}^{n} (1 - \tau_u)^{T_v} \tag{3.47}$$

where p_{e3} is the probability of None of the U_us located in Region I or III start its RTS within the period of (t0, Tv] before the PCP/AP replies a DMG CTS to U_1 and is given by

SC Phy header	64 bits
MAC header	320 bits
Payload	1000 bits
RTS	160 bits + SC Phy header
DMG CTS	208 bits + SC Phy header
ACK	112 bits + SC Phy header
SIFS	3μs
DIFS	13μs
Slot time	5μs

Table 3.1: system configuration

MCS	1	2	3	4
R_l(Mbps)	385.5	770	962.5	1155
D_l(m)	10	8.92	7.08	6.31

Table 3.2: MCS and data transmission ranges

$$p_{e3} = \prod_{u \epsilon N_{I,U_1} or N_{III,U_1}}^{n} (1-\tau_u)^{T_v} \quad (3.48)$$

3.0.15 Calculation of Throughput for Unsaturated network

Throughput S for unsaturated case is given by ,

$$S = \sum_{n=1}^{N} P_r(n) \sum_{u=1}^{n} \tau_u P_{suc,u} E[p]/\sigma \quad (3.49)$$

where $P_r(n)$ is the probability for beam sector m containing n stations and is given by

$$P_r(n) = \binom{N}{n} (\frac{1}{M})^n (1-\frac{1}{M})^{N-n} \quad (3.50)$$

Where τ_u is the transmission probability for a station U under unsaturated network conditions and is given in equation. 3.38, $P_{suc,u}$ is the probability of successful transmission for station U, $E[p]$ is the payload size and σ is the slot time given in table(refer table of parameters).

3.0.16 Results

The parameters used for simulations are given in Table. 3.1 and the data rates related to station's distance are available in Table. 3.2

For the Fig. 3.6 the beam sectors are varying between 3 and 12 and the no.of stations are fixed and are 20. For the Fig. 3.7 the beam sectors are constant and are 3 and the no.of stations are varying between 2 and 20.

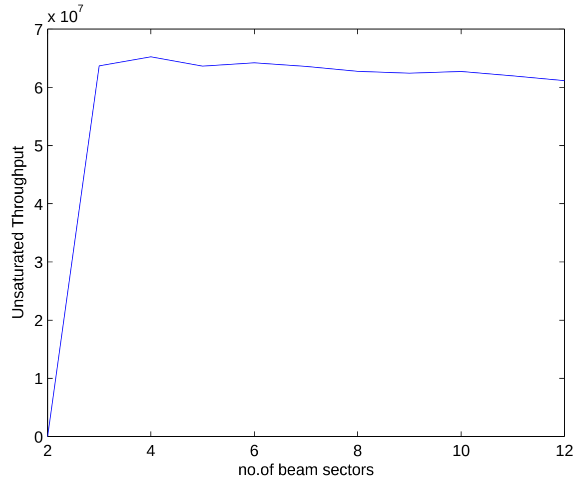

Figure 3.6: Unsaturated Throughput versus no.of beam sectors

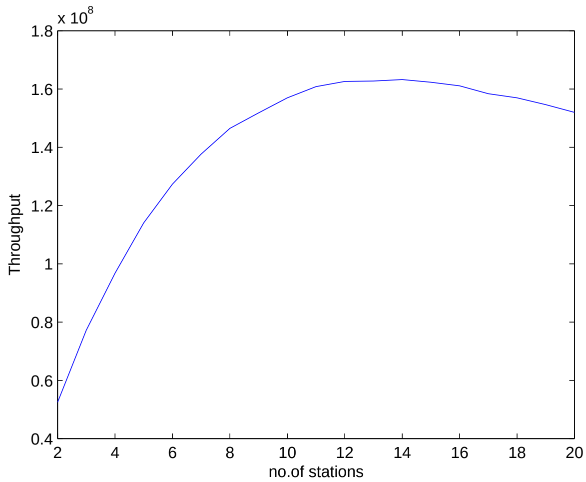

Figure 3.7: Unsaturated Throughput versus no.of stations

References

[1] Wireless LAN medium access control (MAC) and physical layer (PHY) specifications, “AMENDMENT 3: Enhancements for very high throughput in the 60 GHz band (adoption of IEEE Std 802.11ad-2012).”

[2] Thomas Nitsche, Carlos Cordeiro, Adriana B. Flores, Edward W. Knightly, Eldad Perahia,and Joerg C. Widmer, “IEEE 802.11ad: Directional 60 GHz Communication for Multi-Gigabit-per-Second Wi-Fi.”

[3] Qian Chen,David Chong wong,Xiaoming Peng, “Directional cooparative MAC protocol design and performance of IEEE802.11ad WLANs.”

[4] C. Hemanth, T.G. Venkatesh, “Performance analysis of contention-based access periods and service periods of 802.11ad hybrid medium access control.”

[5] Bianchi, “Performance Analysis of the IEEE 802.11 Distributed Coordination Function.”

[6] ZHANG Haitao, ZHANG Xiaomin, CHEN Gaoming,“Performance Analysis of IEEE802.11 DCF in Non-saturated Conditions.”