# Optimal Throughput Analysis for Indoor Multi-Hop Wireless Networks in IEEE 802.11n

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*Abstract*—**The IEEE 802.11 WiFi standard has been widely used in wireless local area networks (WLAN), which specifies an over-the-air interface between wireless clients and access point or between two wireless clients. With the recent development of multiple-input multiple-output (MIMO) systems at the physical (PHY) layer and frame aggregation at the medium access control (MAC) layer, the IEEE 802.11n standard provides the fastest data rates and larger coverage areas in different environments. However, as wireless network proliferates in indoor environments specially homes, the network topology has evolved from simple single access point-based network into more complex multi-hop topologies. This paper deals with the study of throughput delivered to end terminals in a WiFi indoor environment, when additional relays or extenders are placed between the router and the clients to develop a multi-hop system. It is proposed that there are certain optimal locations where the extenders can be placed to give optimal throughput and coverage in wireless home environments.**

## I. Introduction

With the advent of IEEE 802.11 a/b/g standards, the wireless local area networks (WLANS) are capable of providing throughput in tens of megabits per second to wireless clients while keeping reasonable connectivity. However, the sophisticated methodologies of having multiple antennas on a radio not only extend the coverage and reliability of data transmission but also increase the throughput in these wireless systems. The former is achieved by maximal ratio combining (MRC) in multiple input multiple-output (MIMO) systems while the latter can be achieved using spatial multiplexing (SP) [1], both of which are standardized in the specifications of IEEE 802.11n [2-3]. Hence the combination of MIMO and orthogonal frequency division multiple access (OFDM) at the physical layer (PHY) of IEEE 802.11n specifies the bit rates up to 600 Mbps, while the frame aggregation at the medium access control (MAC) layer reduces the transmission times for preambles and frame headers while reducing the waiting times during CSMA-CA (Carrier Sense Multiple Access- Collision Avoidance) random back off period for successive frame transmissions. With these improvements, most wireless networks nowadays use IEEE 802.11n WiFi specifications while maintaining compatibility to a/b/g specifications.

The basic dilemmas in WLAN are drop in throughput, insufficient coverage, and/or the presence of dead spots where the transmitted signal from the transmitter or wireless router cannot reach the desired destination or client. Assuming no radio frequency (RF) interference, this may occur due to numerous phenomenons including multipath fading, antenna correlation, Doppler effects, shadowing, and path loss etc [5]. The problem can be alleviated by transmitting the signal at a higher transmit power; however the radio's transmit power is capped by the IEEE 802.11 specifications. A viable solution for this problem is to use multi-hop communication where the transmitted packet can be delivered to the destination by hopping using multiple radios [9]. The advantages of using multi-hop communication are two-fold, 1) an increased throughput for the clients when the extenders are placed at *optimal locations*, 2) the range extension without increasing the transmit power of individual radios [10]. Because of the half-duplex nature of wireless radios, a bandwidth penalty affects the throughput performance; however, it is shown that the multi-hop communication outperforms single link communication if these extenders are optimally placed between the access points and the clients.

In this paper, we propose solutions to identify the optimal extender location in a wireless multi-hop network operating under IEEE 802.11n standard for indoor home environments. There are many ways of characterizing the throughput of the network for this multi-hop system, e.g., by using capacity analysis or by using probabilistic methods to find the net throughput. However, to keep the study simple, we use the deterministic analysis of link budget to characterize the performance of the system with path loss as the main channel impairment. In our study, we assume that all the radios are equipped with a 3x3 MIMO configuration with various adaptive coding and modulation schemes, which depends on wireless links between them. We characterize the performance of the system in terms of MAC layer throughput while taking into account the basic distribution coordination function (DCF) of IEEE 802.11 WiFi specification [3]. We show various factors that impact the placements of extenders at different locations, which impact the range and throughput of the system. We also derive some heuristics from a user perspective when an extender deployment is made in indoor environments such as homes.

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The rest of the paper is organized as follows. In the next section, we briefly describe the specifications of IEEE 802.11n PHY and MAC layer and the parameters we have used to obtain our simulation results. In Section III, we give various factors that impact the extender placement and when and how to place the extender to get optimal throughput in wireless networks. Section IV deals with some simple tests that can help a user to deploy extender(s) in home environments. The paper then concludes in Section V.

## II. MODEL DESCRIPTION

In this section, we provide an overview of the IEEE 802.11n PHY and MAC layer mechanisms, which are used in calculating the throughput of a wireless network. We assume that there is one transmitter and a single receiver, hence a single-link or one-hop communication is considered. We also describe the parameters that we have used and the link budget model for calculating the connectivity and data rates at the PHY layer.

### A. PHY Layer Parameters and Link Budget Equation

A link budget equation specifies all the gains and the losses from the transmitter, through the medium, to the receiver in any communication system. In general, the received power (in dBm) at a distance $d$ from the base station is given as

$$P_r = P_t + gains - losses - PL. \quad (1)$$

$P_r$ is the received power in dBm and $P_t$ is the transmitted power. The path loss $PL$ describes the loss due to distance between the transmitter and the receiver. In IEEE 802.11n, the allocated maximum power for the transmitter varies between 10-20 dBm.

An appropriate reference for the channel models is [4]. The proposed model is based on empirical data obtained from different experiments carried out to observe the power levels in indoor environments and various results for power loss in dB versus the distance are studied. Measurements are usually specified as line-of-sight (LOS) or non-LOS. The exact value of the distance exponent, which was chosen as 3.5 in this case for NLOS, varies widely depending on the building construction, but 3.5 is a representative value from the large body of results. Similar analysis has been done in [5] and has found the aggregate penetration loss in indoor environments, which varies from 10-22 dB [6].

The deterministic path loss model is given as $PL = 10n\log(d)$, where $n$ is the path loss exponent and $d$ is the transmitter-receiver (TR) separation. Hence the received power at a distance $d$ is given as

$$P_r = P_t + G_t - 10n\log(d) + 20\log(\lambda/4\pi) - APL, \quad (2)$$

where λ is the wavelength at the IEEE 802.11 specified frequency, which is either 2.4 GHz or 5 GHz, $G_t$ is the antenna gain, and $APL$ is the aggregate penetration loss. The values of the parameters assumed throughout this paper for calculation purposes and in the simulation results are given in Table 1.

At the receiver side, the received signal is assumed to be decoded correctly when the received power is greater than or equal to the modulation-dependent threshold. In our deterministic model, when the value of $P_r$ from (2) exceeds the specified threshold, the packet is assumed decoded.

TABLE 1
PHY LAYER PARAMETERS FOR INDOOR WLAN

| Parameters | Values |
|---|---|
| Tx Power | 40mW = 16.02 dBm |
| Frequency | 5GHz |
| Bandwidth | 40MHz |
| Path loss exponent | 3.42 |
| APL | 15 dB |
| Antenna Gain | 4.8 dBi |

IEEE 802.11n specifies different modulation and coding schemes (MCS) at the PHY layer with different MIMO configurations [3]. The model uses a 3x3 MIMO system operating at MCS 16-23 depending upon corresponding receiver sensitivity values as shown in Table 2. In this study, we consider the 800 ns guard band interval for the OFDM symbols transmission, which delivers a maximum data rate of 405 Mbps at MCS 23, however the results can be easily generalized to short guard band interval (400ns), which delivers a maximum data rate of 450 Mbps for the same MCS.

### B. MAC Layer Paramteres

We analyze the throughput of IEEE 802.11n under the basic distributed coordination function (DCF) without the handshaking protocol (RTS/CTS) [7-8]. We assume the maximum throughput scenario when an access point (AP) has always frames backlogged to be transmitted to the other terminal or relay. The frame aggregation at the MAC layer can be performed either by MAC protocol data unit aggregation (A-MPDU) or MAC services data unit aggregation (A-MSDU).

TABLE 2
RECEIVER SENSITIVITIES AND DATA RATES

| Modulation and Coding scheme | Required Sensitivity (dBm) | Data Rates (Mbps) |
|---|---|---|
| BPSK (1/2) | -79 | 40.5 |
| QPSK (1/2) | -76 | 81 |
| QPSK (3/4) | -74 | 121.5 |
| 16 QAM (1/2) | -71 | 162 |
| 16 QAM (3/4) | -67 | 243 |
| 64 QAM (2/3) | -63 | 324 |
| 64 QAM (3/4) | -62 | 364 |
| 64 QAM (5/6) | -61 | 405 |

Although, the net throughput for A-MSDU is larger as compared to A-MPDU, however the performance of A-MPDU is better because of the availability of frame check sequence (FCS) with each sub-frame [3]. This implies that when a station (STA) transmits a block acknowledgement (BACK) to the AP, only corrupted frames would be sent by the AP in the next time slot. Hence in our analysis, we use the A-MPDU aggregation. The number of frames aggregated is denoted by $K$ where $1 \leq K \leq 64$.

A STA transmits a frame after it has observed an idle medium for a distributed inter-frame space (DIFS) plus a backoff duration. When the STA transmits an aggregation, the AP responds with immediate implicit block acknowledgement (BACK) after shortest inter-frame space (SIFS). We observe the MAC timing diagram as shown in Fig. 1.

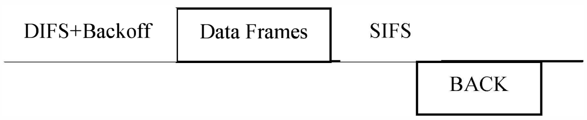


Fig. 1. DCF access scheme in IEEE 802.11

We consider data frames of size 1500 bytes, which is a typical frame size in the internet. We assume that the BACK is transmitted with a lower data rate to ensure maximum reliability, which is assumed 6 Mbps. The other parameters at the MAC layer are specified in Table 3 according to IEEE 802.11 standard.

TABLE 3
PARAMETER SET FOR THE MAC LAYER ANALYSIS

| **Parameter** | **Values** |
| --- | --- |
| $T_{SIFS}$ | 16us |
| $T_{DIFS}$ | 34us |
| $T_{Slot}$ | 9us |
| $T_{Backoff}$ | 63us |
| $L_{Data}$ | 1500bytes |
| R (PHY Data Rate) | From Table 2 |
| $T_{AP}$ (MAC header+FCS+Delimiter) | 276bits/R |
| $T_{PHY}$ (PHY header and preamble) | 48us |
| Frame Aggregation Number (K) | 1-64(max) |

In A-MPDU, each sub-frame has its sub-frame header and frame check sequence (FCS). The advantage is that if some frames are corrupted, then the whole aggregated frame is not re-transmitted; only the corrupted sub-frames are transmitted. However, due to addition of sub-frame address in each sub-frame, the overhead is increased. For a successful A-MPDU packet transmission, the time required is given as

$$T_{MPDU} = T_{DIFS} + T_{Backoff} + T_{Data} + T_{SIFS} + T_{BACK}, \quad (3)$$

where

$$T_{Data} = T_{PHY} + K/R\ (T_{AP} + L_{Data}), \quad (4)$$

and

$$T_{BACK} = 24us + 240/R_b. \quad (5)$$

Here $R$ is the PHY data rate from Table 2 and $R_b$ is the basic data rate, which is kept at 6 Mbps. The throughput is thus given as

$$Throughput = (K \times L_{DATA})/T_{MPDU}. \quad (6)$$

## III. EXNTEDER PLACEMENT

In this section, we analyze the performance of the multi-hop communications using extender radios. In an extender deployment, we assume that an additional access point (AP) is used as a relay/extender to extend the range of the wireless network. In doing so, we need to analyze the data rates and throughputs for the multi-hop wireless network where the hop count can go from 2 to any desired number. Most of our analysis will consider a 2-hop scenario, which can be easily generalized to any number. Specifically for the 2-hop case, we assume that only source *S*, destination *D*, and relay *R* exist in the network, where *R* is acting as a relay and carries no traffic of its own. The purpose of *R* is just to relay the data from *S* to *D*. The data rates from *S-R* and *R-D* links depend upon the wireless channel between these links. Because of the half-duplex nature of the radios, *S* first transmits the packet to *R*. Upon successful reception of the packet, *R* sends acknowledgement back to *S*. After carrier sensing, *R* transmits the packet to *D*, which replies with an ACK upon successful transmission. Hence the total time required to carry out this two-step process at the MAC layer is, on the average, simply twice as given in (3). We use the word *average* because the random back-off time can be different for each transmission. However, we assume a fixed average back-off time for each transmission. Due to changing wireless conditions, the two links i.e., *S-R* and *R-D* can exhibit different throughputs depending on PHY data rates and the net MAC throughput is given in Table 4.

TABLE 4
EXTENDER THROUGHPUT FOR MULTI-RATE DUAL HOP WIRELESS NETWORK

| | | **Data Rate (R-D) Mbps** | | | | | | | |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| | | 40 | 81 | 121 | 162 | 243 | 324 | 364 | 405 |
| **Data Rata (S-R) Mbps** | 40 | 19 | 26 | 29 | 30 | 33 | 34 | 34 | 34 |
| | 81 | 26 | 38 | 45 | 50 | 56 | 60 | 61 | 62 |
| | 121 | 29 | 45 | 56 | 64 | 74 | 80 | 82 | 84 |
| | 162 | 30 | 50 | 64 | 74 | 87 | 96 | 99 | 102 |
| | 243 | 33 | 56 | 74 | 87 | 107 | 120 | 126 | 130 |
| | 324 | 34 | 60 | 80 | 96 | 120 | 138 | 145 | 151 |
| | 364 | 34 | 61 | 82 | 99 | 126 | 145 | 152 | 159 |
| | 405 | 34 | 62 | 84 | 102 | 130 | 151 | 159 | 167 |

In Table 4, the basic data rate (Rb) is assumed 6 Mbps and the frame aggregation number is kept at 40. Another representation of the same result is shown in Fig. 2, where the contours of the MAC throughput are displayed versus distances on both *S-R* and *R-D* links. Hence for a given *S-D* distance, the extender can be places at any location in between and the throughput can be examined. As an example, if *S-D* distance is 30m, there can be variety of combinations of *S-R* and *R-D* distances that make up 30m, e.g., (5,25), (10,20), (15,15) on the (*S-R*, *R-D*) plane in Fig. 2. For each location pair, we notice different net throughput that is delivered to the destination. For the aforementioned cases, the approximate throughput delivered is 100, 120, and 140 Mbps, respectively. It can be noticed that the best extender throughput is obtained when the relay *R* is placed at the mid-point of *S-D* distance.

From the half-duplex nature of radios, we noticed that the spectral efficiency of the system is reduced to one-half by employing an additional extender between the source and the destination. However, employing an extender always doesn't help in providing higher data rates especially when the *S-D* distance is small. This can be attributed to the large delay that is caused by 'hopping' the packet to the destination.

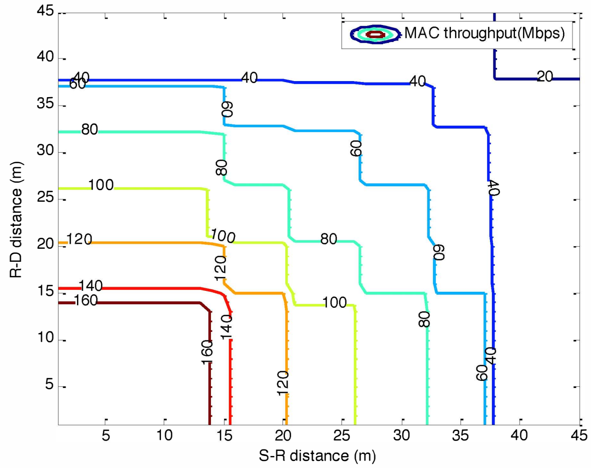


Fig. 2. MAC throughput for a 2-hop network with respect to S-R and S-D distances

Therefore, we are interested in finding those ideal locations of the extender where the multi-hop scheme provides better throughput as compared to direct communication link between the source and the destination. Fig. 3 represents the throughput of a single and multi-hop network with respect to *S-D* distance where the hops can be 1, 2, 3, or 4. It can be seen that there are particular locations for the extender to be placed to obtain maximum throughput. For instance, if the S-D distance is less than 20m, it is not recommended to use the extender because the 1-hop (direct link) throughput is higher than that of 2-hop throughput. However, as the *S-D* distance exceeds 20m, the use of one extender, which implies a 2-hop communication, is preferred to get the maximum throughput. Similarly if the S-D distance is very large, Fig. 3 shows the optimal locations for additional relays to get optimal performance of the system.

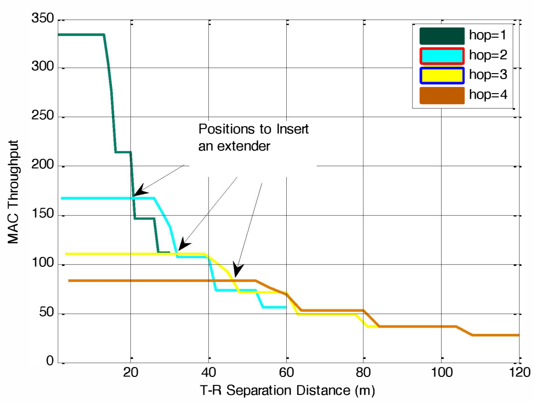


Fig. 3. MAC throughput for a n-hop network for a fixed S-D separation

To get the best spectral efficiency, an important parameter at the MAC layer is the frame aggregation number (*K*). Since the frame aggregation affects the delays in the system, therefore it might be the case that at some locations the extender placement is not beneficial and 1-hop link is better than 2-hop links. Fig. 4 represents the impact of *K* on extender placement to get best system throughput. For a given *K*, we can identify locations where placing the extender will be beneficial for optimal throughput. For instance, if *K=10*, then the *S-D* distance should at least be 27m to get more throughput with 2-hop links than 1-hop link. However, for the same *S-D* distance with *K=30*, the 2-hop performance is better than one-hop performance.

The discussion until now assumes a fixed penetration loss for all the simulations described above. However, with the presence of walls, big obstacles, and other hindrances, the requirements for the number of extenders and their locations can be significantly changed.

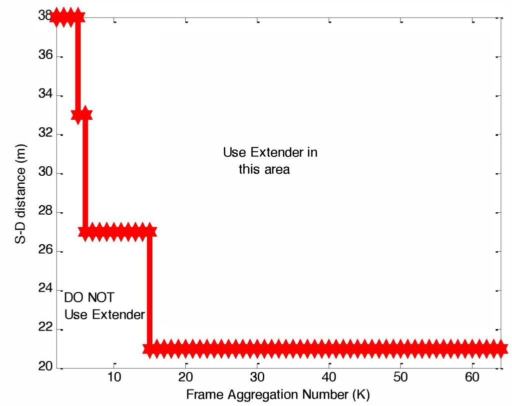


Fig. 4. Lower bounds on the frame aggregation number vs. S-D distance for the optimal use of extender

We also conducted the study to observe the effects of walls and penetration losses in the extender deployment. Fig. 5 shows the *S-D* distance versus the number of extenders required as a function of number of walls. It can be noticed that as the penetration loss increases (with increasing number of walls), more extenders are required to keep the connectivity at the expense of reduced throughput. For instance, if the *S-D* distance is 20m and there is one wall between them, one extender is sufficient to boast the performance of the network with the delivered data rate of 167 Mbps. However, for the same distance and three walls between source and destination, we require at least 2 extenders, which will deliver an approximate throughput of 100 Mbps. Hence, we can find the optimal number of extenders as a function of number of walls and throughput delivered using these extenders.

## IV. EXNTEDER DEPLOYMENT IN HOMES

In this section, we propose simple solutions of deploying extenders in home environments, keeping in view all the discussions and results from the previous sections. We assume that the user has very little or no knowledge of wireless medium, however insufficient coverage of a single AP renders the user to deploy extender(s) for range extension and/or throughput enhancements for long distance clients. When an extender is placed at an arbitrary position, we assume that the extender has the knowledge of the following two parameters

1. Received signal strength indicator (RSSI) from the source, i.e., *S-R* link, and the corresponding data rate for that RSSI (and approximate distance using (2)).

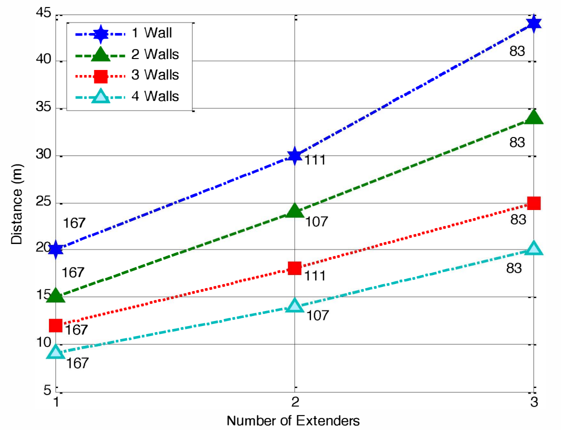


Fig. 5. MAC throughput as a function of number of walls, S-D distance, and number of extenders

2. RSSI for the *R-D* link.

The information for the *S-R* link is readily available to the extender. The information for the *R-D* link can be made available by running an application on the destination and feeding back the information for the *R-D* link back to the extender. In this manner, the extender gets the knowledge of both the links. Once the information is obtained, the extender can simply use the look-up tables, such as Table 4, and is able to deliver the throughput to the destination, which we denote as *T*. By obtaining the value of *T*, the extender evaluates the system performance at that particular location and displays it to the user. This information is conveyed as follows. Let the maximum data rate at the PHY layer that can be delivered by the standard is $DR_{max}$. As we employ a 2-hop network, the maximum throughput will be $DR_{max}/2$. Hence the percentage of throughput delivered by the extender can be given as:

$$\%\ of\ throughput\ delivered,\ P = \frac{T}{DR_{max}/2} * 100 \quad (7)$$

This value of *P* can be displayed on the extender for the user. As an example, if $DR_{max}$ =405 Mbps and $T$ = 170Mbps, then $P$= 83.9%, which shows that the extender is at an optimal location since the value of *P* is quite high. For other extender locations, the values of *P* will indicate the user to place the extender at the ideal location for optimal throughput to the client.

For more than one client, the basic procedure remains the same. However, there are two different ways of finding the values of *P* in a multi-destination scenario. The first is to take the average of all the throughput $T_1, T_2, \ldots, T_n$ for *n* destinations and choose the extender location with $max(P_1, P_2, \ldots, P_n)$. The other way is to use the weighted average of the throughputs. For example, if there are two clients, one requires more data rate as compared to other because of the nature of application running on it, then a weighted average can be taken and place the extender at an optimal location.

Similarly if after placing an extender, one gets no coverage at all or a very poor coverage, which mean the values of $P<30\%$, then there is a need to do 3-hops communications. Thus, two extenders are required to extend the coverage of the network in this scenario.

## V. CONCLUSIONS

Wireless networks are pruned to insufficient coverage at various indoor and outdoor locations due to variable medium and path loss with arbitrary exponent. Multi-hop communications is a way to increase the coverage of wireless networks at the expense of throughput. However, an optimal solution to this range-throughput exists, which depends on many factors. In this paper, we have studied the effects of different PHY and MAC parameters of IEEE 802.11n network, when multi-hop communication between terminals is considered. We have pointed optimal locations of the extender or relays where the multi-hop throughput is larger than the direct-link or single hop throughput. We also characterized simple tests for the placement of extender that can be beneficial for a user to deploy extenders in home environments.

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