Throughput Analysis of IEEE802.11n using OPNET

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Abstract - The aim of this paper is to evaluate the throughput performance of IEEE802.11n WLANs using a well-known commercial simulator called OPNET Modeler. We study the effects of IP packet size, Modulation and Coding Scheme (MCS), Channel Bonding, number of MIMO spatial streams, Block Acknowledgement (BA) and Type of Service (ToS)/Access Category (AC) on maximum throughput and Throughput Efficiency (TE). The impact of multiple users’ access on TE is also analyzed. From these studies we offer fresh insights on underlying configurations and operating conditions which affect the peak throughput performance and efficiency of IEEE802.11n system.

1 Introduction

The widespread adoption of Wireless Local Area Network (WLAN) technologies such as IEEE802.11a, b and g WLAN technology is driving rigorous improvements in particularly on the aspect of capacity. These activities have led to the ratification of IEEE 802.11n-2009 [1] in September 2009. This standard not only offers better performance in terms of capacity, range and reliability, it remains backward compatible with other legacy WLAN standards. In addition, it also supports IEEE802.11e’s QoS protocol which provides differentiated services for voice, video and data.

The main contribution of this paper is the analysis of IEEE 802.11n WLAN throughput performance using OPNET Modeler [2]. OPNET is widely regarded as the most accurate, scalable and comprehensive network simulator in the industry. The Modeler’s library offers more than 400 out-of-the-box protocols, traffic and vendor device models including IPv6, TCP/UDP, VoIP/Video/FTP/HTTP/Email, UMTS, WiMAX, LTE, WLAN (a/b/g/n) and so on. Through this tool we carefully study the effects of IP packet size, Modulation and Coding Scheme (MCS), Channel Bonding, number of Multiple Input Multiple Output (MIMO) spatial streams, block acknowledgement Type of Service (ToS)/Access Category (AC) on maximum throughput and Throughput Efficiency (TE). The impact on TE loss due to multiple user access is also analyzed. Our studies offer valuable insights on the underlying configurations and operating conditions that affect the peak throughput performance of this protocol. The rest of the paper is organized as follows. Section 2 and 3 provide an overview of 802.11n enhancements and related work. We then describe the simulation setup and general parameters used for the case studies in section 4. In section 5 we present the case studies and results. Finally, the conclusion and future work are drawn in section 6.

2 IEEE802.11n enhancements

IEEE 802.11n offers a variety of enhanced features over legacy 802.11 networks (a/b/g). In this paper we only focus on enhancements which have been devised to support higher data rates or throughputs. These enhancements can generally be divided into physical (PHY) layer and medium access control (MAC) layer enhancements.

A. PHY Layer Enhancement

One of the main enhancements in IEEE802.11n is the adoption of MIMO antenna technology for increasing capacity or range or both. The key lies on three MIMO signal processing techniques: 1) Spatial Division Multiplexing (SDM) which enables multiple antennas to transmit and receive simultaneously resulting in higher data rate, 2) Space Time Block Coding (STBC) which sends redundant signal stream using up to four differently-coded spatial streams via separate antennas to improve reliability or range and 3) Transmit Beamforming (TxBF) that steers an outgoing signal towards an target receiver by focusing RF energy on a desired direction hence increasing SNR. The TxBF feature is optional and is not widely implemented [3], [4]. Figure 1 illustrates the operation of MIMO technology in SDM mode.

![Figure 1: MIMO in SDM mode.](image)

The second major enhancement is the Channel Bonding capability whereby it can bond two 20MHz...
orthogonal channels to form one 40 MHz channel. Figure 2 shows a real-time capture which compares IEEE802.11n operating in 5GHz band with and without channel bonding.

![Figure 2: Channel Bonding Illustration](image)

(a) 20MHz (channel 36)

(b) 40MHz (bonding channel 36+40)

**Figure 2: Channel Bonding Illustration**

On the modulation side, the number of orthogonal frequency-division multiplexing (OFDM) data (usable) subcarriers has been increased from 48 in the previous standard to 52 in the 20MHz channel and to 108 in the 40MHz channel. This corresponds to 8% to 125% increase in data rate respectively. On top of that it also provides the option of using shorter guard interval (SGI) of 400ns between each OFDM symbols compared to 800ns in its predecessor. The usage SGI boosts physical data rate by 11% while maintaining sufficient symbol separation for cases when worst-case multipath delay is low [5].

IEEE802.11n also supports up to 32 Modulation and Coding Schemes (MCS) as compared to only 8 in IEEE802.11g. This corresponds to data rate ranging from 6.5 Mbps up to 600 Mbps [6], [7]. However the basic rate with SGI for a SISO system only ranges from 7.2 to 72.2Mbps. Any data rate higher than 72.2Mbps is due to the usage of more than one antenna pairs in SDM mode.

In the previous IEEE802.11 standards, the pause time between frames transmitted by a user or Single Inter-Frame Spacing (SIFS) is set as 10µs at 2.4GHz band and 16µs in 5GHz band. IEEE802.11n defines a smaller inter-frame spacing of 2µs through Reduced Inter-Frame Spacing (RIFS) which is 5 or 8 times lower than SIFS. However RIFS can only be used in IEEE802.11n High Throughput (HT) Greenfield mode whereby all the stations need to operate in 11n mode.

**B. MAC Layer Enhancement**

On the MAC layer, the Frame aggregation technique is proposed to reduce the protocol and contention (time) overheads [8]. There are two levels of aggregation: 1) MAC Service Data Unit Aggregation (A-MSDU) and 2) MAC Protocol Data Unit Aggregation (A-MPDU) as illustrated in Figure 3.

![Figure 3: Illustration of Frame aggregation techniques](image)

In A-MSDU, multiple payload frames from higher layers are combined and processed by the MAC layer as a single entity. Multiple payload frames not only share the same MAC header but also the same PHY. In A-MSDU, the maximum MSDU payload size has been increased from 2,304 bytes in earlier standards to 7,935 bytes (~4 times increment).

A-MPDU takes place after the MAC header encapsulation process. The complete MAC frames (MPDUs) are then grouped into a PHY payload of up to 65,535 bytes per frame as opposed to 4,095 bytes previously. The maximum number of frames per aggregation is 64. While AMPDU frames can be recovered when one or more MPDU delimiters are received with errors, an A-MSDU aggregate fails as a whole even if just one of the enclosed MSDUs contains bit errors [8].

Also due to the manner how MPDUs are packed in A-MPDU, the earlier 802.11 per-MPDU acknowledgement mechanism for unicast frame cannot be used [5]. A Blocked Acknowledgement (BA) mechanism is therefore proposed for A-MPDU which is discussed next. In this paper however, we are unable
to carry out the study on frame aggregation as this feature has yet to be implemented in OPNET at the time of writing.

BA is a feature originally defined in IEEE802.11e where successive frames can be transmitted without the need to acknowledge after receiving every unicast frame [5]. This is particularly suitable for unicast streaming applications such as video conferencing where retransmission is not feasible or critical. With the reduction in protocol and timing overheads, throughput can be significantly increased. Figure 4 illustrates the basic operation of BA. In addition to the BA mechanism introduced in IEEE802.11e, IEEE802.11n offers an enhanced version of BA called compressed BA which utilize smaller bitmap size [10].

![Image of Block Acknowledgement Process](image)

**Figure 4: Block Acknowledgement Process [11].**

### 3 Related work

A significant amount of studies on the performance of IEEE802.11n have been carried out using both experimental and simulation approaches.

In particular, K. Pelechrinis, et al. [4] conducted some experimental studies to examine the achievable throughput and showed that the overhead introduced to 11n by the MAC protocol family has a negative impact on the performance. The utilization of the 802.11n enhancement feature is recommended by the authors in order to achieve throughput close to the actual PHY Layer. Similarly, V. Visoottiviseth, et al. [12] carried out experimental measurements on the 11n performance, considering throughput as the performance metric using a variety of the available commercial devices. The results were compared against 11g’s and significant improvement was demonstrated especially when using BA and frame aggregation for both UDP and TCP traffic on both downlink and uplink. Fiehe, et al. [13] who focused on the performance measurement in a typical office and interference controlled environments and the effects of the Industrial, Scientific and Medium (ISM) technology on the 2.4 GHz 802.11n devices.

The simulation studies conducted by T. Selvam and S. Srikanth on [6] investigated the effects of the different protection mechanisms on the performance of the 11n networks in the presence of the legacy stations. In [14], the performance of PHY layer in terms of the bit error rate and frame error rate was studied with the effects of MIMO, channel bandwidth and conventional encoder constraint length. Similarly in [15] the performance of 802.11n PHY layer was evaluated using a 4x4 antenna system under different STBC rates using 64-QAM.

While the above works provide important insights and useful points of reference or comparison for our work, we provide a more comprehensive analysis using the accurate and comprehensive traffic models, protocols and device models offered by OPNET Modeler.

### 4 Simulation setup and general parameters

In our studies, typical parameters which are usually configurable by the end users such as number of MIMO stream/MCS, channel bonding, BA, GI, CW, number of users admitted, etc., are considered. Figure 5 illustrates the simulation setup in OPNET Modeler.

![Image of simulation setup](image)

**Figure 5: Illustration of simulation setup.**

In order to acquire the required insights, we adopt the following general conditions or parameters:
- There is no frame error and therefore frame drop due to decoding error.
- For single user scenario, no frame is lost due to collision. Hence the Contention Window (CW)
size stays at the minimum Contention Window (CWMin) size.

- The queue size is set to close to infinity to prevent frame being dropped due to buffer overflow. Hence there is no frame drop in our study.
- Only the Enhanced Distributed Coordination Access (EDCA) coordinated access mode is adopted.
- To find the peak throughput, UDP type traffic is pumped into the transmitter in incremental step manner until it exceeds the saturation point.

Table I and II list down the default parameters unless stated otherwise.

### Table I. Default Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Remark</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>PHY</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Frequency band</td>
<td>2.4GHz</td>
<td>Typical band for WLAN</td>
</tr>
<tr>
<td>Guard Interval (GI)</td>
<td>400ns</td>
<td>Short GI</td>
</tr>
<tr>
<td>Default MCS Index</td>
<td>0</td>
<td>BPSK½ (7.2Mbps). MCS=7</td>
</tr>
<tr>
<td></td>
<td></td>
<td>64QAM5/6 (72.2Mbps) also</td>
</tr>
<tr>
<td></td>
<td></td>
<td>supported</td>
</tr>
<tr>
<td>No. of Spatial Stream</td>
<td>1</td>
<td>Up to 4 spatial streams</td>
</tr>
<tr>
<td>Channel Size</td>
<td>20MHz</td>
<td>40MHz when bonding</td>
</tr>
<tr>
<td>Antenna</td>
<td>0dBd</td>
<td>Isotropic</td>
</tr>
<tr>
<td>Propagation model</td>
<td>FSPL</td>
<td>Free Space Path Loss Model</td>
</tr>
<tr>
<td>PHY PLCP header</td>
<td>28μs</td>
<td>Green field mode</td>
</tr>
<tr>
<td>Slot time</td>
<td>9μs</td>
<td>Short slot time</td>
</tr>
<tr>
<td>DIFS</td>
<td>28μs</td>
<td>(SIFS +2* slot_time)</td>
</tr>
<tr>
<td>SIFS</td>
<td>10μs</td>
<td>Short IFS</td>
</tr>
<tr>
<td>RIFS</td>
<td>2μs</td>
<td>Reduced IFS</td>
</tr>
<tr>
<td><strong>MAC</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MAC Header &amp; FCS</td>
<td>30bytes</td>
<td>With QoS</td>
</tr>
<tr>
<td>MAC Frame Size</td>
<td>1462bytes</td>
<td>Constant distribution</td>
</tr>
<tr>
<td>RTS</td>
<td>112 bits</td>
<td>Request to Send frame length</td>
</tr>
<tr>
<td>CTS</td>
<td>112 bits</td>
<td>Clear to Send frame length</td>
</tr>
<tr>
<td>ACK</td>
<td>112 bits</td>
<td>Ack frame length</td>
</tr>
<tr>
<td>BA</td>
<td>1216 bits</td>
<td>Block ACK frame length</td>
</tr>
<tr>
<td>BAR</td>
<td>192 bits</td>
<td>Block ACK Request frame length</td>
</tr>
<tr>
<td>Access Category (AC)</td>
<td>AC_VI</td>
<td>Default AC. See table II</td>
</tr>
</tbody>
</table>

### Table II. Access Category (AC)

<table>
<thead>
<tr>
<th>AC</th>
<th>CWMin</th>
<th>CWMax</th>
<th>AIFSN</th>
<th>MaxTXOP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Background (AC_BK)</td>
<td>15</td>
<td>1023</td>
<td>7</td>
<td>0</td>
</tr>
<tr>
<td>Best Effort (AC_BE)</td>
<td>15</td>
<td>1023</td>
<td>3</td>
<td>0</td>
</tr>
<tr>
<td>Video (AC_VI)</td>
<td>7</td>
<td>15</td>
<td>2</td>
<td>3.008ms</td>
</tr>
<tr>
<td>Voice (AC_VO)</td>
<td>3</td>
<td>7</td>
<td>2</td>
<td>1.504ms</td>
</tr>
</tbody>
</table>

Note: AIFSN = Arbitrary Interframe Space Number and TXOP = Transmit Opportunity.

For each Access Category (AC), AIFSN[AC] = AIFSN[AC]*aSlotTime + aSIFSTime. For other parameters which are not stated here, the OPNET default values (which are usually the IEEE 802.11 standard default values) are preserved.

### 5 Case studies and results

This section presents some case studies for obtaining the required insights.

#### A. Effects of IP Packet Size

Increasing the IP packet size will likely to improve the throughput of the WLAN networks due to reduction in terms of ratio between payload and header. In this study we set the WLAN MTU to a typical size of 1,462 Bytes and vary the size of the IP packet size. In Figure 6, we observe that the throughput reaches the peak at 1,462, 2,924 and 4,386 bytes respectively, which corresponds to multiplication of MTU. After each peak, the throughput experiences sudden drop before it increases gradually again. This observation is consistent with most existing literatures. This is due to fragmentation of the IP packet into more than one MAC frames in order to comply with the MTU. In practice however, the distribution IP packet size is unlikely to exhibit such uniformity. It is to be reminded that even though transmitting large MAC frames over WLAN reduces the overhead imposed by header in proportion, it is vulnerable to higher delay and frame error. The later will incur larger overhead due to the need to retransmit. For the rest of the paper, the IP packet size is set to 1,462 bytes, which is the typical maximum limit acceptable in practical systems.

![Figure 6: Max Link Throughput vs. IP packet size (BA enabled, MCS= BPSK½/7.2Mbps)](image)

#### B. Effects of MCS

In this scenario, the maximum throughput and throughput efficiency are analyzed for different MCSs. In our work, Throughput Efficiency (TE) is defined
as \( \frac{\text{Max\_Throughput}}{\text{Physical\_datarate}} \). As shown in Figure 7, maximum throughput increases quite linearly with the order of MCS as expected. It is also observed that TE is generally higher in the lower order MCS and lower in the higher order MCS for both 11g and 11n. One main reason is that even at higher order MCS, PLCP preamble and PLCP headers are still transmitted using the lowest MCS i.e. BPSK1/2. When comparing 11n with 11g on the same MCS for instance at 64QAM3/4 compared to BPSK1/2. The maximum possible UDP throughput for an 11g system is found to be ~29.7Mbps (using 64QAM3/4) whereas for the same MCS, 11n offers ~47.4Mbps, which is quite consistent with the existing literatures. The maximum possible UDP throughput of 11n is found to be at 52.6Mbps (using 64QAM5/6). As for TE, 11n maintains around 73% even with 64QAM5/6 whereas for 11g, it drops to ~46% using 64QAM3/4. The improved performance of 11n is largely due to the additional subcarriers, usage of BA and RIFS.

![Figure 7: Max Link Throughput and TE vs. MCS for 11g and 11n (BA enabled for 11n, single stream)](image)

### C. Effects of Channel Bandwidth

When analyzing the effect of channel bandwidth as shown in Figure 8, we found that the maximum TE is 89% (6.44Mbps/7.2Mbps) at 20 MHz channel and 84% (12.18Mbps/15Mbps) at 40 MHz channel. Although, the PHY data rate increases by more than two folds due to higher number of data carriers when switching from 20 MHz channel to 40 MHz channel, the throughput increases slightly less than that i.e. 95.9%. Nevertheless as expected, the increase in throughput is quite linear with the increase of physical data rate.

![Figure 8: Effects of Channel Bonding on Max Link Throughput (BA enabled, MCS= BPSK\(\frac{1}{2}/7.2\text{Mbps}\)](image)

### D. Effects of MIMO

Increasing the number of transmit and receive antenna pair will increase the PHY data rate accordingly. Theoretically, the data rate increase is a factor of number of streams of the base data rate and hence the throughput. From Figure 9, we can summarize that the maximum throughput obtained by 1, 2, 3, and 4 spatial streams, throughput efficiency, and gain in the maximum throughput as in Table III.

#### Table III: Summary of MIMO results

<table>
<thead>
<tr>
<th>No. of SS</th>
<th>Physical Data Rate (Mbps)</th>
<th>Throughput (Mbps)</th>
<th>Throughput Gain</th>
<th>TE (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>7.2</td>
<td>6.44</td>
<td>NA</td>
<td>89%</td>
</tr>
<tr>
<td>2</td>
<td>14.4</td>
<td>12.18</td>
<td>1.89</td>
<td>84%</td>
</tr>
<tr>
<td>3</td>
<td>21.7</td>
<td>17.03</td>
<td>2.65</td>
<td>78%</td>
</tr>
<tr>
<td>4</td>
<td>28.8</td>
<td>21.35</td>
<td>3.32</td>
<td>74%</td>
</tr>
</tbody>
</table>

![Figure 9: Effects of MIMO Spatial Streams on Max Link Throughput (BA enabled, MCS= BPSK\(\frac{1}{2}/7.2\text{Mbps}\)](image)

Since we have omitted the effects of the physical environment such as fading, shadowing and interferences while assuming maximum antenna diversity, the results in Table III implies the best-
possible throughput performance we can derive from the 11n standard using MIMO in SM mode.

E. Effects of BA
The earlier 11n PHY enhancements basically increase the maximum PHY data rate. To further increase the throughput, further enhancements at the MAC layer is imperative. BA reduces the MAC layer overhead by reducing the number of ACKs that must be received by transmitter for delivery confirmation and hence indirectly increases the throughput. In this study we also analyze the effect when varying the number of stations. Figure 10 shows the throughput performance with different number of stations, with and without BA. We can see that with BA the overall throughput generally maintains at around 5.7 Mbps and only drops slightly as the number of stations increases. This indicates that the BA mechanism significantly reduces the amount of overhead as well as the number of collisions which in turn results in higher overall aggregated throughput. However this observation only holds at highly loaded case (as shown in Fig. 10) where the maximum possible throughput offered by BPSK1/2 is already reached.

\[ \text{Aggregated Throughput (Mbps)} \]

Figure 10: Aggregated AP Throughput vs. Number of Users (Stations) with and without BA, MCS= BPSK1/2, 7.2Mbps, Single Stream)

F. Effects of Traffic Type (ToS)
11n adopts the user priority (UP) scheme defined in 11e standard. Each ToS is mapped to one of the four Access Categories (AC) as shown in Table IV [16]. As shown in Table II earlier, different ACs have different CW sizes and AIFS, and hence providing differentiated access priorities to different types of service.

In this scenario we pump the traffic between a mobile station and an AP with one type of traffic only. From Figure 11 we can see that Background AC provides the lowest throughput as expected. Interestingly, although Video AC is lower priority than Voice AC, it gives the highest throughput. The reason being although Voice AC has smaller CW (3 slot), its TXOP is double of that of Video AC. When the same TXOP values are used, Voice and Video achieve the maximum throughput of 50.53 and 54.27Mbps respectively. It is important to mention that since the above simulation was performed under a single traffic type environment with only one station, the CW is not affecting the throughput. Under a mixed traffic environment however, the behavior is expected to be very different.

\[
\begin{array}{|c|c|c|}
\hline
\text{Priority} & \text{UP} & \text{Traffic Type} & \text{AC} \\
\hline
\text{Low} & 1 & \text{Background} & \text{Background} \\
\hline
 & 2 & \text{Standard} & \text{Background} \\
\hline
 & 0 & \text{Best Effort} & \text{Best Effort} \\
\hline
 & 3 & \text{Excellent Effort} & \text{Best Effort} \\
\hline
 & 4 & \text{Multimedia Streaming} & \text{Video} \\
\hline
 & 5 & \text{Interactive Multimedia} & \text{Video} \\
\hline
 & 6 & \text{Interactive Voice} & \text{Voice} \\
\hline
 & 7 & \text{Reserved-Network Control} & \text{Voice} \\
\hline
\end{array}
\]

Table IV. Mapping between UP and AC

G. Efficiency Loss due to Multiple Users
The throughput efficiency is expected to decrease in multi user scenario due to the need to coordinate how different stations should share the resource as well as how to resolve contention experienced by each station when accessing the medium. Here, we vary the number of users with the same configurations and same traffic in order to study the degree of efficiency loss. The BA function is disabled in order to have a clearer view of the effect.

As observed in Figure 12, having multiple users in the network decreases the overall throughput of WLAN due to the increase of backoff events caused by contentions between stations. TE drop is more drastic when employing lower order MCS compared to higher
order since the ratio of overhead against effective data rate in lower order MCS is significantly higher. It is also observed that when there are 10 stations, both MCS experience the same TE. Based on the trend, when number of stations > 10, 64QAM5/6 is more efficient.

![Figure 12: Throughput Efficiency vs. Number of Users (BPSK1/2 and 64QAM5/6, Single Stream, BA enabled)](image)

6 Conclusion

In this paper, we have investigated how the maximum throughput and throughput efficiency (TE) are affected by IP packet size, MCS, Channel Bonding, number of MIMO spatial streams, BA and ToS/Access Category (AC). As shown both throughput and TE performances are largely improved with the new PHY and MAC layer enhancements under relatively ideal scenarios and optimal configurations. Future work should look into the effects of frame aggregation (A-MPDU/A-MSDU) and mixed mode operation with legacy system.

Acknowledgement

The views and conclusions contained here are those of the authors and should not be interpreted as necessarily reflect those of MIMOS or OPNET.

References