Throughput and Coverage Performance for IEEE 802.11ad Millimeter-Wave WPANs

Xiaoyi Zhu*, Angela Doufexi†, and Taskin Kocak*†

Abstract— Recently, the development and requirement for ultra-high data rate wireless communication applications has increased dramatically. The 60 GHz millimeter-wave wireless technology is getting increasing attention, and the IEEE 802.11 Task Group AD is making standardization efforts for multi-gigabit data rate communications on both the physical (PHY) and medium access control (MAC) layers. This paper presents a performance evaluation of the PHY and MAC layers of IEEE 802.11ad. Packet error rate and PHY throughput are presented for different modes, and the theoretical MAC throughput is analyzed for different bit error rates, packet sizes and modes. In addition, a space-time block coding (STBC) is employed for range extension. The cross layer results show our approach enhance the throughput and coverage compared to the case of single antenna.

Keywords- WPAN; 60 GHz; IEEE 802.11ad; MIMO-STBC; PHY; Channel Model; MAC

I. INTRODUCTION

With the increasing demands for high quality multimedia and data services, the 60 GHz millimeter-wave (mmWave) band is of much interest in recent years, because it is unlicensed and with a large amount of spectral space available around the world. Several international groups have been making standardization efforts for wireless personal area networks (WPANs), including IEEE 802.11ad, IEEE 802.15.3c, WirelessHD, WiGig, and ECMA-387. These systems define adaptive physical (PHY) layer data rates up to 7 Gbps within the 57.24-65.88 GHz band, and also enhance the medium access control (MAC) layer to accommodate the characteristics of the 60 GHz mmWave.

The IEEE 802.11ad task group began to develop a 60 GHz amendment to 802.11 in January 2009, and expected to complete by the end of 2012. The first draft was published in May 2010 [1]. The beginning of the standardization was close to IEEE 802.15.3c, which some authors have studied in [3-5]. However, one key advantage of IEEE 802.11ad over the other 60 GHz standards is that it builds on the existing wireless local area networks (WLANs), which already have a very strong market presence. It extends the successful WLAN system, and it will support fast session transfer among 2.4/5 GHz and 60 GHz. It also supports coexistence with other 60 GHz systems.

The 60GHz high spectrum leads to dense frequency reuse, smaller sizes of radio frequency (RF) components, high antenna gain and secure data transmission [2]. However, the high attenuation resulted by oxygen absorption, path loss and multi-path effects make the high data rate transmission difficult to deploy. In order to enhance the performance, multiple transmit and receive antennas can be applied to provide diversity. The space-time block coding (STBC) has been widely used to increase power efficiency by maximum special diversity. In this paper, we employ STBC to our physical layer simulator in order to improve the throughput and coverage of IEEE 802.11ad standard under different channel conditions. The theoretical MAC throughput is also investigated, and the cross layer analysis enables us to evaluate the achievable throughput and coverage for IEEE 802.11ad WPANs.

The rest of the paper is organized as follows. Section II describes the IEEE 802.11ad PHY layer and MAC layer. The simulation setup and channel model for IEEE 802.11ad are also described in this section. Simulation results for the PHY and MAC throughput are given in Section III, and we conclude this paper in section IV.

II. OVERVIEW OF IEEE 802.11AD WPANS

The IEEE 802.11ad WPAN defines three scenarios addressing the most likely markets. These scenarios are conference room, living room and enterprise cubicle. There are seven usage models defined in the different environments including wireless displaying uncompressed video stream, rapid file transferring, and other wireless I/O. The PHY and MAC features specified in the IEEE 802.11ad WPAN standard are summarized below.

A. Physical Layer

The IEEE 802.11ad standard specifies two operating modes working in 2.16 GHz channel bandwidth. The orthogonal frequency division multiplexing (OFDM) mode is designed for high performance applications on frequency selective channels. The single carrier (SC) mode is used for low power and low complexity transceivers. It is also employed for control signaling. We investigate the OFDM mode performance in this paper. Fig. 1 describes the block diagram of the transmitter for IEEE 802.11ad WPANs. The scrambled data are firstly encoded with a LDPC encoder. The irregular LDPC(672, 336), LDPC(672, 420), LDPC(672, 504) and LDPC(672, 546) codes are used for the coding rates of 1/2, 5/8, 3/4, and 13/16 respectively. The binary serial input data is then mapped to...
data symbols according to the modulation schemes. Overall the modulation and coding schemes (MCS) we considered in this paper are listed in Table I. A tone interleaver is applied before the modulated data are sent to the OFDM modulator. 512 size IFFT is implemented to form one OFDM symbol, and 336 out of 512 subcarriers are data carriers. The OFDM sample rate is 2.64 GHz and the guard interval length is 128. The receiver performs the reverse process. In this paper, a multiple input and multiple output (MIMO) $2 \times 2$ STBC architecture has been adopted to provide transmit and receive diversity. This scheme uses a transmission matrix $[x_1, x_2, x_3, x_4]$, where $x_1$ and $x_2$ are two consecutive OFDM symbols.

TABLE I. MODULATION AND CODING SCHEMES

<table>
<thead>
<tr>
<th>Modulation</th>
<th>Coding Rate</th>
<th>Coded Bits/Symbol</th>
<th>Data Bits/Symbol</th>
<th>Data Rate (Mbps)</th>
</tr>
</thead>
<tbody>
<tr>
<td>QPSK</td>
<td>1/2</td>
<td>672</td>
<td>336</td>
<td>1386.00</td>
</tr>
<tr>
<td>QPSK</td>
<td>5/8</td>
<td>672</td>
<td>420</td>
<td>1732.50</td>
</tr>
<tr>
<td>QPSK</td>
<td>3/4</td>
<td>672</td>
<td>504</td>
<td>2079.00</td>
</tr>
<tr>
<td>16-QAM</td>
<td>1/2</td>
<td>1344</td>
<td>672</td>
<td>2772.00</td>
</tr>
<tr>
<td>16-QAM</td>
<td>5/8</td>
<td>1344</td>
<td>840</td>
<td>3465.00</td>
</tr>
<tr>
<td>16-QAM</td>
<td>3/4</td>
<td>1344</td>
<td>1008</td>
<td>4158.00</td>
</tr>
<tr>
<td>16-QAM</td>
<td>13/16</td>
<td>1344</td>
<td>1092</td>
<td>4504.50</td>
</tr>
<tr>
<td>64-QAM</td>
<td>5/8</td>
<td>2016</td>
<td>1260</td>
<td>5197.50</td>
</tr>
<tr>
<td>64-QAM</td>
<td>3/4</td>
<td>2016</td>
<td>1512</td>
<td>6237.00</td>
</tr>
<tr>
<td>64-QAM</td>
<td>13/16</td>
<td>2016</td>
<td>1638</td>
<td>6756.75</td>
</tr>
</tbody>
</table>

A frame header is added to the resulting payload to convey information in the PHY and the MAC headers necessary for a successful decoding of the frame. A PHY preamble is added prior to the frame header to aid receiver algorithms related to frame detection, frequency recovery, frame synchronization, and channel estimation.

B. Medium Access Control Layer

A hybrid multiple access of contention-based CSMA/CA (carrier sense multiple access with collision avoidance) and contention-free TDMA (time division multiple access) is used in IEEE 802.11ad. The CSMA/CA is used for a burst-type of application such as web browsing because of the lower average latency, while the TDMA is more desirable for video transmission due to its better quality of service and efficiency. Polling is used on the top of the access periods in order to dynamic allocate the channel time [1].

The MAC layer throughput is determined by the amount of information bits exchanged between the transceivers MAC, and the duration needed for successfully delivering the information. It can be calculated by the following equation:

$$MAC\ Throughput = \frac{Payload}{Transmission\ Duration} \quad (1)$$

Sources of overhead include gap time, preamble, header, and acknowledgment (ACK) frames. There are three types of ACK mechanisms defined for transmitting data frames: No-ACK, immediate ACK (Imm-ACK), and block ACK (Blk-ACK). In this paper, we also apply delayed ACK (Dly-ACK) and block NAK (Blk-NAK) for comparison. The processes of different ACKs are shown in Fig. 2 [4]. For the No-ACK, ACK is not sent back after a frame reception. The Imm-ACK is sent out after a short inter-frame space (SIFS) when an individual frame is received. The Dly-ACK allows the transmitter to send multiple frames, and each frame is followed by a minimum inter-frame space (RIFS). Then the ACKs for each frame are grouped into a single ACK to send to the transmitter. The Blk-ACK is used for acknowledging each subframe (SF) in the aggregated frame, and the Blk-NAK only acknowledges the error SFs in the aggregated frame.

C. Channel Model and Simulation Setup

Based on the clustering phenomenon in both the temporal and spatial domain, a statistic channel model was proposed for the 60 GHz WPAN [6]. Because the channel model is based on a combination of measurements and ray-tracing, which require lots of experimental efforts, the current version only supports the conference room scenario (cr) [7]. In this paper, we consider four different channel scenarios, and the channels are generated in line-of-sight (LOS) and non-line-of-sight (NLOS) cases with either an isotropic radiator (omni), or a steerable directional antenna (DA). To evaluate the performance of MIMO $2 \times 2$ STBC in IEEE 802.11ad, different degrees of correlation are considered. The average channel matrix determinant values across all channel realizations are 0.1 (low), 0.5 (medium) and 0.9 (high). The path loss (PL) model for the conference room can be modeled as [6]:

$$PL[dB] = A + 20 \log_{10}\left(\frac{f}{f_0}\right) + 10n \log_{10}\left(D/D_0\right) \quad (2)$$

where for LOS scenario $A = 32.5$ dB, $n = 2.0$, and for NLOS scenario $A = 51.5$ dB, $n = 0.6$, $f$ is the carrier frequency in GHz, $D$ is the distance between the transceivers in meter.
### III. PERFORMANCE ANALYSIS

#### A. Packet Error Rate (PER) Performance

In this section, firstly single input single output (SISO) and MIMO-STBC PER and throughput results are presented using our IEEE 802.11ad PHY MATLAB simulator and the channel models described in the previous section. The PHY payload size is 1 Kilobyte (KB) for all modes. Fig. 3 presents the SISO PER performance of all the modes versus the average signal-to-noise-ratio (SNR) for the channel cr_LOS_omni (conference room, line-of-sight, isotropic radiator). From this figure, it can be seen that generally higher data rate requires higher SNR to maintain a certain PER. The system cannot provide any service when the SNR is below 1dB in such scenario, while given the PER transmission target of 1%, the system will be at the highest MCS at approximately 22dB.

![Figure 3. PER performance of all modes in cr_LOS_omni](image)

Fig. 4 shows simulated PER performances versus SNR for MCSIQPSK 1/2 for four different channel scenarios. It can be seen that the NLOS scenario needs 3dB more SNR than LOS to maintain the same PER at 1%. It is also shown that employing directional antenna provides a performance gain compared to isotropic radiator.

In order to improve the throughput performance, the MIMO 2×2 STBC are employed. For LOS scenario, only high correlation is considered, whereas various correlation factors are assumed for NLOS scenario. Fig. 5 shows the PER performance of all the modes for the LOS scenario with high correlation coefficient (0.9). We can observe that STBC offers a significant performance gain of more than 8 dB compared to the SISO scenario for all transmission modes. In particular, a higher coding rate provides more diversity gain than others.

![Figure 5. MIMO 2×2 STBC PER performance of all modes in cr_LOS_omni with high correlation coefficient (0.9)](image)

Fig. 6 compares the PER performance of different scenarios and correlation factors for the same mode. It can be seen that in the same scenario, the performance of STBC varies depending on the different level of correlation. However, the performance only drops by less than 2 dB at the PER target of 1%. It also shows that MIMO 2×2 STBC improves throughput compared to the SISO case in IEEE 802.11ad standard in both scenarios.

![Figure 6. PER performance for QPSK 1/2 for different scenarios and correlation coefficients](image)

#### B. Link Throughput and Ranges

In order to enable the system to adapt the transmission mode to the link quality, the PHY modes with different MCSs are selected by a link adaptation scheme. When a negative ACK is received, the transmitter will retransmit the packet. The link throughput when retransmission is employed is given by [8]:

\[ \text{Throughput} = R \cdot (1 - \text{PER}) \]

where \( R \) and \( \text{PER} \) are the peak data rate and packet error rate for a specific mode respectively. The mode with the highest throughput is chosen for each instantaneous SNR value. Fig. 7 and Fig. 8 present the link
To estimate the achievable operation range, the link budget can be described as:

\[ P_T - PL > kTB + NF + \text{ReceiverSNR} \]  \hspace{1cm} (3)

where \( P_T \) is the maximum transmit power (10dBm), \( PL \) can be obtained by (2), \( k \) is Boltzmann’s constant, \( T \) is the temperature (290K), \( B \) is the bandwidth, \( NF \) represents the noise figure (10dB) of such devices, and \( \text{ReceiverSNR} \) is the SNR required for the demodulation. Fig. 9 shows the maximum data rate that can be achieved over distance, based on equation (3) and the results of link throughput. It can be seen that in LOS scenario, the distance that the system can tolerate is within 12m, and the guaranteed high throughput at least 3 Gbps is within about 4m for SISO case. However, MIMO 2×2 STBC requires only a little additional complexity but extend the effective transmission range up to 25m. In NLOS scenario, the system can hardly work beyond 1m, but MIMO 2×2 STBC can maintain the service up to 7m. At a given transceivers distance, the achievable throughput varies according to different correlation degrees, but is still higher than the SISO case.

C. MAC performance

Fig. 10 shows the MAC layer throughput achieved in MCS QPSK 1/2 for different bit error rate (BER) and ACKs with 1 KB payload size. The lengths of preamble and header are 1.745μs and 0.242μs. The slot time, SIFS and RIFS are 3μs, 3μs and 1μs respectively. The aggregated frame is composed of 16 SFs, and we assume there is no collision happens. It can be seen that frame aggregation with Blk-ACK increases the MAC efficiency dramatically compared to Imm-ACK and Dly-ACK. The throughput reaches to the peak when the BER≤10^{-6}.

Fig. 11 demonstrates the MAC layer throughput achieved in MCS QPSK 1/2 for different PHY payload sizes and ACKs at a BER=10^{-6}. It is shown that the MAC throughput increases to a certain point with the increase of the frame size. This is because a large frame size reduces the number of inter frame space, and results in increased frame transmission efficiency. However, the throughput decreases after exceeding a certain value of frame size. The reason is that when the frames are larger, the PER becomes higher, and the retransmission increases to be the majority of overhead. It is also shown that the maximum throughputs for the different ACKs are corresponding to different frame sizes, and this is due to the different overhead durations in each ACK.

The MAC layer throughput for a realistic traffic is illustrated in Fig. 12. It can be seen that for the 1 KB payload, the throughputs with Imm-ACK does not significantly depend on the PHY mode. The reason is that the Imm-ACK frame does not have payload, so the transmission time is fixed by the
due to the overhead, the maximum achievable throughput reduced to approximately 3.6 Gbps. Some higher MCSs can not be selected by the link adaptation mechanism because of the high PER at the receiver. It can be seen that using STBC can still effectively extend the operation range at the same MAC throughput compared to SISO case in the same scenario.

IV. CONCLUSION

This paper has presented a performance evaluation of the IEEE 802.11ad 60 GHz mmWave WPAN technology. The system throughput was studied by simulating the PHY modes over 60 GHz typical channel models. The link adaptation mechanism was described and the link throughput results were presented. The performances of MIMO 2×2 STBC in different channel conditions were also studied. The theoretical MAC throughput for different BER, frame sizes and ACKs were calculated. The enhanced methods with frame aggregation and Blk-ACK/Blk-NAK could increase the MAC throughput greatly, and expected to guarantee a high quality of service. Finally, the MAC throughput with both the PHY layer simulation results and the MAC layer efficiency was presented. It has been shown that applying MIMO 2×2 STBC can maintain the high peak throughput and also enhance the transmission coverage significantly. The maximum MAC throughput decreases due to the overheads, but can be improved by choosing an optimum PHY packet size. Hence the results indicated that the cross layer research approach on 60 GHz WPANs is essential.

ACKNOWLEDGMENT

The authors would like to express their sincere appreciation to Blu-Wireless Technology for technical input, and also want to acknowledge the financial support provided by ClearSpeed Technology Ltd and Great Western Research (GWR).

REFERENCES