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On the Performance of IEEE 802.15.3c Millimeter-Wave WPANs: PHY and MAC

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Abstract— The large amount of unlicensed bandwidth available in the millimeter-wave has enabled very high data rate wireless applications. The IEEE 802.15 Task Group 3c has completed 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 the newly published standard. Packet error rate (PER) and PHY throughput are simulated for different modes based on a typical 60 GHz channel model. The theoretical MAC throughput is calculated for different packet sizes and modes under different link conditions. The link adaptation mechanism is used to analyze the operating range versus data rate. The results show that very high data rates can be achieved over low distances.

Keywords— WPAN; 60 GHz; IEEE 802.15.3c; PHY; Channel Model; MAC

I. INTRODUCTION

The demands for multi gigabit per second (Gbps) wireless multimedia services such as uncompressed video and data transmissions have increased in recent years. The 60 GHz millimeter-wave (mmWave) band is of much interest, because it is unlicensed and with a large amount of spectrum available worldwide. The IEEE 802.15 Task Group 3c (IEEE 802.15.3c) is an early formed group working on the wireless personal area network (WPAN), and the standard has been completed in September 2009 [5]. Besides, WirelessHD [1], the Wireless Gigabit Alliance (WiGig) [2], the IEEE 802.11ad working group [3] and the ECMA-387 [4] have been also making standardization efforts on the 60 GHz frequency band.

The IEEE 802.15.3c standard specifies three operating modes and one common mode allowing devices using different PHY modes to communicate. The single carrier (SC) mode is designed for low power and low complexity applications. The high-speed interface (HSI) mode is designed for low latency bidirectional data transferring, and the audio/video (AV) mode is used for delivery of uncompressed high definition video and audio. In [6]–[7], the PHY layer performance of the SC mode is discussed, and an enhancement of the mmWave WPAN MAC is proposed. In this paper, the simulated PHY performance and theoretical MAC throughput of the orthogonal frequency-division multiplexing (OFDM) based HSI and AV modes are investigated. Further, to evaluate the transmission performance,

we analyze the link budget in the considered environment and present throughput results over range.

The rest of the paper is organized as follows. Section II describes the overview of both the IEEE 802.15.3c PHY layer and MAC layer. The channel model for 60 GHz WPANs is described in Section III. Simulation results for the PHY and MAC throughput for both the HSI and AV modes are given in Section IV, and we conclude this paper in section V.

II. OVERVIEW OF IEEE 802.15.3c WPANs

The IEEE 802.15.3c WPAN usage model is defined as a piconet, and the basic component of a piconet is its devices (DEVs). One of the devices is required to act as a piconet coordinator (PNC), which is responsible for registering the members in the piconet, broadcasting timing allocations and managing the piconet. The PHY and MAC features specified in the IEEE 802.15.3c WPAN standard are summarized below.

A. Physical Layer (PHY)

The mmWave PHY operates within the 57.24–65.88 GHz band as allocated by the regulatory agencies worldwide, and the spectrum is then equally divided into four channels. This high spectrum leads to dense frequency reuse, smaller sizes of radio frequency (RF) components, high antenna gain and secure data transmission [8]. However, the high attenuation resulted by oxygen absorption, path loss and multi-path effects make the high data rate transmission difficult to deploy. In baseband, modulation methods are of critical challenge for mmWave communications. The PHY layer of both the HSI and AV modes are very similar and are based on the use of OFDM.

The HSI mode is typically used in an ad-hoc system to connect computers and devices around a conference table. On the other hand, the AV mode supports omni-directional coverage via the low-rate PHY (LRP) to set up connections and uses the high-rate PHY (HRP) to transmit uncompressed HD video streaming. The main difference is that the HSI mode uses OFDM with forward error correction (FEC) based on low-density parity-check (LDPC) code, whereas the AV modes uses FEC based on convolutional code (CC).

Fig. 1 describes the block diagram of the transmitter for the IEEE 802.15.3c WPANs. Data are firstly split into upper and lower branches. The scrambled data are encoded with an LDPC

Figure 1. The block diagram of the transmitter

encoder in the HSI mode, whereas for the AV mode, a Reed-Solomon (RS) code and a convolutional encoder are implemented. For the unequal error protection (UEP) modulation and coding schemes (MCSs), different coding rates are applied to the most significant bits (MSBs) and least significant bits (LSBs). The binary serial input data is then mapped to data symbols according to the modulation schemes. A normalization factor is multiplied to each modulation scheme in order to achieve the same average power. Overall the equal error protection (EEP) modulation dependent parameters and the data rates are listed in Table I.

TABLE I. MODULATION DEPENDENT PARAMETERS

MCS index	Data rate (Mb/s)	Modulation scheme	FEC rate
HSI Mode			
1	1540	QPSK	1/2
2	2310	QPSK	3/4
3	2695	QPSK	7/8
4	3080	16-QAM	1/2
5	4620	16-QAM	3/4
6	5390	16-QAM	7/8
7	5775	64-QAM	5/8
AV Mode			
0	952	QPSK	1/3
1	1904	QPSK	2/3
2	3807	16-QAM	2/3

A tone interleaver is applied before the modulated data are sent to the OFDM modulator. 512 sized IFFT is implemented to form one OFDM symbol, and 336 out of 512 subcarriers are data carriers. The FFT related parameters are listed in Table II. The receiver performs the reverse process.

Figure 2. PHY frame format

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. Fig. 2 shows the format of a PHY frame, including PHY preamble, frame header and payload.

TABLE II. FFT RELATED PARAMETERS

Parameter	Value	
	HSI mode	AV mode
Channel bandwidth (MHz)	1815	1760
Sampling frequency (MHz)	2640	2538
Sample duration (ns)	~0.38	~0.39
Subcarrier frequency spacing (MHz)	5.16	4.96
IFFT and FFT period (ns)	~193.94	~202
OFDM symbol duration (ns)	~218.18	~227
Number of subcarrier/FFT size	512	
Number of data subcarriers	336	
Number of pilot subcarriers	16	
Number of guard subcarriers	141	
Number of DC subcarriers	3	
Number of reserved subcarriers	16	
Guard interval length in samples	64	

B. Medium Access Control Layer (MAC)

In IEEE 802.15.3c, 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. The CSMA/CA is mainly used for control signal transmission, while the TDMA is used for high-speed data transmission. This hybrid multiple access can reduce the data transmission collisions, and also maximize throughput by applying an optimum access time [9].

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

$$\text{Throughput} = \text{Payload} / \text{Transmission Duration} \quad (1)$$

Sources of overhead include gap time, preamble, header fields for the PHY and MAC layers, and ACK frames. The durations of the overhead are listed in Table III. The lengths of acknowledgments (ACKs) are also shown in the table, where n is the number of grouped ACKs. The length of the ACK frames depends on the type of ACK, and there are five types of ACK defined for transmitting data frames in the piconet [5]: no ACK

TABLE III. TIMING AND SPACE PARAMETERS

PHY Parameter	MAC Parameter	Duration (μs)	
		HSI	AV
pPHYMIFSTime	MIFS	0.5	0.5
pPHYSIFSTime	SIFS	2.5	2.08
pCCADetectTime		2.5	9
2×pPHYSIFSTime+pCCADetectTime	RIFS	7.5	13.16
PHY Preamble ($T_{Preamble}$)		1.31	1.82
Frame Header (T_{Header})		0.44	92 octets
Imm-ACK		$T_{Preamble} + T_{Header}$	
Dly-ACK, Blk-ACK, Blk-NAK		$T_{Preamble} + T_{Header} + (7 + 2 \times n) \text{ octets}$

Figure 3. The operations of different acknowledgments [7]

(no-ACK), immediate ACK (Imm-ACK), delayed ACK (Dly-ACK), implied ACK (Imp-ACK), and block ACK (Blk-ACK).

The processes of different ACKs are shown in Fig. 3 [7]. For the No-ACK, the transmitting DEV assumes that the frame is successfully received, and ACK is not sent back to the sender. The Imm-ACK is sent out after a short inter-frame space (SIFS) when an individual frame is received. The Dly-ACK allows the transmitting DEV to send multiple frames, and each frame is followed by a minimum inter-frame space (MIFS). Then the ACKs for each frame are grouped into a single ACK to send back together. The Imp-ACK allows the bi-directional data frames to be used as ACK. 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. The transmitting DEV sends the retransmission frame after the end of a retransmission inter-frame space (RIFS).

III. 60 GHz CHANNEL MODEL

The generic mmWave channel model (CM) includes the characteristics of both large and small scale fading. If the shadowing effect is not taken into account, the average path loss (PL) as a function of distance can be modeled as [11]:

$$\overline{PL}(d)[dB] = PL_0 + 10 \cdot n \cdot \log_{10} \left(\frac{d}{d_0} \right) \quad (2)$$

where PL_0 , n , d_0 and d denote: free space PL at reference distance, PL exponent for mmWave, reference distance and the distance between the transceivers, respectively.

Based on the clustering phenomenon in both the temporal and spatial domains, a statistic channel model, the TSV-model was proposed for the 60 GHz band WPAN small scale fading [10]. It merges the Saleh-Valenzuela model [14] and the two-path model to express sensitive device position dependent fading inherent to mmWave WPAN systems and long delayed spread scattering multipath responses, so that it is suitable when the mmWave devices communicate with directional antennas. The scenario can be classified as residential, office, library, desktop and Kiosk, and for each environment, there are both line-of-sight (LOS) and non-line-of-sight (NLOS) cases. Each of the channel models can be configured by different antenna beam-widths, so we can generate channel responses to reflect the real scenarios. The typical channel model is CM1.3, which is a home environment with multiple furnished rooms, and the antenna beam-width is Tx-30°, Rx-15°.

Figure 4. Example of the power delay profile for CM 1.3

Fig. 4 shows an example of the power delay profile (PDP) of the CM 1.3. The average cluster arrival rate is 21.5 ns, and the average ray arrival rate is 4.35 ns. This channel has the average Rician factor of 11.9 dB. It can be seen that the maximum excess delay is very long (~ 200 ns) due to multipath, and this effect could introduce inter symbol interference (ISI) when OFDM is implemented.

IV. PERFORMANCE ANALYSIS

In this section, firstly the packet error rate (PER) and throughput results are presented using our IEEE 802.15.3c PHY MATLAB simulator and the channel model described in the previous sections. We will then use these results in a link throughput analysis for each mode and present the PHY data rate over range. We will also analyze the MAC layer throughput achieved by each mode considering different ACK strategies, and show the achievable throughput at the MAC layer.

A. PER Performance

Fig. 5 presents the PER performance of the different HSI and AV modes versus the average signal-to-noise-ratio (SNR) for CM 1.3. The PHY payload size of 1 Kilobyte (KB) is used for all modes.

Figure 5. PER performance of different modes, CM1.3

In the HSI mode, the irregular LDPC(672, 336), LDPC(672, 504), LDPC(672, 420) and LDPC(672, 588) codes are used for the FEC rates of 1/2, 5/8, 3/4 and 7/8 respectively. Convolutional encoding with code rate 1/3 is implemented in the AV mode, and then the data are punctured to the desired code rate shown in Table I. At the receiver, the convolutional code is decoded using a soft decision Viterbi algorithm. It can be seen that generally higher data rate requires higher SNR to maintain a certain PER.

Figure 6. PER performance of AV mode 0, CM 1.3, different packet sizes

Fig. 6 presents the PER performance of the AV mode 0 for different payload lengths. It can be seen that larger packet size results in higher SNR requirement to maintain PER performance, which means that either an increase in transmit power or a change of mode might be required. Other modes perform similarly. For this reason, although the maximum frame size is defined as 1 Megabyte (MB) in the standard, large packet sizes are not recommended to be used in the system.

B. Link Throughput and Ranges

The PHY modes with different MCSs are selected by a link adaptation scheme. This enables the system to adapt the transmission mode to the radio link quality. Each packet uses CRC (Cyclic Redundancy Check) block codes for error detection. If a negative ACK is received, the transmitting DEV

will retransmit the packet. The link throughput when retransmission is employed is given by [13]:

$$\text{Throughput} = R(1 - \text{PER}) \quad (3)$$

where R represents the peak error-free transmission rate for a specific mode. The mode with the highest throughput is chosen for each instantaneous SNR value. Fig. 7 and Fig. 8 show the link throughput for the HSI and AV modes respectively, and the link adaptation mechanism is used to enable the system to adapt the transmission mode to the link quality.

Figure 7. Link throughput of HSI mode, CM 1.3

Figure 8. Link throughput of AV mode, CM 1.3

As we discussed in Section III, the operation range of each data rate mode can be calculated from the maximum tolerable path loss. In the 60 GHz systems, the maximum transmit power is 10 dBm [5], and the minimum achievable noise figure (NF) of such devices is 4 dB [15]. Using these numbers we can estimate the link budget initially without considering the antenna gain as: $+10 \text{ dBm} - PL > -84 \text{ dBm (kTB)} + 4 \text{ dB (NF)} + \text{ReceiverSNR}$, or $PL < 90 \text{ dB} - \text{ReceiverSNR}$, where ReceiverSNR is the SNR required for the demodulation. The value of $d_0 = 1 \text{ m}$ is used, and $n = 1.53$, $PL_0 = 75.1 \text{ dB}$ are given from measurements for CM 1 at the mid-band frequency point [12]. Fig. 9 shows the maximum data rate that can be achieved over distance for both the HSI and AV modes, based on equation (2) and the results of Fig. 7 and 8. It can be seen that for the AV mode, the maximum distance the system can tolerant is within about 7 meters, and that the guaranteed high

Figure 9. Maximum PHY data rate over distance for AV mode, CM 1.3

throughput is within about 2 meters. In the HSI mode, the operating range is about 8 meters. These data rates and operating ranges can easily support the typical 60 GHz applications; however, if we want to transmit high data rate beyond this range, higher antenna gain or diversity techniques are required.

C. MAC performance

Using the parameters listed in Table III, we can calculate the theoretical MAC throughput by equation (1). Fig. 10 shows the MAC layer throughput achieved in the HSI mode 4 for different PHY payload sizes and ACKs at a BER= 10^{-6} . 16 blocks for an aggregated frame are assumed. The results for other modes are very similar, but have different achievable throughputs due to the different PHY layer data rates. This figure shows that the MAC throughput increases up to a certain point with the increase of the frame size. This is because a large frame size reduces the number of SIFS and MIFS, 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. In contrast, Fig. 11 shows that the MAC throughput increases as the frame size becomes larger when the BER= 10^{-9} . The reason is that retransmissions do not frequently

Figure 10. Maximum throughput for different packet sizes at a BER= 10^{-6}

Figure 11. Maximum throughput for different packet sizes at a BER= 10^{-9}

occur at good quality channel conditions. It can be seen that frame aggregation with Blk-ACK dramatically increases the MAC efficiency by up to 30% compared to Imm-ACK and Dly-ACK. When the frame size is small, Blk-NAK has even higher efficiency. When the transmitting frame size increases, the throughput for the different ACKs is getting worse since retransmissions occur more frequently due to higher PERs (as shown in Fig. 6). It is also shown that the maximum throughput for the different ACKs is corresponding to different frame sizes, and this is due to the different overhead durations in each ACK.

Figure 12. Maximum MAC throughput achieved by each mode

The MAC layer throughput for a realistic traffic for both the HSI and AV modes are 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 consists of null payload, and the overhead duration is larger compared to the payload for every mode. On the other hand, the theoretical MAC efficiency with Blk-ACK for 1 KB payload varies depending on the PHY mode. This is because for the same sized packets, less transmission time is required in higher data rate modes. However, the time required for SIFS, MIFS and RIFS is independent of the mode, and results in a higher percentage of overhead transmission time for the higher data rate modes. As a result, the higher data rate modes are affected by the ACK more.

D. MAC Layer Results

Fig. 13 and Fig. 14 show the HSI and AV modes link throughput considering the MAC layer overhead for 1 KB payload respectively. It can be seen that although the MAC efficiency with Blk-ACK for 1 KB payload varies from 72% to 96% (as shown in Fig. 12), the mode with the highest throughput for each instantaneous SNR value does not change. However, the link throughput decreases due to the MAC layer overhead, and the percentage of each data rate operation changes, so the maximum achievable distance would decrease correspondingly.

Figure 13. HSI mode cross layer link throughput for 1 KB packet

Figure 14. AV mode cross layer link throughput for 1 KB packet

V. CONCLUSION

In this paper, we have presented a detailed study of the IEEE 802.15.3c standard. The system throughput was studied by simulating both the HSI and AV modes over a 60 GHz typical channel model. The link adaptation mechanism was described and the link throughput results were presented. The achievable transmission range was also investigated. The theoretical MAC throughput for different frame sizes and ACKs was calculated. The maximum achievable MAC throughput also relies on the link quality conditions. The enhanced methods with frame aggregation and Blk-ACK/Blk-NAK could increase the MAC throughput by 30%, and is

expected to guarantee a high quality of service. It has been shown that approximately a 10-30 KB frame size could achieve the maximum MAC throughput under 10^{-6} BER, but this may result in increased retransmissions and delay. Smaller PHY frame sizes can maintain a lower PER at the same SNR requirement, but result in low MAC throughput efficiency. Hence, an optimum packet size needs to be carefully chosen. Finally, the MAC layer throughput considering both the PHY layer simulation results and the MAC layer efficiency were presented.

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REFERENCES

- [1] WirelessHD. [Online]. Available: <http://www.wirelesshd.org/>.
- [2] Wireless Gigabit Alliance. [Online]. Available: <http://wirelessgigabitalliance.org/>.
- [3] IEEE 802.11 Working Group, Very High Throughput in 60 GHz. [Online]. Available: http://www.ieee802.org/11/Reports/tgad_update.htm.
- [4] Standard ECMA-387. High Rate 60 GHz PHY, MAC and HDMI PAL. [Online]. Available: <http://www.ecma-international.org/>.
- [5] IEEE Std 802.15.3c: "Wireless Medium Access Control (MAC) and Physical Layer (PHY) Specifications for High Rate Wireless Personal Area Networks (WPANs), Amendment 2: Millimeter-wave-based Alternative Physical Layer Extension", IEEE, October 2009.
- [6] S. Kato, *et al*, "Single Carrier Transmission for Multi-gigabit 60-GHz WPAN Systems", *IEEE Journal on Selected Areas in Communications*, vol. 27, No. 8, pp. 1466-1478, October 2009.
- [7] C. W. Pyo, F. Kojima, J. Wang, H. Harada, and S. Kato, "MAC Enhancement for High Speed Communications in the 802.15.3c mmWave WPAN", *Wireless Personal Communications*, vol. 51, No. 4, pp. 825-841, December 2009.
- [8] N. Guo, R. C. Qiu, S. S. Mo, and Kazuaki Takahashi, "60-GHz Millimeter-Wave Radio: Principle, Technology, and New Results", *EURASIP Journal on Wireless Communications and Networking*, Volume 2007, Article ID 68253, 8 pages.
- [9] C. W. Pyo, and H. Harada, "Throughput Analysis and Improvement of Hybrid Multiple Access in IEEE 802.15.3c mm-Wave WPAN", *IEEE Journal on Selected Areas in Communications*, vol. 27, No. 8, pp. 1414-1424, October 2009.
- [10] H. Sawada, Y. Shoji, C. S. Choi, "Proposal of Novel Statistic Channel Model for Millimeter Wave WPAN", *Asia-Pacific Microwave Conference*, pp. 1855-1858, December 2006.
- [11] S. K. Yong, "TG3c Channel Modeling Sub-committee Final Report", IEEE 15-07-0584-01-003c, August 2009.
- [12] P. Pagani, I. Siaud, N. Malhouroux W. Li, "Adaptation of the France Telecom 60 GHz channel model to the TG3c framework", IEEE 802.15-06-0218-00-003c, April 2006.
- [13] A. Doufexi, S. Armour, M. Butler, A. Nix, D. Bull, J. McGeehan, and P. Karlsson, "A Comparison of the Hiperlan/2 and IEEE 802.11a Wireless LAN Standards", *IEEE Communications Magazine*, vol. 40, issue 5, pp. 172-180, May 2002.
- [14] A. A. M. Saleh, R. A. Valenzuela, "A Statistical Model for Indoor Multipath Propagation", *IEEE Journal on Selected Areas in Communications*, vol. 5, No. 2, pp. 128-137, February 1987.
- [15] A. M. Niknejad, "Siliconization of 60 GHz", *IEEE Microwave Magazine*, vol. 11, No. 1, pp. 78-85, January 2010.