Analytical and Comparative Investigation of 60 GHz Wireless Channels

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Abstract—**This work analytically studies the channel characteristics of 60 GHz wireless communication, particularly from five aspects: path loss, multi-path fading, spatial diversity, peak-to-average power ratio of OFDM and clear channel assessment. This investigation is performed in comparison to the 2.4 GHz wireless system. The observed merits of the 60 GHz wireless channels include: 1) the support of packing a large number of antennas at a transceiver to exploit spatial diversity, 2) light effect from multi-path fading due to its small average fade duration and 3) a fast detection of signals in carrier sense to achieve clear channel assessment. Its weaknesses consists of: 1) large path losses that lead to short communication ranges and 2) high peak-to-average power ratio that increases the cost and complexity in implementing OFDM in transceivers.**

I. INTRODUCTION

Wireless communication at 60 GHz spectrum is allocated of a large unlicensed bandwidth of at least 5 GHz in many countries around the world. This wide bandwidth makes 60 GHz wireless communications promising to achieve bit rates at Gbps (gigabit per second) to support many bandwidth consuming applications, such as high-definition video, sync-and-go file transfer and wireless display. With these applications and advances in technologies for low cost solutions, 60 GHz technology attracts intensive interests from academia, industry and standardization bodies. For example, IEEE 802.15.3c [1] aims at supporting high rate WPAN transmission and ECMA 387 [2] is developed for high-rate 60 GHz PHY and MAC for short-range unlicensed communications. WirelessHD [3] is a protocol developed for high-definition audio/video streaming. WiGig [4] is dedicated to various Gbps data rate applications and IEEE 802.11-ad is under development to enable Gbps WiFi networks. Compared with conventional unlicensed wireless communication at 2.4/5 GHz, 60 GHz system faces some new technical challenges.

The 60 GHz wireless channel is significantly different in characteristics from the traditional open access spectrum of 2.4/5 GHz. The path loss at 60 GHz is at least 20 dB higher than at 2.4 GHz. To mitigate the significant signal strength attenuation due to the path loss, directional antennas and antenna array with high transmitted power are proposed to achieve a high antenna gain. With the carrier wavelength of 5 mm, antenna array can be implemented intensively at both transmitter and receiver. Besides, 60GHz regulation allows high transmission power to tackle the severe signal attenuation problem. MIMO with multiple antennas can also alleviate the effect of flat fading by exploiting the transmitter and/or receiver diversity. The multi-path fading problem is worsened on the large bandwidth provided by the 60 GHz system for very high data rates. As a result, the frequency selective fading dominates the wireless communication on 60 GHz spectrum. Technologies that address the frequency-selective fading must be taken into consideration. OFDM is a simple and flexible solution. However, the high peak-to-average signal strength ratio presents challenges, especially when a large bandwidth is split into a number of sub-channels in OFDM. Another problem of the 60GHz system is the overhead of the MAC layer. As the immense increase of the data rate, MAC layer protocols require renovation for high utilization and efficiency.

In this paper, we analytically investigate the wireless commutation at 60 GHz in comparison with the traditional 2.4 GHz in **five** aspects. *First*, we present the large path loss of the 60 GHz frequency band upon the communication distance that is determined on the cell coverage area and the outage probability. *Second*, after analyzing the effects of large-scale propagation, we then visit the small-scale multi-path fading in the wireless communication. The average fade duration is inspected. *Third*, to counteract the multi-path fading, we compare the performance of the spatial diversity gain that can be achieved with the antenna array. *Fourth*, to eliminate the frequency-selective fading, OFDM multi-carrier modulation technology can be employed. We present the high peak-to-average signal strength ratio problem in OFDM due to the large bandwidth of 60 GHz system. *Finally*, we examine the detection time of clear channel assessment and suggest our enhancement that can lead to significant improvement on the protocol efficiency at the MAC layer at 60 GHz.

The rest of this paper is organized as follows. We briefly introduce the related work in Section II. Then, the merits of 60 GHz are summarized in Section III and the weaknesses are presented in Section IV. Finally, the paper is concluded in Section VI.

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II. SUMMARY OF RELATED WORK

From 2.4/5 GHz to 60 GHz carrier frequency, there are some unprecedented challenges. Particularly, large path loss is one of the major challenges, which makes the 60 GHz band unsuitable for outdoor long-distance wireless communication. Most of literature work focused on measurement-based study of the wireless channels at 60 GHz in short-distance communication and indoor environments. Xu *etc.* [5] presented the measurements that reveal the spatial and temporal properties of millimeter-wave (another name of 60 GHz wireless) channels. Anderson *etc.* [6] described the measured data of the path loss in an office building. Moraitis *etc.* [7] reported the path loss measurements for both line-of-sight (LOS) and non-line-of-sight (NLOS) cases between fixed terminals. Geng *etc.* [8] showed the measurement results of the 60 GHz radio propagation in various indoor environments. All these works provide the understanding of the radio wave propagation at millimeter wave length at 60 GHz frequency. The empirical data can be useful for designing wireless systems working on 60 GHz channels. Though, we present an analytical study of 60 GHz channels in this work.

III. MERITS OF 60 GHZ WIRELESS CHANNELS

A. The detection time of Clear Channel Assessment

Wireless communication at 60 GHz spectrum provides much higher data rates than at 2.4GHz. However, the considerable overhead of the MAC layer incurred by the high bit rates significantly hurt the efficiency and utilization of the channel and system. Recent research work [19] revealed that the overhead reaches 45% at 54 Mbps and 82% at 300 Mbps and rises up to 91% at 600 Mbps. This inefficiency can be easily understood from an illustration. Let us define utilization as $\lambda = \frac{t}{T+t}$ where t represents the time in transmitting a frame and T refers to the time of protocol overhead. In current IEEE 802.11 standard, T consists mainly of the backoff process, physical layer preamble, and channel piloting. In T, the backoff process is based on a number of time slots and the physical preamble is *always* sent at the base rate of 6 Mbps. The time slot has a constant duration regardless of the bit rate. Therefore, T does not vary much because it is dominated by the preamble transmission and the backoff procedure (constant time slot size) while t decreases when the frame transmission rate increases. For example, if the bit rate increases from 100 Mbps to 1 Gbps, then the channel utilization at 1 Gbps becomes $\lambda = \frac{0.1t}{T+0.1t} = \frac{t}{10T+t}$, much worse than $\frac{t}{T+t}$ in 100 Mbps networks. It is clear that the channel utilization is significantly hurt at high bit rates, because *the time spent on transmitting data frames drastically decreases with high bit rates while the time in protocol overhead remains almost constant (regardless of frame bit rate)*. Therefore, as the bit rate increase, the inefficiency worsens as well.

One possible solution to address the problem mentioned above is to redesign the time to spend on carrier sense and thus shorten the time slot duration that depends on the carrier sense time. Clear Channel Assessment (CCA) is the core of carrier sense in the medium access control protocols for wireless networks, which is implemented at the PHY layer. Therefore, it is of most interest for us to analyze the CCA at 60 GHz. The energy detection technique employed in the analysis is a simple and energy-efficient method, called Neyman-Pearson detector [20], that is widely used in the wireless channel sensing. The performance is analyzed with Neyman-Pearson theorem [20]. Figure 1 plots the detection probability (detection accuracy) on the y-axis upon SNR and the number of symbols monitored in the detection on the x-axis.

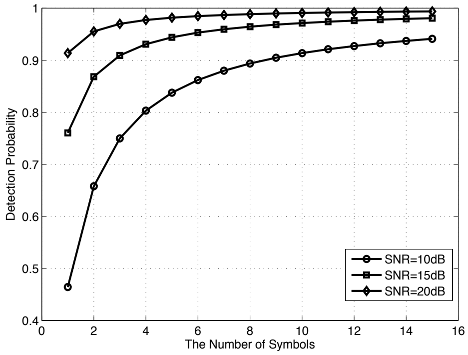

Fig. 1: CCA accuracy upon SNR and the number of symbols

From the figure, the CCA accuracy varies upon the number of symbols involved in the detection. Therefore, the CCA detection is normally conducted by detecting the signal strength of a designated number of symbols. The probability of detection is subject to a given probability of false alarm. Assume that the required probability of false alarm is 0.01 and the required probability of detection is greater than 0.9. The typical minimum receive SNR sensitivity is 10 dB. From Figure 1, eight symbols are required for accurate CCA.

After the required number of symbols for the CCA is determined, the CCA time relies on the bit rate at which these symbols is transmuted. With a specific CCA detection technique that works on the same number of symbols, because the 60 GHz system provides much higher bit rates than the 2.4 GHz system, the CCA detection time can be greatly shortened. Specifically, for BPSK modulation, the basic bit rate at 2.4 GHz is 2 Mbps, but it is 200 Mbps at 60 GHz with a bandwidth of 200 MHz. As a result, the detection time at 60GHz can be as small as 0.04μs, which is significantly shorter than that at 2.4 GHz.

B. The effect of multi-path fading

In wireless communication on the land, the signal normally propagates through multiple paths to arrive at a receiver due to reflection, diffraction and scattering from the surrounding environment. The multi-path phenomenon is particularly popular in urban and indoor environments. The signal strength of the received signal widely varies in both space and time due to multi-path fading. For some low latency and high-quality wireless applications, such as real-time wireless display and gaming, small-scale multi-path fading highly affects the performance of these applications. The low latency service requires stable data communication, that says, it expects the duration in which the received signal strength drops below the minimum level due to multi-path fading is as short as possible. The average fade duration delineates how fast the multi-path fading is and how much it affects the communication performance. It is defined as the average time that the received signal strength falls below the minimum level required to maintain acceptable performance. The average fade duration tells the impact of multi-path fading on the performance of wireless communication. A large average fade duration is likely to incur Inter-Symbol-Interference (ISI) because the prior signal coming from the longest path may arrive when the current signal is being received. The thumb rule is that *the shorter the average fade duration is, the less the transmitted signal is affected.*

We analyze the the average multi-path fading duration at both 60 GHz and 2.4 GHz. In our analysis, Rayleigh fading [15] is used as the channel model because it is widely accepted for urban and indoor wireless communication. The average fade duration on Rayleigh fading channels [11] can be calculated as:

$$\bar{T} = \frac{e^{\rho^2} - 1}{\rho f_D \sqrt{2\pi}} \qquad (1)$$

, where f_D is the maximum Doppler shift, and $\rho = \sqrt{P_{min}/\bar{P}_r}$. P_{min} is the required minimal received power; and $\bar{P}_r$ is the average received power. For Rayleigh fading, the received signal strength varies due to the constructive and destructive addition of multi-path signal components. Our calculation takes the typical value 0.1 for ρ. The average fade duration decreases with the maximum Doppler shift f_D. In the indoor case with pedestrian speed (about 1.5 meters per second), the maximum Doppler shift is about 300 Hz for the 60 GHz system and 12 Hz for the 2.4GHz system. According to Formula 1, the average fade durations are 11.1 ms and 0.44 ms respectively for 2.4 GHz and 60 GHz respectively. Therefore, 60 GHz shows small average fade duration that leads to *light* fast fading impact. This is validated by the following illustration. We plot the signal strength variation over the time in Figure 2. The communication at 2.4 GHz is enabled at 100 Mbps (a typical bit rate in the IEEE 801.11n) and that at 60 GHz is enabled at 1 Gbps. It is obvious from the figure that the signal strength of the 60 GHz communication varies much faster than the 2.4 GHz communication. Namely, the average fade duration of 60 GHz is much shorter. Therefore, the 60GHz is robust to multi-path fading in short distance communication. Even though the data rate is increased to 1 Gbps at 60 GHz, it is still less likely for the information bits to be damaged by fast fading within the average fading duration than in the 2.4 GHz system.

C. Spatial Diversity for Fading Mitigation

Fading over wireless channels leads to signal degradation, especially over deep fading channels. To mitigate the effects of fading, one possible solution is to constructively combine at a receiver the signals from multiple independent paths by positively exploiting the multi-path propagation popular in land wireless communication. Because it is mostly unlikely that all transmissions on these paths experience deep fading at the same time, the combined signal at the receiver normally reduces the error probability. The fact that each propagation path results in different fading in wireless communication is called spatial diversity. One approach to exploit the spatial diversity is to equip multiple antennas so that the signal transmitted or received from each antenna propagates over different path. The benefit of multiple antennas at a sender is called transmuter diversity and that at a receiver is called receiver diversity.

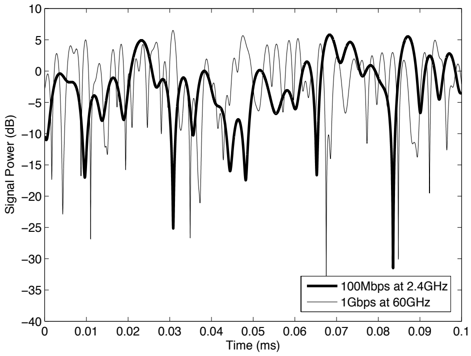

Fig. 2: The variance of received signal amplitude over time due to fast fading

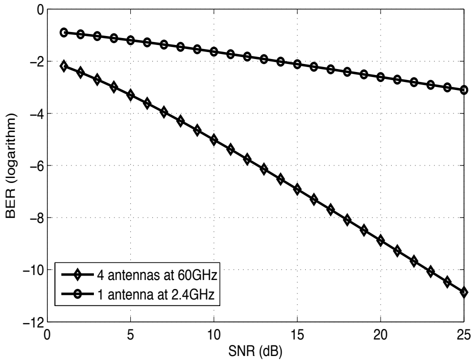

Fig. 3: Bit Error Rate in Spatial Diversity

The number of antennas can be equipped is constrained by the wavelength of the carrier frequency: the distance between two antennas is required to be at least 0.4 of the wavelength. Because of its short wavelength, the 60 GHz system allows packing more antennas on a chip than the 2.4 GHz system. The wavelength at 60GHz is 5 mm. On the other hand, the wavelength at 2.4GHz is 125 mm, which is 25 times of that at 60GHz. The separation distances between antennas required for independent fading paths are 50mm and 2mm for systems at 2.4GHz and 60GHz respectively. As a result, in an area of $30 \times 30\, mm^2$, we can only install one antenna for the 2.4 GHz system, but four antennas or even more to provide diversity gain for the 60 GHz system.

With multiple antennas, the 60GHz system can significantly mitigate the impact of the multi-path fading. In addition, the gain of antenna array enables high level modulation that leads to high bit rate, while maintaining low bite-error-rate

(BER). In Figure 3, we plot the BER for the wireless channels at both 60 GHz with four antennas and 2.4 GHz but with only one antenna with the assumption of the antenna area of $30 \times 30\,mm^2$. The y-axis refers to the BER and the x-axis stands for the signal-to-noise-ratio (SNR). The figure shows the significant improvement on the BER with the antenna array exploiting the spatial diversity. Therefore, although the path loss in the 60 GHz system is large and fast, the signal strength degradation can be compensated to some degree by exploring the spatial diversity with multiple antennas, which are facilitated due to the short wavelength of the 60 GHz spectrum.

IV. WEAKNESSES OF 60 GHZ WIRELESS CHANNELS

A. *Large-scale Propagation*

Large-scale propagation is important for the link budget and network planning. The carrier frequency spectrum of 60 GHz incurs large path losses. As a result, the ranges of the communication system are greatly shrunk. The large-scale propagation consists of two portions: path loss and shadowing. Path loss refers to the attenuation of transmitted signal strength over the communication distance. It is defined as the ratio of the transmitted signal strength to the receive signal strength. Shadowing is a result of the variation of the propagation path. Log-normal shadowing is the most common model for shadowing. Many measurements have suggested that shadowing on 60 GHz channels follows log-normal distributions [9], [10]. The received signal strength in long-distance wireless communications is primarily determined by the path loss and shadowing. Therefore, the communication range of a wireless system is designed upon the path loss and shadowing models. The conventional simplified models can be used to capture the large-scale propagation and analyze the valid communication range, which depend on two factors: outage probability and cell coverage.

In wireless communication, outage probability and cell coverage are two critical metrics in performance analysis [11]. The outage probability, as in Formula 2, is the probability that the received signal strength at a given distance falls below the minimum required signal strength.

$$p(P(d) \leq P_{min}) = 1 - Q(\frac{P_{min} - (P_t - PL(d))}{\sigma}) \qquad (2)$$

,where P_{min} is the required minimum received power; σ is the standard variation of shadowing fading; and $Q(x)$ is the probability that a Gaussian random variable X ,with the mean of 0 and the variance of 1, is greater than x.

The cell coverage, as in Formula 3, is the expected percentage of the area within a cell where the received signal strength is above a given minimum:

$$C \approx Q(\alpha) + exp(\frac{2 - 2\alpha\beta}{\beta^2}) \cdot Q(\frac{2 - \alpha\beta}{\beta}) \qquad (3)$$

$$\alpha = \frac{P_{min} - P_r(D)}{\sigma}, \quad \beta = \frac{10n \cdot log_{10}(e)}{\sigma}$$

, where $P_r(D)$ is the received power at the edge of the cell; σ and $Q(x)$ are similarly defined as in Formula 2. The size of the cell should be so determined that the minimal received SNR is guaranteed to maintain the quality of service.

The cell coverage and the outage probability are crucial for system cost analysis and network planning. In designing the range of a wireless communication system, we must keep the outage probability below a certain level, while keeping the cellular coverage above a specific level in order to maintain the acceptable performance in most areas of the cell.

In the following, we analyze the cell size of 60 GHz wireless communication and compare it to that of 2.4 GHz technology. The analysis is focused on the indoor non-line-of-sight (NLOS) case where there is no direct path between a sender and a receiver. We employ the path loss model as in Formula 4 proposed by the IEEE 802.11n [12], [13] for 2.4 GHz wireless channels and the model as in Formula 5 proposed by the IEEE 802.11ad [14] for 60 GHz wireless channels.

$$PL(d) = PL_{FS}(d) \quad d \leq d_{BP} \qquad (4)$$
$$PL(d) = PL_{FS}(d_{BP}) + 35log_{10}(d/d_{BP}) \quad d > d_{BP}$$

In the IEEE 802.11n channel model for 2.4GHz, the path loss model consists of the free space loss PL_{FS} up to a breakpoint distance and a slope of 3.5 after the breakpoint distance. In our analysis, d_{BP} is set to 5 meters; and the standard variation of the shadowing is 4 dB.

$$PL(d) = K + 20 \cdot log_{10}(f_c) + 10n \cdot log_{10}(d) \qquad (5)$$

In the IEEE 802.11ad channel model for 60 GHz, K and n are constants that depend on the scenarios. f_c is the carrier frequency which is 60GHz. In our analysis, we consider the living room NLOS scenario, where K is 44.7 and n is 1.5. The standard variation of the shadowing is 3.4 dB.

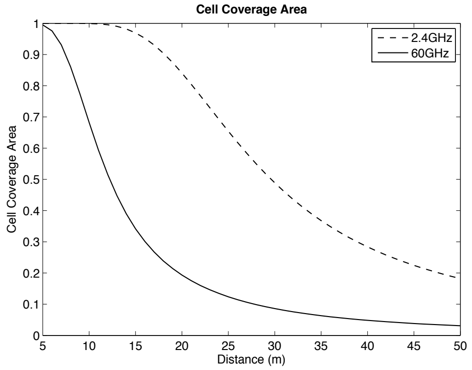

Fig. 4: Analysis of cell size (coverage)

In the analysis, the transmitted signal strengths take the suggested values from the regulations: 35 dBm for 60 GHz and 25 dBm for 2.4 GHz. The receiver minimum input sensitivity is assumed the typical value of -60 dBm in calculating the coverage and the outage probability. Figure 4 depicts the coverage variation on the y-axis upon the communication distance on the x-axis. From the figure, to provide 99.5% coverage of a cell, the 60 GHz communication can only support a cell of 5 meters in radius due to its fast path loss upon distance, while the 2.4 GHz communication can support up to about

11 meters. Figure 5 shows the outage probability analysis with the probability on the y-axis and the distance on the x-axis. Similar to the coverage, to limit the outage probability to no greater than 1%, which approximately corresponds to the 99.5% coverage, the communication in the 60 GHz system has to be remained within 5 meters while the 2.4 GHz system doubles the range to 11 meters. From these two figures, even with higher suggested transmission power, the range of the communication system at 60 GHz is significantly smaller than that at 2.4 GHz. Some possible solutions to compensate the high path loss are to take advantage of directional antenna technologies or antenna array to achieve antenna gains or transmitter/receiver diversity.

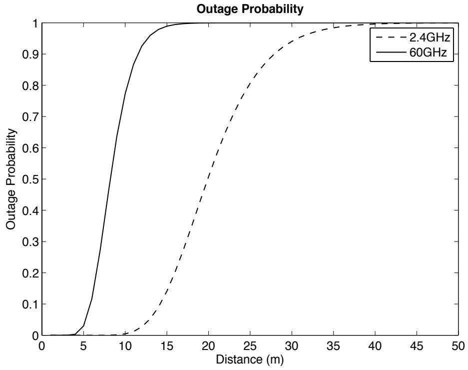

Fig. 5: Analysis of outage probability

V. PEAK-TO-AVERAGE SIGNAL STRENGTH RATIO OF OFDM

In 60GHz wireless communication system, a wide bandwidth is provided for high data rate transmissions. However, the wide bandwidth also leads to frequency-selective fading that incurs unstable wireless channels and worsens bit errors. To achieve a high data rate while maintaining a high quality of service, technologies that overcome the frequency-selective fading must be employed.

Orthogonal frequency division multiplexing (OFDM) is widely used in wireless networks to mitigate frequency-selective fading. In OFDM, a wide bandwidth is split into a number of small sub-channels (subcarriers). Each sub-channel has a narrow bandwidth so that the channel experiences flat fading. Although the bit rate of each sub-channel is lower, the aggregated bit rates of all sub-channels is similar to that of the whole wide bandwidth. The information bits will be scheduled to transmit across sub-channels in parallel. OFDM exhibits excellent performance in wireless communication that suffers from frequency-selective fading. In addition, the cyclic prefix of OFDM avoids the inter-symbol interference.

The main problem of OFDM is the high peak-to-average signal strength ratio (PAR). PAR is defined as the ratio of the maximum instant signal strength to the average signal strength. OFDM multi-carrier signals normally experience a much larger variance of PAR than single-carrier signals because it sums up the signals of all subcarriers. The high PAR requires the transmitted signal strength amplifier have a large linear region to avoid signal distortion and spectral growth. Besides, the receiver A/D converter must support large dynamic range of the signal. These requirements add complexity and cost of the implementation of transceivers.

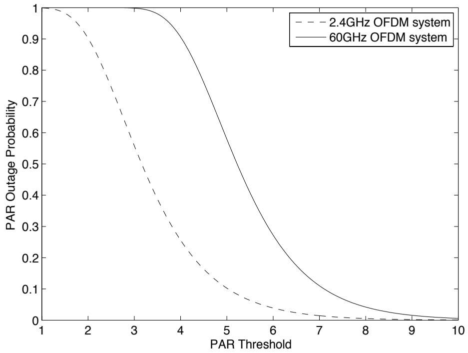

Fig. 6: PAR outage probability

We analyze the PAR performance of OFDM at 60 GHz. Because the maximum instant signal strength rarely occurs, the cumulative distribution of the PAR above a given threshold is normally used to evaluate the PAR performance. Our analysis considers indoor environments that typically have the delay spread (T_{ds}) of 50 ns. In the 2.4 GHz system, the bandwidth is taken as 20 MHz as suggested by the IEEE 802.11 standard. In the 60 GHz system, the bandwidth is considered of 200 MHz for communication. The number of approximately flat-fading subcarriers (N) generated in each spectrum must be large enough to guarantee that each subcarrier bandwidth (B/N) is much smaller than the coherent bandwidth B_c, namely, $B/N \ll B_c$ or, in practice, $B/N \approx 0.1 \times B_c$, where B refers to the total bandwidth. With the relation: $B_c \approx \frac{1}{T_{ds}}$ and the practical Fast Fourier Transformation (FFT) implementation, accordingly, the required minimum numbers of subcarriers are 16 and 128 for 2.4 GHz and 60 GHz respectively. The probability that PAR exceeds a threshold (P_0) is

$$p(PAR \geq P_0) = 1 - (1 - e^{-P_0})^N \tag{6}$$

, where N is the number of sub-channels [11], [16]. Figure 6 shows the PAR outage probability for OFDM at 6o GHz of 128 subcarriers and 2.4 GHz of 16 subcarriers.

The 60 GHz system is allocated of a larger bandwidth than 2.4 GHz. Therefore, it can support much higher bit rates, but requires more subcarriers in order to mitigate the frequency-selective fading at the cost of higher PAR and outage probability. Therefore, it calls for innovative schemes to reduce the PAR with low signal distortion at 60 GHz [17], [18].

VI. CONCLUSION

This paper analytically investigates the wireless channel characteristics at 60 GHz band by comparing with those at 2.4 GHz. With high bit rates from the wide bandwidth, the 60GHz system can achieve a fast detection of signals in Clear Channel Assessment in performing carrier sense. For the small-scale multi-path fading, the Doppler shift increases when the frequency shifts from 2.4 GHz to 60 GHz. As a result, the average fading duration becomes shorter at 60 GHz. Therefore, the 60GHz system suffers less from multi-path fading than the 2.4GHz system. The spatial diversity is a feasible approach to overcome the multi-path fading. With a 5 mm wave length, the 60 GHz system allows to pack more antennas in a tiny area at a transceiver than the 2.4GHz system. Therefore, the spatial diversity can be exploited to support Gbps data rates with low bit error rate. Wireless communication at 60GHz carrier frequency has a wide bandwidth. Due to fast and large path loss, the 60 GHz system can support only a communication range approximately half of the range at 2.4GHz with 1% outage probability and 99.9% cell coverage. The wide bandwidth leads to the problem of frequency-selective fading. OFDM is an effective way to alleviate this problem. However, large bandwidth requires a large number of sub-channels in OFDM. As a result, the high peak-to-average power ratio incurs high implementation cost for transceivers.

VII. ACKNOWLEDGEMENT

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