Research Article

An Overview of Multigigabit Wireless through Millimeter Wave Technology: Potentials and Technical Challenges

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This paper presents an overview of 60 GHz technology and its potentials to provide next generation multigigabit wireless communications systems. We begin by reviewing the state-of-art of the 60 GHz radio. Then, the current status of worldwide regulatory efforts and standardization activities for 60 GHz band is summarized. As a result of the worldwide unlicensed 60 GHz band allocation, a number of key applications can be identified using millimeter-wave technology. Despite of its huge potentials to achieve multigigabit wireless communications, 60 GHz radio presents a series of technical challenges that needs to be resolved before its full deployment. Specifically, we will focus on the link budget analysis from the 60 GHz radio propagation standpoint and highlight the roles of antennas in establishing a reliable 60 GHz radio.

1. INTRODUCTION

Despite millimeter wave (mmWave) technology has been known for many decades, the mmWave systems have mainly been deployed for military applications. With the advances of process technologies and low-cost integration solutions, mmWave technology has started to gain a great deal of momentum from academia, industry, and standardization body. In a very broad term, mmWave can be classified as electromagnetic spectrum that spans between 30 GHz to 300 GHz, which corresponds to wavelengths from 10 mm to 1 mm [1]. In this paper, however, we will focus specifically on 60 GHz radio (unless otherwise specified, the terms 60 GHz and mmWave can be used interchangeably), which has emerged as one of the most promising candidates for multigigabit wireless indoor communication systems [2]. 60 GHz technology offers various advantages over current or existing communications systems [3]. One of the deciding factors that makes 60 GHz technology gaining significant interest recently is due to the huge unlicensed bandwidth (up to 7 GHz) available worldwide. While this is comparable to the unlicensed bandwidth allocated for ultra wideband (UWB) purposes [4], 60 GHz bandwidth is continuous and less restricted in terms of power limits. This is due to the fact

that UWB system is an overlay system and thus subject to very strict and different regulations [5]. The large bandwidth at 60 GHz band is one of the largest unlicensed bandwidths being allocated in history. This huge bandwidth represents high potentials in terms of capacity and flexibility that makes 60 GHz technology particularly attractive for gigabit wireless applications. Furthermore, 60 GHz regulation allows much higher transmit power compared to other existing wireless local area networks (WLANs) and wireless personal area networks (WPANs) systems. The higher transmit power is necessary to overcome the higher path loss at 60 GHz. While the high path loss seems to be disadvantage at 60 GHz, it however confines the 60 GHz operation to within a room in an indoor environment. Hence, the effective interference levels for 60 GHz are less severe than those systems located in the congested 2–2.5 GHz and 5–5.8 GHz regions. In addition, higher frequency reuse can also be achieved per indoor environment thus allowing a very high throughput network. The compact size of the 60 GHz radio also permits multiple antennas solutions at the user terminal that are otherwise difficult, if not impossible, at lower frequencies. Comparing to 5 GHz system, the form factor of mmWave systems is approximately 140 times smaller and can be conveniently integrated into consumer electronic products.
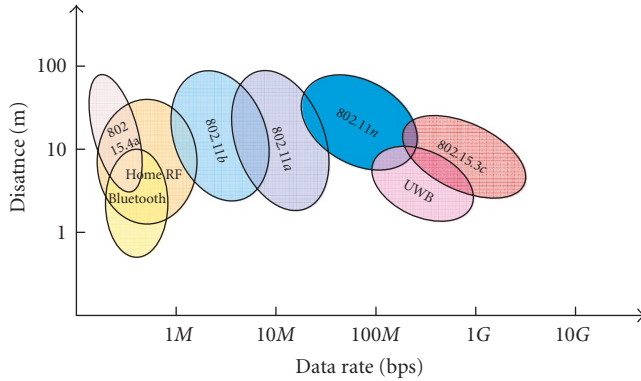
FIGURE 1: Data rates and range requirements for WLAN and WPAN standards and applications. Millimeter wave technology, that is, IEEE 802.15.3c is aiming for very high data rates.

Despite the various advantages offered, mmWave based communications suffer a number of critical problems that must be resolved. Figure 1 shows the data rates and range requirements for number of WLAN and WPAN systems. Since there is a need to distinguish between different standards for broader market exploitation, the IEEE 802.15.3c is positioned to provide gigabit rates and longer operating range. At these rate and range, it will be a nontrivial task for mmWave systems to provide sufficient power margin to ensure reliable communication link. Furthermore, delay spread of the channel under study is another limiting factor for high speed transmissions. Large delay spread values can easily increase the complexity of the system beyond the practical limit for equalization.

The remainder of the paper is organized as follows: Section 2 describes the worldwide regulatory efforts and standardization activities; Section 3 presents a number of application scenarios and highlights the requirements for a specific application namely uncompressed high definition video streaming; Section 4 analyses the achievable data rate in both additive white Gaussian noise (AWGN) and fading channel based on the application requirements described in Section 3 and the roles of antenna in 60 GHz communications are also discussed; Section 5 describes the technical challenges that need to be resolved ahead for the full deployment of 60 GHz radio; finally, in Section 6 appropriate conclusions wrap up this paper.

2. WORLDWIDE REGULATIONS AND STANDARDIZATION

This section discusses the current status of worldwide regulation and standardization efforts for 60 GHz band. Regulatory body in United States, Japan, Canada, and Australia have already set frequency bands and regulations for 60 GHz operation while in Korea and Europe intense efforts are currently underway. A summary for the issued and proposed frequency allocations and main specifications for radio regulation in a number of countries is given in Table 1.

2.1. 60 GHz regulations in North America

In 2001, the United States Federal Communication Commissions (FCC) allocated 7 GHz in the 54–66 GHz band for unlicensed use [6]. In terms of the power limits, FCC rules allow emission with average power density of $9 \mu W/cm^2$ at 3 meters and maximum power density of $18 \mu W/cm^2$ at 3 meters, from the radiating source. These figures translate to average equivalent isotropic radiated power (EIRP) and maximum EIRP of 40 dBm and 43 dBm, respectively. FCC also specified the total maximum transmit power of 500 mW for an emission bandwidth greater than 100 MHz.

The devices must also comply with the radio frequency (RF) radiation exposure requirements specified in [6, Sections 1.307(b), 2.1091, and 2.1093]. After taking the RF safety issues into account, the maximum transmit power is limited to 10 dBm. Furthermore, each transmitter must transmit at least one transmitter identification within one-second interval of the signal transmission. It is important to note that the 60 GHz regulation in Canada, which is regulated by Industry Canada Spectrum Management and Telecommunications (IC-SMT) [7], is harmonized with the US.

2.2. 60 GHz regulations in Japan

In year 2000, the Ministry of Public Management, Home Affairs, Posts, and Telecommunications (MPHPT) of Japan issued 60 GHz radio regulations for unlicensed utilization in the 59–66 GHz band [8]. The 54.25–59 GHz band is however allocated for licensed use. The maximum transmit power for the unlicensed use is limited to 10 dBm with maximum allowable antenna gain of 47 dBi. Unlike in North America, Japanese regulations specified that the maximum transmission bandwidth must not exceed 2.5 GHz. There is no specification for RF radiation exposure and transmitter identification requirements.

2.3. 60 GHz regulation in Australia

Following the release of regulations in Japan and North America, the Australian Communications and Media Authority (ACMA) has taken a similar step to regulate 60 GHz band [9]. However, only 3.5 GHz bandwidth is allocated for unlicensed use, that is, from 59.4–62.9 GHz. The maximum transmit power and maximum EIRP are limited to 10 dBm and 51.7 dBm, respectively. The data communication transmitters that operate in this frequency band are limited to land and maritime deployments.

2.4. 60 GHz regulation in Korea

In June 2005, mmWave Frequency Study Group (MFSG) was formed under the Korean Radio Promotion Association [12]. The MFSG has recommended a 7 GHz unlicensed spectrum from 57–64 GHz without limitation on the types of application to be used. The maximum transmit power is the same as in Japan and Australia, that is, 10 dBm but the maximum allowable antenna gain is still under discussion. Currently, the

TABLE 1: Frequency band plan and limits on transmit power, EIRP, and antenna gain for various countries.

Region	Unlicensed bandwidth (GHz)	Tx Power	EIRP	Max. Antenna gain	Ref	Comment
USA	7 GHz (57–64)	500 mW (max)*	40 dBm (ave)* 43 dBm (max)#	NS	[6]	* For bandwidth> 100 MHz + Translate from average PD of 9 uW/cm² at 3 m # Translate from average PD of 18 uW/cm² at 3 m
Canada	7 GHz (57–64)	500 mW (max)*	40 dBm (ave)* 43 dBm (max)#	NS	[7]	* For bandwidth> 100 MHz + Translate from average PD of 9 uW/cm² at 3 m # Translate from average PD of 18 uW/cm² at 3 m
Japan	7 GHz (59–66), max 2.5 GHz	10 mW (max)	NS	47 dBi	[8]	
Australia	3.5 GHz (59.4–62.9)	10 mW (max)	150 W (max)	NS	[9]	Limited to land and maritime deployment
Korea	7 GHz (57–64)	10 mW (max)	TBD	TBD	[10]	Frequency allocation expected in Jun, 06 Radio regulation expected by End of 06
Europe	9 GHz (57–66), min 500 MHz	20 mW (max)	57 dBm (max)	37 dBi	[11]	Recommendation by ETSI

60 GHz regulation efforts in Korea are in the final stage of public hearing forum [10] in which the frequency band allocation is expected to take place in June 2006. The final radio regulation is scheduled to be completed by December 2006.

2.5. 60 GHz regulation in Europe

The European Telecommunications Standards Institute (ETSI) and European Conference of Postal and Telecommunications Administrations (CEPT) have been working closely to establish a legal framework for the deployment of unlicensed 60 GHz devices. In general, 59–66 GHz band has been allocated for mobile services without specific decision on the regulations. The CEPT Recommendation T/R 22–03 has provisionally recommended the use of 54.25–66 GHz band for terrestrial and fixed mobile systems [13]. However, this provisional allocation has been recently withdrawn.

The European Radiocommunication Committee (ERC) considered the use of 57–59 GHz band for fixed services without requiring frequency planning [14]. Later, the Electronic Communications Committee (ECC) within CEPT recommended the use of point-to-point fixed services in the 64–66 GHz band [15]. In the most recent development, ETSI proposed 60 GHz regulations to be considered by ECC for WPAN applications [11]. Under this proposal, 9 GHz unlicensed spectrum is allocated for 60 GHz operation. This band represents the union of the bands currently

approved and under proposed as described from Section 2.1 to Section 2.4. In addition, a minimum spectrum of 500 MHz is required for the transmitted signal with maximum EIRP of 57 dBm. No specification is given for the maximum transmit power and maximum antenna gain. This proposal is expected to be submitted to ECC by September 2006 and ETSI would request ECC to finalize the new deliverable proposal by the end of 2006.

2.6. Industrial standardization efforts

The first international industry standard that covers 60 GHz band is the IEEE 802.16 Standard for local and metropolitan area networks [16]. However, this is a licensed band and is used for line-of-sight (LOS) outdoor communications for last mile connectivity. In Japan, two standards related to 60 GHz band were issued by Association of Radio Industries and Business (ARIB), that is, the ARIB-STD T69 [17] and ARIB-STD T74 [18]. The former is the standard for mmWave video transmission equipment for specified low-power radio station (point-to-point system), while the latter is the standard for mmWave ultra high-speed WLAN for specified low-power radio station (point-to-multipoint). Both standards cover the 59–66 GHz band defined in Japan.

The interest in 60 GHz radio continued to grow with the formation on mmWave Interest Group and Study Group within the IEEE 802.15 Working Group for WPAN. In March

2005, the IEEE 802.15.3c Task Group (TG3c) was formed to develop an mmWave-based alternative physical layer (PHY) for the existing IEEE 802.15.3 WPAN Standard 802.15.3-2003 [2]. The developed PHY is aimed to support minimum data rate of 2 Gbps over few meters with optional data rates in excess of 3 Gbps. This is the first standard that addresses multigigabit wireless systems and will form the key solutions to many data rates starving applications especially related wireless multimedia distribution.

In other development, WiMedia Alliance has recently announced the formation of WiMedia 60 GHz Study Group with the aim to provide recommendations to the WiMedia Board of Directors on the feasibility issues related to 60 GHz technology. Decision will be taken in the near future about WiMedia direction and involvement in 60 GHz market [19].

3. APPLICATION SCENARIOS

With the allocated bandwidth of 7 GHz in most countries, mmWave radio has become the technology enabler for many gigabit transmission applications that are technically constrained at lower frequency. Due to the higher path loss and oxygen absorption of 15 dB/km around 60 GHz band, 60 GHz radio is thus limited for indoor applications. A number of applications are envisioned such as high definition multimedia interface (HDMI) cable replacement/uncompressed high definition (HD) video streaming, mobile distributed computing, wireless docking station, wireless gigabit Ethernet, fast bulky file transfer, wireless gaming, and so forth. However, as shown in the IEEE 802.15.3c meeting in Jacksonville, FL, USA, TG3c envisaged the wireless HD streaming is the most attractive application among the others [20]. We will therefore concentrate on this particular application scenario and describe the technical requirements for its operation.

Depending on the progressive scan resolution and number of pixels per line, the data rates required varies from several hundreds Mbps to few Gbps. The latest commercially available high definition television (HDTV) resolution is 1920 × 1080 with refresh rate of 60 Hz. Considering RGB video formats with 8 bits per channel per pixel, the required data rates turns out to be approximately 3 Gbps. In the future, a higher number of bits per channel as well as higher refresh rates are expected to improve the quality of next generation HDTV. This easily scales the data rate to well beyond 5 Gbps. Table 2 summarizes data rates requirements for some current and future HDTV specifications. Furthermore, uncompressed HD streaming is an asymmetry transmission with significantly different data flow in both uplink and downlink directions. This application also requires very low latency of tens of microseconds and very low error probability down to 10^{-12} to ensure high quality video. Table 3 recapitulates the key requirements for uncompressed HD video streaming as well as outlines the large scale parameters for home environment and conference room within an office environment [21], which this application is mainly deployed.

TABLE 2: Data rate requirements for different resolutions, frame rates, and numbers of bits per channel per pixel for HDTV standard.

Pixels per line	Active lines per picture	Frame rate	# of bits per channel per pixel	Data rate (Gbps)
1280	720	24	24	0.531
1280	720	30	24	0.664
1440	480	60	24	0.995
1280	720	50	24	1.106
1280	720	60	24	1.327
1920	1080	50	24	2.488
1920	1080	60	24	2.986
1920	1080	60	30	3.732
1920	1080	60	36	4.479
1920	1080	60	42	5.225
1920	1080	90	24	4.479
1920	1080	90	30	5.599

4. FEASIBILITY STUDY

In this section, we perform a basic feasibility study on the 60 GHz radio technology. The study is based on the application scenarios described in Section 3 for the uncompressed HD video streaming. We begin by analyzing the achievable Shannon capacity for an omni-directional antenna at both sides of the transmitter (Tx) and receiver (Rx). Then, we determine what is the minimum gain required in order to operate under certain environment and target specifications. The analysis also considers the effect of multipath and investigates the role of antenna to provide sufficient power margin for 60 GHz wireless communications. Unless otherwise specified, the parameters in Table 4 are assumed in our analysis.

4.1. Power margin

Using the above parameters, one can compute the ratio of signal power to noise power at the Rx as given by

$$
\begin{aligned}
\text{SNR} = P_T + G_T + G_R - PL_0 - PL(d) - I_L \\
- (KT + 10\log_{10}(B) - NF),
\end{aligned}
\tag{1}
$$

where G_T and G_R denote the transmit and received antenna gain, respectively. Inserting (1) into the well-known Shannon capacity formula, that is, $C = B\log_2(\text{SNR}+1)$, the maximum achievable capacity in AWGN can be computed. Figure 2 shows the Shannon capacity limit for indoor office in LOS and non-LOS (NLOS) case using omni-omni antenna setup. It can be observed that for LOS condition, a 5 Gbps data rates is impossible at any distance. On the other hand, the operating distance for NLOS condition is limited to below 3 m though the capacity for NLOS decreases more drastically as a function of distance. To improve the capacity for a given operating distance, one can either increase the bandwidth or signal-to-noise ratio (SNR) or both. It can also be seen from Figure 2 that increasing the bandwidth used by more than 4 times only significantly improves the capacity for distance below 5 m. Beyond this distance, the capacity for the 7 GHz case only slightly above the case of 1.5 GHz bandwidth, since

TABLE 3: Key requirements for uncompressed HD video streaming application and the large scale fading parameters for conference room and home environment, respectively.

Applications	Data Rate	BER	Data type	Environment	n	Shadowing	Ref
Uncompressed HD video streaming	0.05–5.5 Gbps	1.00E-12	Isochronous	Home 5–10 m (LOS/NLOS)	1.55/2.44	1.5/6.2	[22]
				Conf. room 20 m (LOS/NLOS)	1.77/3.83	6/7.6	[23]

TABLE 4: Parameters used in the analysis.

Tx Power, PT	10 dBm
Center frequency, f_c	60 GHz
Noise figure, NF	6 dB
Implementation loss, IL	6 dB
Thermal noise, N	174 dBm/MHz
Bandwidth, B	1.5 GHz
Distance	20 m
Pah loss at 1 m, PL_0	57.5 dB

the SNR at the Rx is reduced considerably at longer distance due to higher path loss. On the other hand, the overall capacity over the considered distance increases notably if a 10 dBi transmit antenna gain is employed as compared to the omni-directional antenna for both 1.5 GHz and 7 GHz bandwidths. This clearly shows the importance of antenna gain in providing a very high data application at 60 GHz which is not possible to be provided with omni-omni antenna configuration. But the question remains, how much gain is required?

To answer that question, the capacity as a function of combined Tx and Rx gain for operating distance at 20 m is plotted as depicted in **Figure 3**. To achieve 5 Gbps at 20 m, a combined gain of 25 dBi and 37 dBi are required for LOS and NLOS, respectively. This seems to be practical value since it is a combined Tx and Rx gain. However, to achieve the same data rates in multipath channel, higher gain is needed to overcome the fading margin. Now consider what additional gains are required in a more realistic scenario where the propagation channel is corrupted by multipath fading instead of AWGN. To ease the analysis, we use the closed-form bit error probability (BEP) results for the noncoherent binary frequency-shift keying (BFSK) [22]. Specifically, we use

$$P_b = \frac{1+K}{2+2K+\overline{\gamma}_b} \exp\left(-\frac{K\overline{\gamma}_b}{2+2K+\overline{\gamma}_b}\right), \qquad (2)$$

where K and $\overline{\gamma}_b$ are the Ricean K-factor and the average energy-per-bit-to-noise ratio, respectively. Equation (2) can be reduced to the case of Rayleigh fading when $K = 0$ and simultaneously approximates the AWGN case when $K \to \infty$.

Clearly from **Figure 4**, one can see that for uncoded system, the required additional combined Tx-Rx gain becomes prohibitively impractical in order to achieve BEP of 10^{-12} in Ricean and Rayleigh fading channels, respectively, over the AWGN case. Thus, coded systems, diversity systems or/and
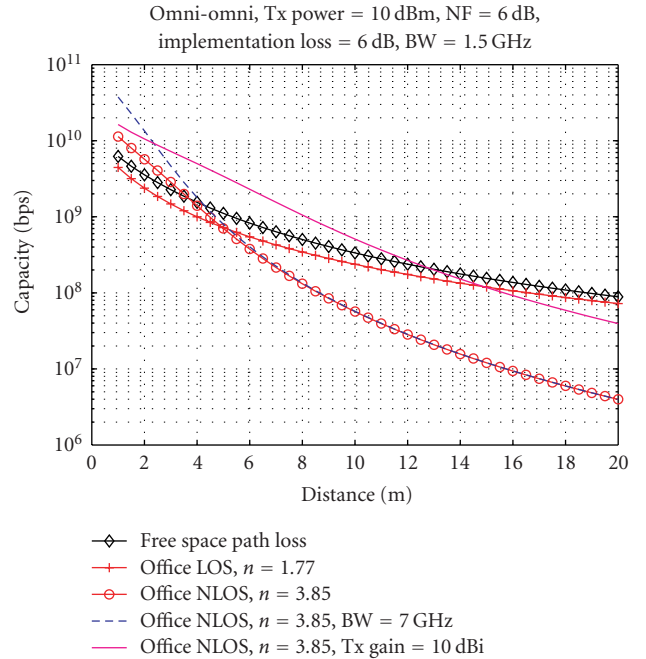

Omni-omni, Tx power = 10 dBm, NF = 6 dB, implementation loss = 6 dB, BW = 1.5 GHz

— Free space path loss
—+— Office LOS, $n = 1.77$
—o— Office NLOS, $n = 3.85$
‒ ‒ ‒ Office NLOS, $n = 3.85$, BW = 7 GHz
—— Office NLOS, $n = 3.85$, Tx gain = 10 dBi

FIGURE 2: Shannon capacity limits for the case of indoor office using omni-omni antenna setup.

high gain antenna systems have to be used in order to reduce the fading margin associated with the multipath channel. For diversity technique employing maximum ratio combining in a flat Rayleigh fading channel, the BEP for uncoded BFSK can be expressed as [22]

$$P_b = \left[\frac{1}{2}(1-\mu)\right]^L \sum_{k=0}^{L-1} \binom{L-1+k}{k} \left[\frac{1}{2}(1+\mu)\right]^k, \qquad (3)$$

where L is the number of diversity channels that are assumed to be statistically independent Rayleigh fading and μ is given as

$$\mu = \frac{\overline{\gamma}_c}{\overline{\gamma}_c + 2}, \qquad (4)$$

where $\overline{\gamma}_c$ is the average SNR per channel. As shown in **Figure 4**, the use of diversity technique for the case of two and four channels provides diversity gain of approximately 65 dB to 80 dB over the single channel at BEP of 10^{-12}. However, in
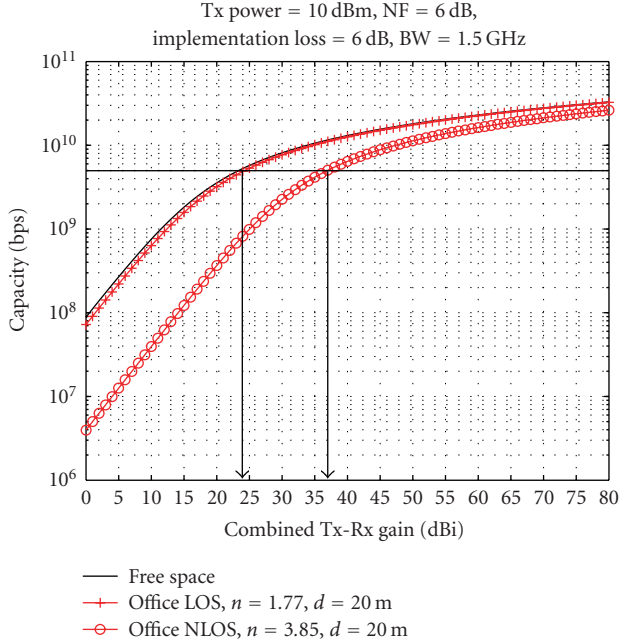
FIGURE 3: The required combined Tx-Rx antenna gain to achieve a target capacity.

FIGURE 4: The BEP for the case of uncoded, coded, and diversity systems in Rayleigh fading channel.

practice these gains are expected to be much lower as channel is not independent and identical distributed and subject to fading correlation. Similarly, the use of channel coding can improve the BEP significantly over the uncoded case. In our example, the use of Golay (24,12) code (with Hamming distance $d_{\min} = 8$) is shown to have coding gain of approximately 92 dB over the single channel Rayleigh fading case.

For the cases discussed above, to achieve 5 Gbps data rate at BEP of 10^{-12}, in the case of Rayleigh fading channel and assuming that bandwidth is equal to the data rate, one can compute the power margin as the difference between the received E_b/N_0 over the required E_b/N_0 to achieve the target BEP. The power margin for the case of Rayleigh channel with coding and diversity as well as AWGN can be shown to be given by

$$M_{\text{Ray\_Coded}} = G_T + G_R - 61,$$
$$M_{\text{Ray\_Div}} = G_T + G_R - 73, \quad (5)$$
$$M_{\text{AWGN}} = G_T + G_R - 37.$$

For high quality video transmission link at 60 GHz, a sufficiently large link margin is required due to the highly variable shadowing and human blockage effects. Experiments show that the shadowing effect is log-normally distributed with zero mean and standard deviation as high as 7–10 dB [23, 24]. On the other hand, the effect of human blockage varies between 18–36 dB [25, 26]. Assuming a margin of 10 dB is required, then the required combined Tx-Rx gain for the three cases given in (5) are 71 dB, 83 dB, and 47 dB, respectively. From the regulatory standpoint, we see that the maximum transmit antenna gain that is allowed for a Tx
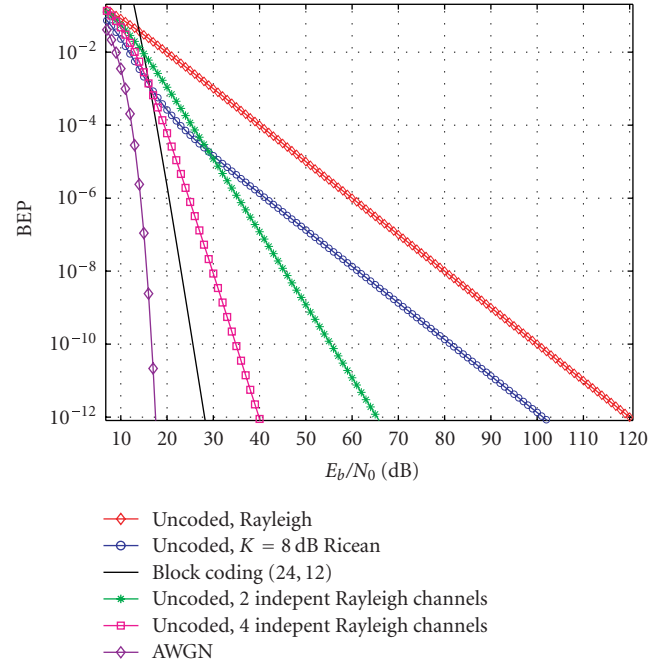
power of 10 dBm is 33 dBi. This sets the Rx gain to be very high, namely, 38 dBi, 50 dBi, and 14 dBi, respectively, for the three cases considered above.

4.2. The role of antenna

For a single antenna element with antenna gain more than 30 dBi with half power beamwidth (HPBW) of approximately $6.5°$, a reliable communication link is difficult to establish even in LOS condition at 60 GHz. This is due to the human blockage which can easily block and attenuate such a narrowbeam signal. To overcome this problem, a switched beam antenna array or adaptive antenna array is required to search and beamform to the available signal path. The array is subsequently required to track the signal path periodically. One might be interested to know how many antenna elements are required to achieve the intended antenna gain. This is different from the array gain which referred to the performance improvement in terms of SNR over single antenna. On the other hand, the gain of the antenna array can be described by the product of the directivity of the array with the efficiency of the antenna array. The directivity of the linear array is given by [27]

$$D = \frac{4\pi}{\iint |F_n(\phi, \theta)|^2 \sin\theta \, d\theta}, \quad (6)$$

where $F_n(\phi, \theta)$ is the normalized field pattern which can be expressed as a product of normalized element pattern and normalized array factor. The variables ϕ and θ denote the azimuth and elevation angle, respectively. For uniform linear

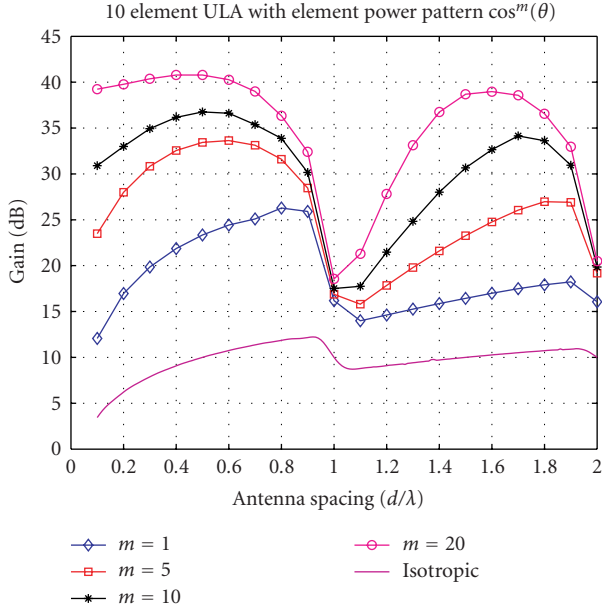10 element ULA with element power pattern $\cos^m(\theta)$

FIGURE 5: The antenna array gain as a function of antenna spacing for 10 elements ULA with different element gains.

array (ULA), the normalized array factor can be expressed as

$$f_n(\phi, \theta) = \frac{\sin\left((N/2)(kd\cos\theta + \beta)\right)}{N\sin\left((1/2)(kd\cos\theta + \beta)\right)}, \qquad (7)$$

where N, d, and β are the number of antenna elements, antenna spacing between two adjacent elements, and phase shift, respectively. For omni-directional antenna, it can be shown that up to 100 elements are required to achieve only 23 dBi gain which is far from the required specification shown previously. Hence a more directive element is required to improve the overall gain of the array. As shown in Figure 5, to achieve a 40 dBi gain, 10 elements ULA with 16 dBi element spaced around $\lambda/2$ is required.

5. TECHNICAL CHALLENGES

Despite many advantages offered and high potentials applications envisaged in 60 GHz, there are number of technical challenges and open issues that must be solved prior to the successful deployment of this technology. These challenges can be broadly classified into channel propagation issues, antenna technology, RF solution, and choice of modulation.

Channel propagation

Although many channel measurements and modeling effort have been reported in the literature for various frequency range such as the 5 GHz WLAN band [28–30] and 3–10 GHz UWB band [31–39], there are still lack of channel measurements and modeling effort for the frequency range at 60 GHz. In general, the path loss at 60 GHz is significantly higher than those at lower frequencies. This is also true for transmission loss at 60 GHz for many materials

[23, 24, 40, 41]. The higher path loss and transmission loss at 60 GHz effectively limits the operation to one room. In order to have wider coverage, relays or regenerative repeaters are required. Furthermore, as described in Section 4, the use of high gain antenna is necessary to compensate the high path loss incurred, and the use of this single high gain antenna is only feasible if clear LOS condition is always guaranteed. In scenario where clear LOS is not guaranteed due to, for example, a movement of human, the antenna arrays solution becomes highly desirable. Unfortunately, there is no specific channel model at 60 GHz that sufficiently addresses the spatial properties and effect of human movement. Recent contributions which measured the angle of arrival of the received signal using antenna array [42] and rotational of directive antenna [43] show that an angle spread of approximately 14° in corridor and desktop environment, respectively. However, more measurements are required to further characterize and validate these results.

Furthermore, all of the channel models available are *radio channel* which are antenna dependent and are only valid for the particular antenna setups used in the measurement. To overcome this limitation, a *propagation channel* is required which excludes the effects of antenna [44] and allows the investigation of the effects of different type of antenna setups with different gain/beamwidth on the 60 GHz system performance. This is very important as measurements and ray tracings have shown that the use of high gain antenna can significantly reduce the delay spread of the radio channel when the Tx and Rx antennas are aligned [45]. However, a detrimental effect would be resulted for a slight pointing error of the main lobe of the antenna off the direction of arrival of the signal [46, 47]. In addition, measurements also demonstrated the effects of multipath suppression using circular polarization over linear polarization [48], but more extensive measurements are needed to affirm these results and to what extent this suppression occurs at 60 GHz.

Antenna technology

Many types of antenna structures are considered not suitable for 60 GHz WPAN/WLAN applications due to the requirements for low cost, small size, light weight, and high gain. In addition, 60 GHz antennas also require to be operated with approximately constant gain and high efficiency over the broad frequency range (57–66 GHz). The importance of beamforming at 60 GHz has been discussed in Section 4, which can be achieved by either switched beam arrays or phase arrays. Switched beam arrays have multiple fixed beams that can be selected to cover a given service area. It can be implemented much easier compared to the phase arrays which required the capability of continuously varying the progressive phase shift between the elements. The complexity of phase arrays at 60 GHz typically limits the number of elements. In [49], a 2×2 beam steering antenna with circular polarization at 61 GHz is developed. The gain is approximately 14 dBi with 20° HPBW. Similarly in [50], another 60 GHz integrated 4-element planar array is developed with average conversion loss of less that 10.6 dB for the four

channels. The implementation of larger phase array, however, presents some technical challenges such as requirement for higher feed network loss, more complex phase control network, stronger coupling between antennas as well as feedlines, and so forth. These challenges make the design and fabrication of the larger phase arrays become more complex and expensive. Hence, more research are required to develop a low cost, small size, light weigh, and high gain steerable antenna array that can be integrated into the RF front end electronics.

Integrated circuit technology

The choice of integrated circuit (IC) technology depends on the implementation aspects and system requirements. The former is related to the issues such as power consumption, efficiency, dynamic range, linearity requirements, integration level, and so forth, while the later is related to the transmission rate, cost and size, modulation scheme, transmit power, bandwidth, and so forth. At mmWave, there are three competing IC technologies, namely: (1) group III and IV semiconductor technology such as Gallium Arsenide (GaAs) and Indium Phosphide (InP); (2) Silicon Germanium (SiGe) technology such as HBT and BiCMOS; and (3) Silicon technology such as CMOS and BiCMOS. There is no single technology that can simultaneously meet all the objectives defined in the technical challenges and system requirements. For example, GaAs technology allows fast, high gain, and low noise implementation but suffers poor integration and expensive implementation. On the other hand, SiGe technology is a cheaper alternative to the GaAs with comparable performance. In [51], the first mmWave fully antenna integrated SiGe chip has been demonstrated.

Typically, as have been witnessed in the past, for broad market exploitation and mass deployment, the size and cost are the key factors that drive to the success of a particular technology. In this regard, CMOS technology appears to be the leading candidate as it provides low-cost and high-integration solutions compared to the others at the expense of performance degradation such as low gain, linearity constraint, poor noise, lower transit frequency, and lower maximum oscillation frequency. Recent advances in CMOS technology [52] have demonstrated the feasibility of bulk CMOS process at 130 nm for 60 GHz RF building blocks, active and passive elements. More future research and investigations in developing a fully integrated CMOS chip solution have to be performed. Future technology should also aim at 90 nm and 65 nm CMOS processes in order to further improve the gain and lower power consumption of the devices.

Modulation schemes

The choice of modulation schemes for 60 GHz radio will be highly dependent on the propagation channel, the use of high gain antenna/antenna array, and the limitations imposed by the RF technology. For instance, if the delay spread of the underlying propagation channel is high, then an orthogonal frequency division multiplexing (OFDM) is an obvious choice of modulation since OFDM can effectively turn the frequency selective channel into flat fading channel by dividing the high-rate stream into a set of parallel lower rate substreams. This simplifies the equalization technique for multi gigabit wireless system. On the other hand, high gain or circular polarized antenna systems can be used to significantly reduce the effect of multipath and therefore will favor simple modulation such as single carrier to save power consumption and cost.

Typically, in CMOS circuit implementation, the 60 GHz power amplifier has lower power and higher linearity requirement. This implies that the use of simple modulation than the OFDM system which suffers large peak-to-average ratio (PAPR) and can greatly reduce the efficiency of the power amplifier. Furthermore, the poor phase noise characteristic of 60 GHz CMOS also restricts the use of higher order modulation for quadrature amplitude modulation (QAM), phase shift keying (PSK), and frequency shift keying (FSK) to less than 16 QAM/16 PSK/16 FSK. The use of lower order modulation is also motivated by the huge unlicensed bandwidth available at 60 GHz. Hence, the choice of modulation is clearly a tradeoff of a number of issues which need to be well understood and characterized before a robust modulation scheme can be sought.

6. CONCLUSION

In this paper, an overview of the 60 GHz technology is presented. The huge unlicensed bandwidth coupled with higher allowable transmit power, small form factor, and advances in integrated circuit technology have made 60 GHz a very promising candidate for multigigabit applications. Intense efforts are underway to expedite the commercialization of this fascinating technology from standardization activities, industrial alliances and regulatory bodies. A simple feasibility study on wireless uncompressed video streaming on HDTV using realistic parameters revealed the roles of antenna in establishing a reliable 60 GHz communication link. The importance of antenna system are to provide sufficient power margin through array gain as well as to beamform the signal to other significant paths in case of human blockage of the main path. Despite the clear advantages of 60 GHz system, a number of open issues and technical challenges have yet to be fully addressed. The propagation and implementation issues are the two aspects that require further optimization and research in order to obtain a truly efficient and low cost 60 GHz communication system.

REFERENCES

[1] A. D. Oliver, "Millimeter wave systems - past, present and future," *IEE Proceedings*, vol. 136, no. 1, pp. 35–52, 1989.

[2] http://www.ieee802.org/15/pub/TG3c.html.

[3] S. K. Yong, "Multi gigabit wireless through millimeter wave in 60 GHz band," in *Proceedings of Wireless Conference Asia*, Singapore, November 2005.

[4] FCC, "First Report and Order," February 2002, http://hraunfoss.fcc.gov/edocs_public/.

[5] C.-C. Chong, F. Watanabe, and H. Inamura, "Potential of UWB technology for the next generation wireless communications," in *Proceedings of IEEE 9th International Symposium on Spread Spectrum Techniques and Applications (ISSSTA '06)*, pp. 422–429, Manaus, Amazon, Brazil, August 2006.

[6] FCC, "Code of Federal Regulation, title 47 Telecommunication, chapter 1, part 15.255," October 2004.

[7] Spectrum Management Telecommunications, "Radio Standard Specification-210, Issue 6, Low-Power Licensed-Exempt Radio Communication Devices (All Frequency Bands): Category 1 Equipment," September 2005.

[8] Regulations for enforcement of the radio law 6-4-2 specified low power radio station (11) 59-66GHz band.

[9] ACMA, "Radiocommunications (Low Interference Potential Devices) Class License Variation 2005 (no. 1)," August 2005.

[10] Ministry of Information Communication of Korea, "Frequency Allocation Comment of 60 GHz Band," April 2006.

[11] ETSI DTR/ERM-RM-049, "Electromagnetic compatibility and Radio spectrum Matters (ERM); System Reference Document; Technical Characteristics of Multiple Gigabit Wireless Systems in the 60 GHz Range," March 2006.

[12] *Korean Frequency Policy & Technology Workshop, Session 7*, pp. 13–32, November 2005.

[13] CEPT Recommendation T/R 22-03, "Provisional recommended use of the frequency range 54.25-66 GHz by terrestrial fixed and mobile systems," in *Proceedings of European Postal and Telecommunications Administration Collection (CEPT '90)*, pp. 1–3, Athens, Greece, January 1990, http://www.ero.dk/documentation/.

[14] ERC Recommendation 12-09, "Radio Frequency Channel Arrangement for Fixed Service Systems Operating in the Band 57.0 - 59.0 GHz Which Do Not Require Frequency Planning, The Hague 1998 revised Stockholm," October 2004.

[15] ECC Recommendation (05)02, "Use of the 64-66 GHz Frequency Band for Fixed Services," June 2005.

[16] IEEE Standard 802.16 2001, "IEEE Standard for Local and Metropolitan Area Networks—Part 16 - Air Interface for Fixed Broadband Wireless Access Systems," 2001.

[17] ARIB STD-T69, "Millimeter-Wave Video Transmission Equipment for Specified Low Power Radio Station," July 2004.

[18] ARIB STD-T69, "Millimeter-Wave Data Transmission Equipment for Specified Low Power Radio Station (Ultra High Speed Wireless LAN System)," May 2001.

[19] R. Roberts, "WiMedia 60 GHz Study Group," IEEE 802.15-05-0248-00-003c, Jacksonville, Fla, USA, May 2006.

[20] A. Sadri, "802.15.3c Usage Model Document," IEEE 802.15-06-0055-14-003c, Jacksonville, Fla, USA, May 2006.

[21] S. K. Yong, "TG3c Channel Modeling Sub-Committee Final Report (Draft)," IEEE 802.15-06-0195-02-003c, Jacksonville, Fla, USA, May 2006.

[22] M. K. Simon and M. S. Alouini, *Digital Communication over Fading Channels*, Wiley-IEEE Press, New York, NY, USA, 2nd edition, 2004.

[23] M. Fiacoo and S. Saunders, "Final report for OFCOM - indoor propagation factors at 17 GHz and 60 GHz," August 1998.

[24] C. R. Anderson and T. S. Rappaport, "In-building wideband partition loss measurements at 2.5 and 60 GHz," *IEEE Transactions on Wireless Communications*, vol. 3, no. 3, pp. 922–928, 2004.

[25] S. Collonge, G. Zaharia, and G. E. Zein, "Influence of the human activity on wide-band characteristics of the 60 GHz indoor radio channel," *IEEE Transactions on Wireless Communications*, vol. 3, no. 6, pp. 2396–2406, 2004.

[26] P. F. M. Smulders, *Broadband wireless LANs: a feasibility study*, Ph.D. thesis, Eindhoven University of Technology, Eindhoven, The Netherlands, 1995.

[27] C. A. Balanis, *Antenna Theory: Analysis and Design*, John Wiley & Sons, New York, NY, USA, 2nd edition, 1997.

[28] C.-C. Chong, C.-M. Tan, D. I. Laurenson, S. McLaughlin, M. A. Beach, and A. R. Nix, "A new statistical wideband spatio-temporal channel model for 5-GHz band WLAN systems," *IEEE Journal on Selected Areas in Communications*, vol. 21, no. 2, pp. 139–150, 2003.

[29] C.-C. Chong, D. I. Laurenson, and S. McLaughlin, "Spatio-temporal correlation properties for the 5.2-GHz indoor propagation environments," *IEEE Antennas and Wireless Propagation Letters*, vol. 2, no. 1, pp. 114–117, 2003.

[30] C.-C. Chong, C.-M. Tan, D. I. Laurenson, S. McLaughlin, and M. A. Beach, "A novel wideband dynamic directional indoor channel model based on a Markov process," *IEEE Transactions on Wireless Communications*, vol. 4, no. 4, pp. 1539–1552, 2005.

[31] M. Z. Win and R. A. Scholtz, "On the robustness of ultra-wide bandwidth signals in dense multipath environments," *IEEE Communications Letters*, vol. 2, no. 2, pp. 51–53, 1998.

[32] M. Z. Win and R. A. Scholtz, "On the energy capture of ultra-wide bandwidth signals in dense multipath environments," *IEEE Communication Letters*, vol. 2, no. 9, pp. 245–247, 1998.

[33] R. J. Cramer, R. A. Scholtz, and M. Z. Win, "An evaluation of the ultra-wideband propagation channel," *IEEE Transactions on Antennas and Propagation*, vol. 50, no. 5, pp. 561–570, 2002.

[34] D. Cassioli, M. Z. Win, and A. F. Molisch, "The ultra-wide bandwidth indoor channel: from statistical model to simulations," *IEEE Journal on Selected Areas in Communications*, vol. 20, no. 6, pp. 1247–1257, 2002.

[35] M. Z. Win and R. A. Scholtz, "Characterization of ultra-wide bandwidth wireless indoor channels: a communication-theoretic view," *IEEE Journal on Selected Areas in Communications*, vol. 20, no. 9, pp. 1613–1627, 2002.

[36] C.-C. Chong and S. K. Yong, "A generic statistical-based UWB channel model for high-rise apartments," *IEEE Transactions on Antennas and Propagation*, vol. 53, no. 8, pp. 2389–2399, 2005.

[37] C.-C. Chong, Y.-E. Kim, S. K. Yong, and S.-S. Lee, "Statistical characterization of the UWB propagation channel in indoor residential environment," *Wireless Communications and Mobile Computing*, vol. 5, no. 5, pp. 503–512, 2005.

[38] C.-C. Chong, "UWB channel modeling and impact of wideband channel on system design," in *UWB Wireless Communications*, H. Arslan and Z. N. Chen, Eds., chapter 8, John Wiley & Sons, New York, NY, USA, 2006.

[39] A. F. Molisch, D. Cassioli, C.-C. Chong, et al., "A comprehensive standardized model for ultrawideband propagation channels," *IEEE Transactions on Antennas and Propagation*, vol. 54, no. 11, pp. 3151–3166, 2006.

[40] E. J. Violette, R. H. Espeland, R. O. DeBolt, and F. K. Schwering, "Millimeter-wave propagation at street level in an urban environment," *IEEE Transactions on Geoscience and Remote Sensing*, vol. 26, no. 3, pp. 368–380, 1988.

[41] B. Langen, G. Lober, and W. Herzig, "Reflection and transmission behaviour of building materials at 60GHz," in *Proceedings of the 5th IEEE International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC '94)*, vol. 2, pp. 505–509, The Hague, Netherlands, September 1994.

[42] M.-S. Choi, G. Grosskopf, and D. Rohde, "Statistical characteristics of 60 GHz wideband indoor propagation channel," in *Proceedings of the 16th International Symposium on Personal,*

Indoor and Mobile Radio Communications (PIMRC '05), vol. 1, pp. 599–603, Berlin, Germany, September 2005.

[43] C. S. Liu, et al., "NICTA Indoor 60 GHz Channel Measurements and Analysis update," IEEE 802.15-06-222-00-003c, Jacksonville, Fla, May 2006.

[44] M. Steinbauer, A. F. Molisch, and E. Bonek, "The double-directional radio channel," *IEEE Antennas and Propagation Magazine*, vol. 43, no. 4, pp. 51–63, 2001.

[45] H. Yang, P. F. M. Smulders, and M. H. A. J. Herben, "Frequency selectivity of 60 GHz LOS and NLOS indoor radio channels," in *Proceedings of IEEE Vehicular Technology Conference (VTC '06)*, Melbourne, Australia, May 2006.

[46] M. R. Williamson, G. E. Athanasiadou, and A. R. Nix, "Investigating the effects of antenna directivity on wireless indoor communication at 60GHz," in *Proceedings of IEEE International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC '97)*, vol. 2, pp. 635–639, Helsinki, Finland, September 1997.

[47] T. Manabe, Y. Miura, and T. Ihara, "Effects of antenna directivity and polarization on indoor multipath propagation characteristics at 60 GHz," *IEEE Journal on Selected Areas in Communications*, vol. 14, no. 3, pp. 441–448, 1996.

[48] T. Manabe, K. Sato, H. Masuzawa, et al., "Polarization dependence of multipath propagation and high-speed transmission characteristics of indoor millimeter-wave channel at 60 GHz," *IEEE Transactions on Vehicular Technology*, vol. 44, no. 2, pp. 268–274, 1995.

[49] K.-C. Huang and Z. Wang, "Millimeter-wave circular polarized beam-steering antenna array for gigabit wireless communications," *IEEE Transactions on Antennas and Propagation*, vol. 54, no. 2, part 2, pp. 743–746, 2006.

[50] J.-Y. Park, Y. Wang, and T. Itoh, "A 60 GHz integrated antenna array for high-speed digital beamforming applications," in *Proceedings of IEEE MTT-S International Microwave Symposium Digest*, vol. 3, pp. 1677–1680, Philadelphia, Pa, USA, June 2003.

[51] B. Gaucher, "Completely Integrated 60 GHz ISM Band Front End Chip Set and Test Results," IEEE 802.15-15-06-0003-00-003c, Big Island, Hawaii, USA, January 2006.

[52] C. H. Doan, S. Emami, A. M. Niknejad, and R. W. Broderson, "Millimeter-wave CMOS design," *IEEE Journal of Solid-State Circuits*, vol. 40, no. 1, pp. 144–155, 2005.