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Feasibility Study of 60 GHz UWB System for Gigabit M2M Communications

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Abstract

In this paper, the feasibility and performance of millimeter wave (mmWave) 60 GHz ultra-wide band (UWB) systems for gigabit machine-to-machine (M2M) communications are analyzed. Specifically, based on specifications, channel measurements and models for both line-of-sight (LOS) and non-LOS (NLOS) scenarios, 60 GHz propagation mechanisms are summarized, and 60 GHz UWB link budget and performance are analyzed. Tests are performed for determining ranges and antenna configurations. Results show that gigabit capacity can be achieved with omni-directional antennas configuration at the transceiver, especially in LOS conditions. When the LOS path is blocked by a moving person or by radiowave propagation in the NLOS situation, omni-directional and directional antennas configuration at the transceiver is required, especially for a larger range between machines in office rooms. Therefore, it is essential to keep a clear LOS path in M2M applications like gigabit data transfer. The goal of this work is to provide useful information for standardizations and design of 60 GHz UWB systems.

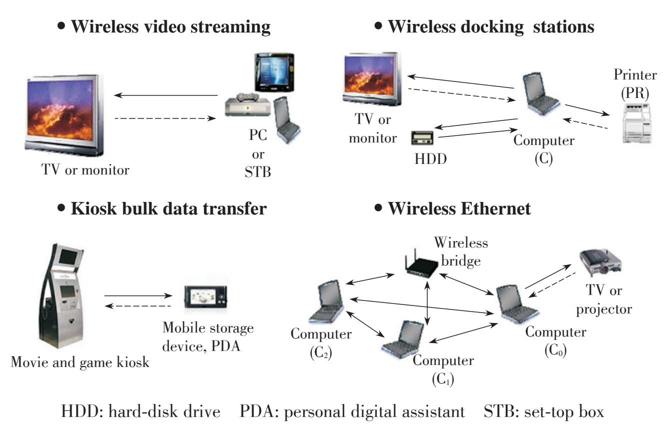
Keywords

mmWave 60 GHz; UWB; M2M; gigabit communications

1 Introduction

The millimeter wave (mmWave) 60 GHz band is seen as the major candidate for enabling wireless interface for gigabit applications, due to the intrinsic high transmission bandwidth available in the band [1], [2], [3]. The large bandwidth (as a thumb of rule the available bandwidth B is about 10% of the center frequency for transmission) makes 60 GHz radio particularly interesting for gigabit wireless communications [4]. There is 7 GHz unlicensed spectrum (from 57 to 64 GHz) around 60 GHz allocated worldwide today. The 60 GHz radio is often viewed as a shifted version of ultra-wide band (UWB), which is defined as any device emitting signals with fractional bandwidth greater than 0.2 or a bandwidth of at least 500 MHz at all times of transmission. Today, gigabit wireless applications are emerging, especially gigabit machine-to-machine (M2M) applications, e.g., wireless audio/video (A/V) cable replacement, wireless high data transfer, high quality multimedia services, etc. In high definition television (HDTV) applications, up to several Gb/s rate is required for supporting uncompressed exchange of information between TV, cameras, DVD and other appliances. **Fig. 1** shows examples of the 60 GHz radio for gigabit wireless applications in M2M networks.

The 60 GHz band regulation and standardization efforts are currently underway worldwide. At present, the international standards for 60 GHz band are ECMA-387, IEEE 802.15.3c and IEEE 802.11ad. In China, the study progress of 60 GHz



HDD: hard-disk drive PDA: personal digital assistant STB: set-top box

▲Figure 1. Examples of the 60 GHz radio for gigabit M2M communications.

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band has been attracting more and more attention in recent years. In 2010, the 60 GHz wireless network project group (PG4) was established. The PG4 and the IEEE 802.11 working group formed a formal partnership. The IEEE 802.11-aj task group was founded according to the China millimeter wave band for next generation in September 2012. The IMT-2020 (5G) group was founded on February 19, 2013 for promoting the standard formulation in the 60 GHz band for 5G technology, and the first standard plan was completed in 2014 [5], [6].

However, the output power of 60 GHz devices is limited by regulations, and the free space path loss for a 60 GHz band carrier is much higher than that for a microwave carrier. Though it is possible to use high gain antennas to compensate for the high path loss at mmWave, the drawbacks of high gain antenna are that systems suffer from poor flexibility and limited mobility. In this work, we analyze 60 GHz UWB system link budget and performance, considering office room M2M applications (e.g. computer-to-computer data transfer) in the range of 1 m−5 m and employing the experimental path loss models of line-of-sight (LOS), non-LOS (NLOS) and LOS path blocked by moving persons studied in our previous works [7], [8]. Tests are also performed for determining ranges and antenna gains. The goal of this study is to provide useful information for the design of 60 GHz UWB systems in gigabit M2M communications and standardization. The 60 GHz band is planned and limited on transmit power, and the effective isotropic radiated power (EIRP) and antenna gain for various countries [9] including specifications in China [10] are summarized in **Table 1**.

2 MmWave 60 GHz Propagation Mechanisms

In design and optimization of wireless communications systems, channel models featuring the relevant characteristics of radiowave propagation are required. Ray tracing is a well-established tool for channel modeling. In the ray-tracing algorithm, reflection and diffraction are the main physical processes for LOS and NLOS environments. In our previous works [7], [8], mmWave 60 GHz propagation mechanism is studied based on direction-of-arrival (DOA) measurements. The DOA measurements require the detailed knowledge of the propagation channels. The measured power angle profiles (PAPs) and power delay profiles (PDPs) can then be connected with site-specific information of the measurement environments to find the origin of the arriving of signals. From [8] mmWave 60 GHz propagation mechanism can be concluded as:

▼Table 1. 60 GHz band plans and limits on transmit power, EIRP and antenna gain for various countries [9], [10]

Region	Frequency band	TX power (max)	EIRP	Antenna gain	Comments
USA	7 GHz (57 GHz−64 GHz)	500 mW	40 dBm (ave.) 43 dBm (max)	NS	For B>100 MHz, translate average PD from 9 μW/cm^2 to 18 μW/cm^2 at 3 m
Canada	7 GHz (57 GHz−64 GHz)	500 mW	40 dBm (ave.) 43 dBm (max)	NS	For B>100 MHz, translate average PD from 9 μW/cm^2 to 18 μW/cm^2 at 3 m
Japan	7 GHz (59 GHz−66 GHz) max 2.5 GHz	10 mW	NS	47 dBi (max)	
Australia	3.5 GHz (59.4 GHz−62.9 GHz)	10 mW	150 W (max)	NS	Limited to land and maritime
Korea	7 GHz (57 GHz−64 GHz)	10 mW	TBD	TBD	
Europe	9 GHz (57 GHz−66 GHz) min 50 MHz	20 mW	57 dBm (max)	37 dBi (max)	Recommendation by ETSI
China	5 GHz (59 GHz−64 GHz)	10 mW	44 dBm (ave.) 47 dBm (max)	NS	

EIRP: effective isotropic radiated power
ETSI: European Telecommunications Standards Institute
NS: no specification
PD: power density
TBD: to be determined

- Direct path and the first-order reflected waves from smooth surfaces form the main contributions in LOS propagation environments.
- Diffraction is a significant propagation mechanism in NLOS cases. Moreover, the signal levels of diffraction and second-order reflection are comparable.
- Transmission loss through concrete or brick walls is very high.

The person blocking effect (PBE) is also measured in our previous work [7], as the movement of persons is quite usual in office rooms in reality. The PBE is a major concern for propagation research and system development and PBE at 60 GHz has been studied by many researchers [11], [12]. In [7], PBE is measured by employing DOA measurement techniques as described below.

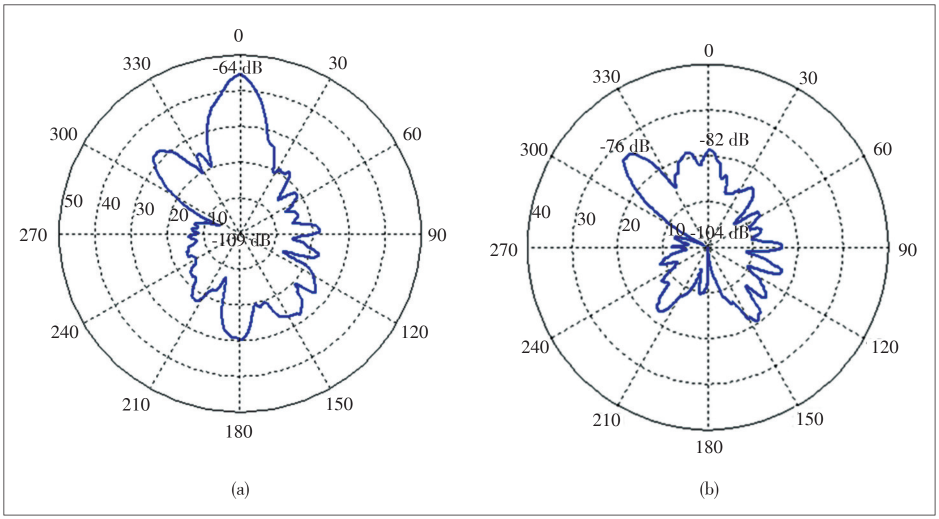
2.1 PBE Measurements

The PBE measurements were performed in a room at Aalto University, Finland, where the TX and RX positions are fixed with 5 m apart. When keeping a clear LOS path and a person blocked in the middle of the LOS path, measuring the PAPs of the clear LOS path and the blocked path, as shown in **Figs. 2a** and **2b**. It is seen that there is about 18 dB person attenuation in the blocked path ($\varphi=0^\circ$). However, the PBE can be reduced to 12 dB by using selection diversity technique, i.e., selecting another stronger path (at $\varphi=315^\circ$), which is considered as the first-order reflection from window glass in the room [8].

When the LOS path undergoes a deep fading (person blocking), the fading effects can be mitigated by selecting another independent strong signal. This selection diversity is a powerful communication receiver technique for link improvement. Therefore, the effective PBE=12 dB is considered in 60 GHz UWB system parameter analysis of this paper.

2.2 Radiowave Propagation Mechanisms in NLOS Cases

We know that in the LOS propagation environments, direct path and the first-order reflected waves from smooth surfaces form the main contributions of receiving signals [8]. This is also proved in [13] where a two-ray model (LOS path and first-order reflection from desktop) is proposed for 60 GHz M2M sys-



(a) (b)

▲**Figure 2. The measured power angle profiles of (a) clear LOS path and the (b) the LOS path blocked by a person in person block effect measurements.**

tems. In NLOS cases, diffraction is a significant propagation mechanism, and the signal levels of diffraction and second-order reflection are comparable [8]. This indicates that radio links are relayed by direction and/or the second-order reflections in the NLOS propagation scenarios in 60 GHz band. As an example, **Fig. 3** shows the radiowave propagation in office room environment with NLOS scenario. In Fig. 3, the diffraction and second-order reflection rays are denoted by dot and real lines, respectively. It should be noted that in the NLOS case, signal power loss increases greatly with the increasing of distance between the TX and RX. Thus, propagation range is major concern in NLOS environments in system development.

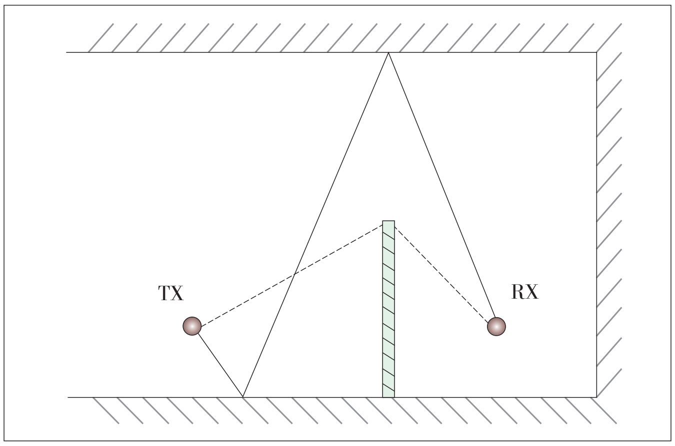
3 Analysis of 60 GHz UWB System Link Budget

In wireless communication systems, the upper bound of capacity is determined by Shannon theorem, which is function of bandwidth B and signal-to-noise ratio (SNR) with expression as:

$$C = B\cdot\log_2(1+SNR)\,. \tag{1}$$

A system capacity increases with B and SNR. However, increasing of bandwidth will lead to high noise power of system. For example, noise power is 18 dB higher with a UWB B=7 GHz channel than a narrowband B=100 MHz channel (when antenna noise temperature is T=290 K).

In this study, SNR=10 dB and B=1 GHz are considered for performing a basic feasibility study for achieving gigabit capacity of 60 GHz UWB systems.



▲**Figure 3. MmWave radio links are relayed by diffraction and/or double-reflection in the NLOS case.**

3.1 Parameters for 60 GHz UWB System Link Budget

In wireless communication systems, the performance and robustness is often determined by SNR from radio link budget:

$$SNR = P_t + G_t + G_r - PL - N_0 - IL\,, \tag{2}$$

where P_t is the transmitted power, G_t and G_r are the transmitter (TX) and receiver (RX) antenna gains, PL denotes path loss in propagation channel, N_0 is the total noise power at RX, and IL denotes the implementation loss of system. P_t is often limited by regulations of radio systems. In this work, it is chosen as $P_t = 10$ dBm, as it was specified by most of countries including China. The other system parameters are set as practical values, i.e., $IL = 6$ dB and noise figure NF = 6 dB in calculating total noise power: $N_0 = 10\log_{10}(kTB) + NF$, where k is Boltzmann's constant and T is the standard noise temperature T =290 K.

3.2 Path Loss Models in 60 GHz UWB Systems

Path loss characterizes channel large-scale fading, which is a key impact on the coverage and reliability of system. Path loss PL denotes the mean signal power loss and usually obeys the power distance law. Due to variations in the propagation environments, the signal power observed at any given pints will deviate from its mean, and this phenomenon is called shadowing. Because of shadowing, a fading margin FM is often considered in system design. Thus path loss PL is modeled as a combination of mean path loss and fading margin FM:

$$PL = \underbrace{PL_0(d_0) + 10n\log_{10}\left(\frac{d}{d_0}\right)}_{mean\ path\ loss} + FM\,, \tag{3}$$

where the free space path loss PL_0 is frequency-dependent, $PL_0 = 68$ dB at reference distance $d_0 = 1$ m, path loss exponent n is environment-dependent, and FM is mainly system-dependent. UWB system naturally leads to shadow fading improvement relative to narrow band systems.

Based on our results that *FM* decreases with channel bandwidth *B*, and is less than 4 dB for a minimum bandwidth ($B=500$ MHz) in UWB channel with 90% link success probability [14], fading margin is considered as $FM=2$ dB for the 60 GHz UWB ($B=1$ GHz) system in this work.

The studies show that path loss exponent ranges in 2−3.5 in LOS and NLOS office room environments [8], [13]. In this work, path loss models of LOS ($n=2$), LOS path blocked by moving person and NLOS ($n=3.5$) are considered, and they are $PL_1(dB)=68+20\log_{10}(d)+FM$, $PL_2(dB)=68+20\log_{10}(d)+FM+PBE$, and $PL_3(dB)=68+35\log_{10}(d)+FM$ respectively. The path loss model of LOS+PBE is more feasible when comparing with the NLOS model. Since the blocking effect is modeled independently on mobile position, which reflects a real case that movement of persons is quite typical in office rooms. Whereas, the NLOS model accounts for high path loss due to large distances practically. **Table 2** summarizes the parameters used in the 60 GHz UWB system link budget analysis, in which the maximum range is chosen as 5 m considering office room M2M applications (e.g. computer-to-computer data transfer).

4 Analysis of 60 GHz UWB System Performance

As transmission power is restricted in regulations of 60 GHz radio systems, and further, path loss of the 60 GHz channel is high (e.g. free space path loss at 60 GHz is 22 dB higher than 5 GHz frequency band at $d_0=1$ m), the antenna gains become very important in guaranteeing radio links for achieving gigabit capacity of system. In the following, tests are being performed in order to determine ranges and combined antenna gains (sum of gains at TX and RX), when using the parameters and path loss models of LOS ($n=2$), LOS + PBE and NLOS ($n=3.5$) in Table 2.

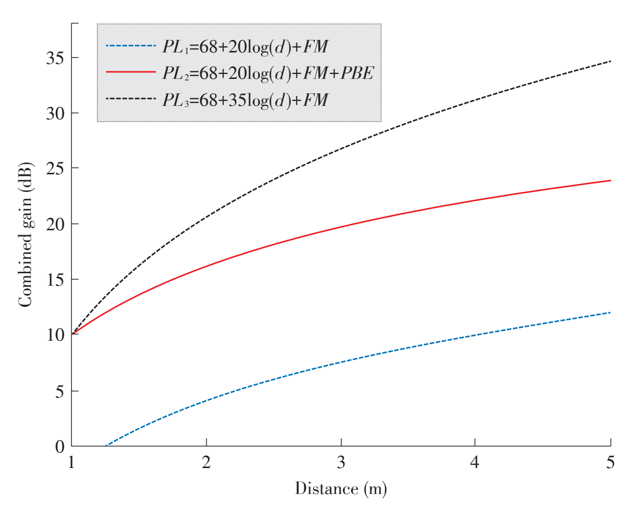
Fig. 4 shows the combined antenna gain vs. distance for the 60 GHz UWB system. It is seen that gigabit capacity can be achieved with omni-directional antennas configuration at the transceiver in LOS condition. However, at further distance of $d=5$, only with the LOS path loss PL_1 model antenna configuration of omni-directional is feasible for gigabit capacity. With another two path loss models of PL_2 (LOS + PBE) and PL_3 (NLOS $n=3.5$), antenna configuration of omni-directional is required for the 60 GHz UWB system.

Note that directional antenna is with high gain, for instance, the half power beam width (HPBW) is approximately 6.5 for an antenna with more than 30 dBi gain [9]. The drawbacks of high gain antenna are that systems suffer from poor flexibility and limited mobility. It should be noted that the path loss model of LOS + PBE in Fig. 4 is more feasible when comparing with the NLOS model, because the blocking effect is modeled independently on mobile position, which reflects the real case that movement of persons is quite typical in office rooms. Whereas, the NLOS model accounts for high path loss due to large distances practically. The results show that it is essential to keep a clear LOS path of 60 GHz UWB systems in gigabit M2M applications.

▼**Table 2. Radio link budget of 60 GHz UWB system**

60 GHz UWB system	
Data rate	> Gbps
Maximum range	5 m
Bandwidth	1 GHz
TX power	10 dBm
SNR	10 dB
Noise power	-78 dBm
Fading margin	2 dB
Implementation loss	6 dB
Effective person block effect	12 dB
Employed path loss models	LOS: $PL_1(dB)=68+20\log_{10}(d)+FM$ LOS + PBE: $PL_2(dB)=68+20\log_{10}(d)+FM+PBE$ NLOS: $PL_3(dB)=68+35\log_{10}(d)+FM$

LOS: line-of-sight PBE: person blocking effect UWB: ultra-wide band
NLOS: non-LOS SNR: signal-to-noise ratio



▲**Figure 4. Combined antenna gains in 60 GHz UWB system with link budget in Table 2.**

5 Conclusions

The feasibility and performance of mmWave 60 GHz UWB systems for gigabit M2M wireless communications are analyzed in this work. Specifically, based on specifications and experimental channel measurements and models for both LOS and NLOS scenarios, the 60 GHz propagation mechanisms are concluded, 60 GHz UWB radio link budget including person block effect and channel fading margin are provided, and system performance is analyzed further. Tests are also performed for determining communication ranges and antenna configurations. Results show that when having a clear LOS path and employing omni-directional antennas at the transceiver, gigabit capacity can be achieved. When the LOS path is blocked by a moving person or radiowave propagation in NLOS situation, omni-directional and directional antennas at the transceiver are required for achieving gigabit capacity in the range of 5 m between machines in office rooms. The high gain antenna systems suffer from poor flexibility and limited mobility. Therefore, it is essential to keep a clear LOS path in gigabit M2M applications like data transfer in office rooms. The goal of this study is to provide useful information for the design of 60 GHz UWB systems in gigabit M2M communications.

References

[1] C. Gustafson, K. Haneda, S. Wyne, and F. Stufvesson, "On mm-wave multipath clustering and channel modeling," *IEEE Transactions on Antennas and Propagation*, vol. 62, no. 3, pp.1445–1455, Mar. 2014. doi: 10.1109/TAP.2013.2295836.

[2] X. Song, C. Jans, L. Landau, D. Cvetkovski, and G. Fettweis, "A 60 GHz los MIMO backhaul design combining spatial multiplexing and beamforming for a 100 Gbps throughput," in *Proc. IEEE Global Communications Conference*, San Diego, USA, Dec. 2015. doi: 10.1109/GLOCOM.2015.7417737.

[3] T. S. Rappaport, S. Sun, R. Mayzus, et al., "Millimeter wave mobile communications for 5G cellular: it will work!" *IEEE Access-Practical Innovations/Open Solutions*, vol. 1, pp. 335–349, May. 2013. doi: 10.1109/ACCESS.2013.2260813.

[4] T. Baykas, S. Chin-Sean; L. Zhou, et al., "IEEE 802.15.3c: the first IEEE wireless standard for data rates over 1 Gb/s," *IEEE Communications Magazine*, vol.49, no.7, pp.114–121, Jul. 2011. doi: 10.1109/MCOM.2011.5936164.

[5] X. Peng and L. Zhuo, "The 60 GHz Band Wireless Communications Standardizations (in Chinese)," *Information Technology & Standardization*, pp. 49–53, Dec. 2012.

[6] S. Geng, S. Liu, and X. Zhao, "60-GHz Channel Characteristic Interdependence Investigation for M2M Networks," in *International Conference on Communications and Networking*, Maoming, China, Aug. 2014, pp.402–406. doi: 10.1109/CHINACOM.2014.7054327.

[7] S. Geng, J. Kivinen, X. Zhao, and P. Vainikainen, "Measurements and analysis of wideband indoor radio channels at 60 GHz," in *3rd ESA Workshop on Millimeter Wave Technology and Applications*, Espoo, Finland, May. 2003, pp. 39–44.

[8] S. Geng, J. Kivinen, X. Zhao, and P. Vainikainen, "Millimeter-wave propagation channel characterization for short-range wireless communications," *IEEE Transactions on Vehicular Technology*, vol. 58, no. 1, pp. 3– 13, Jan. 2009. doi: 10.1109/TVT.2008.924990.

[9] S. K. Yong and C. C. Chong, "An overview of multigigabit wireless through millimeter wave technology: potentials and technical challenges," *EURASIP Journal on Wireless Communications and Networking*, no. 1, 2007. doi: 10.1155/2007/78907.

[10] National Radio Administration. (2016, Oct.). *Chinese specifications of the 60 GHz band transmission power for short-range wireless applications (in Chinese)* [Online]. Available: www.miit.gov.cn

[11] M. Jacob, S. Priebe, A. Maltsev, et al., "A ray tracing based stochastic human blockage model for the IEEE 802.11ad 60 GHz channel model," in *Proc. 5th European Conference on Antennas and Propagation (EUCAP)*, Rome, Italy, Apr. 2011, pp.3084–3088.

[12] K. Dong, X. Liao, and S. Zhu, "Link blockage analysis for indoor 60 GHz radio systems," *Electronics Letters* , vol.48, no.23, pp.1506– 1508, Nov. 2012. doi: 10.1049/el.2012.2994.

[13] Y. Shoji, H. Sawada, C. Chang-Soon, and H. Ogawa, "A modified SV-model suitable for line-of-sight desktop usage of millimeter-wave WPAN systems," *IEEE Transactions on Antennas and Propagation*, vol. 57, no. 10, pp. 2940–2948, Oct. 2009. doi: 10.1109/TAP.2009.2029286.

[14] S. Geng and P. Vainikainen, "Experimental Investigation of the Properties of Multiband UWB Propagation Channels," in *IEEE International Symposium on Wireless Personal Multimedia (PIMRC07)*, Athens, Greek, Sept. 2007. doi: 10.1109/PIMRC.2007.4394334.

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