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Research Article

60 GHz Modular Antenna Array Link Budget Estimation with WiGig Baseband and Millimeter-Wave Specific Attenuation

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This paper provides practical 60 GHz link budget estimation results with IEEE 802.11ad standard-defined parameters and 60 GHz specific attenuation factors. In addition, the parameters from currently developing modular antenna arrays (MAAs) are adopted for estimating the actual link budgets of our 60 GHz integrated MAA platforms. Based on the practical link budget analysis results, we can estimate fundamental limits in terms of achievable data rates over 60 GHz millimeter-wave wireless links.

1. Introduction

Among the various requirements for next-generation wireless systems (for both cellular and access), achieving multigigabit/s data rates is one of key requirements, and millimeter-wave (mmWave) wireless technologies have been mainly considered to achieve this goal where the considering mmWave frequencies are 28 GHz [1], 38 GHz (or 39 GHz) [2, 3], 60 GHz [4], and 73 GHz [5] bands. The use of mmWave bands for next-generation wireless systems could offer ultra-wideband spectrum availability and increased channel capacity. All these benefits come at the expense of potentially greater system complexity particularly in terms of radio frequency (RF) front end and antenna design, but the recent advancements around mmWave wireless systems development have produced cost effective solutions that can be leveraged to overcome these challenges. Among the potential candidates in mmWave bands for future wireless systems, 60 GHz frequency is considered here because it is only one mmWave band which has its own standardized protocol, that is, the Wireless Gigabit Alliance (WiGig) standard which is equivalent to IEEE 802.11ad.

In this paper, practical link budget estimation is performed based on WiGig/IEEE 802.11ad standard-defined modulation and coding scheme (MCS) modes and 60 GHz mmWave specific path-loss and auxiliary attenuation factors. The considered systems parameters for this link budget estimation are obtained from real-world hardware prototype which is now actively conducting research for next-generation mmWave mesh backhaul networks in industry.

The remainder of this paper is organized as follows: Section 2 introduces our real-world prototype for 60 GHz mmWave backhaul networks. Section 3 presents the details of link budget estimation procedure. Section 4 shows link budget estimation results and Section 5 concludes this paper.

2. 60 GHz Integrated MAA Platform

Traditional antenna system architectures are generally not capable of combining wide-angles with high directionality. To achieve the necessary wide directionality, the phased antenna arrays should consist of a large number of antenna elements. Nowadays, the phased antenna array architectures are widely used for mass production and intended for personal mobile devices comprising a single module containing RF integrated circuits (RFIC) chip that includes controlled analogue phase shifters capable of providing several phase shifting levels. The antenna elements are connected to the RFIC via feeding lines. According to the loss on the feeding lines, this approach allows implementing antenna arrays with limited dimensions of up to 8-by-8, thus achieving gains of about 15–20 dB.

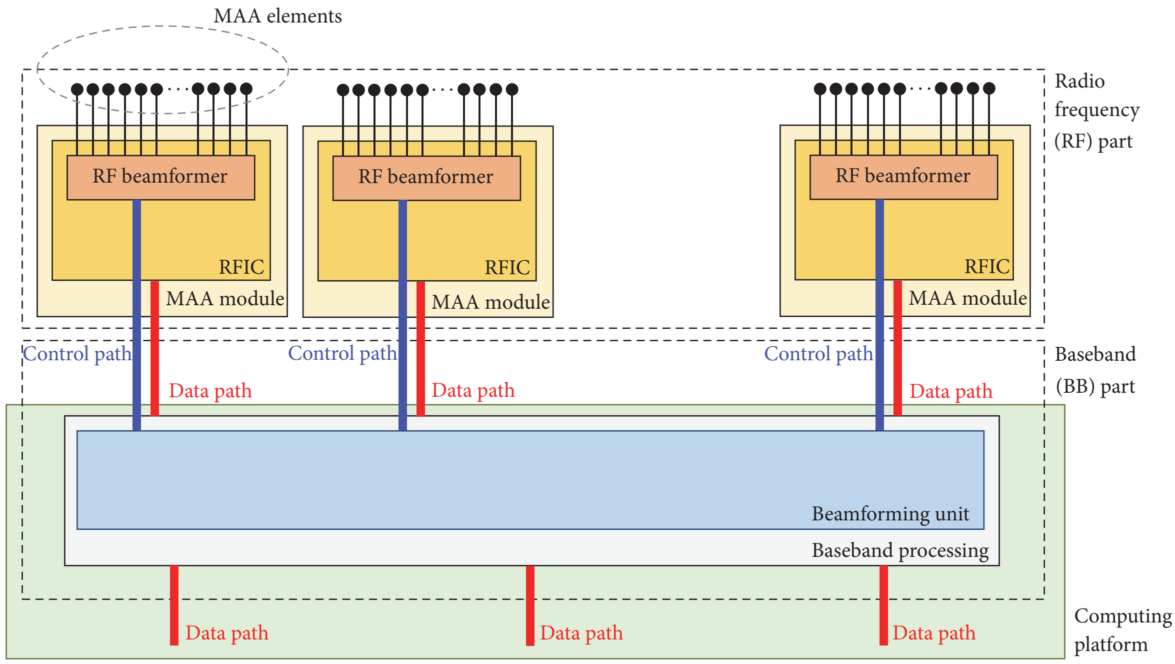


FIGURE 1: High level block diagram of the proposed modular antenna array (MAA) architecture.

One of novel antenna array architectures for the 60 GHz band that provides simultaneous flexibility in form factor choice, beam steering, and high array gain in a conceivably more cost-efficient manner is to construct modular antenna arrays (MAAs). As shown in Figure 1, the MAA architecture consists of baseband part and RF part. The baseband part is embedded in a computing platform. The data from the computing platform will be delivered to the baseband. The baseband part has baseband processing (which is for data processing and also for sending the data to RFIC) and beamforming unit (which is for forming beams toward one dedicated direction and also for setting phase shifting values for the RF beamformers in connected MAA modules). The phase shifting values for the RF beamformers in MAA modules are transmitted through interconnection control paths from baseband beamforming unit to MAA modules. Each module is implemented in a traditional way with dedicated RFIC serving 16 (i.e., 8-by-2) MAA elements through an RF beamformer. The RFIC receives data from baseband processing unit and sends the information to its own RF beamformer in order to transmit over 60 GHz mmWave wireless channels.

The aperture of MAA and total transmitted power may exceed that of an individual MAA module proportionally to the number of the MAA modules used. Therefore, much narrower beams may be created and, thus, much greater antenna gains may be achieved with the MAA as opposed to individual subarrays. It is also possible that sectors of different subarrays may be configured in such a way as to vary the coverage angle of the composite array, thereby creating several coverage angles. Each MAA module has an 8-by-2 elements where the transmit power and the transmit antenna again are determined as 10 dBm and 15 dBi. In Figure 2, currently developing integrated 8-module MAA prototype is presented.

More various usage scenarios and details of the proposed MAA architectures are presented in [6].

3. Link Budget Estimation

The link budget estimation procedure is illustrated in Figure 3. As shown in Figure 3, the transmitted signal from a transmitter MAA (Tx-MAA) toward a receiver MAA (Rx-MAA) over 60 GHz mmWave channels will be attenuated by path-loss, oxygen absorption, and rain effects depending on the distance between the Tx-MAA and the Rx-MAA. When the signal arrives at the Rx-MAA after experiencing attenuation effects, a receiver antenna gain will be added on top of the received signal strength. This procedure can be formulated as follows:

$$P^{\mathrm{Rx}}_{\mathrm{dBm}}(d) = \mathrm{EIRP}_{\mathrm{dBm}} - \mathrm{PL}(d) - O(d) - R(d) + G^{\mathrm{Rx}}_{\mathrm{dBi}}, \quad (1)$$

where $P^{\mathrm{Rx}}_{\mathrm{dBm}}(d)$ is a received signal strength at an Rx-MAA, $\mathrm{EIRP}_{\mathrm{dBm}}$ is equivalent isotropically radiated power (EIRP), the limit in USA is 43 dBm (peak) [7–9], $\mathrm{PL}(d)$ is path-loss depending on the separation distance between a Tx-MAA and an Rx-MAA d, $O(d)$ is oxygen attenuation depending on the separation distance, $R(d)$ is rain attenuation depending on the separation distance, and $G^{\mathrm{Rx}}_{\mathrm{dBi}}$ is a receive antenna gain at an Rx-MAA, respectively.

In WiGig/IEEE 802.11ad [10], supportable MCS indices and their corresponding data rates depending on receiver sensitivity values are defined in Tables 21-3. The given Tables 21-3 in WiGig/IEEE 802.11ad can be reproduced as

Table 1: WiGig/IEEE 802.11ad MCS Index Table (regenerated from Table 21-3 in WiGig/IEEE 802.11ad [10]), assuming that (i) 5 dB implementation loss, (ii) 10 dB noise factor (Noise Figure), and (iii) packet error rate (PER) shall be less than 1% when the payload length is 4000 bytes.

Receiver Sensitivity	MCS index (Achievable rates, unit: Mbps)	SC-based MCS (Mandatory SC)	Full MCS (Including optional OFDM)
−78 dBm	MCS0 (27.5)	MCS0 (i_{MCS} = 1)	MCS0 (i_{MCS} = 1)
−68 dBm	MCS1 (385)	MCS1 (i_{MCS} = 2)	MCS1 (i_{MCS} = 2)
−66 dBm	MCS2 (770), MCS13 (693)	MCS2 (i_{MCS} = 3)	MCS2 (i_{MCS} = 3)
−65 dBm	MCS3 (962.5)	MCS3 (i_{MCS} = 4)	MCS3 (i_{MCS} = 4)
−64 dBm	MCS4 (1155), MCS14 (866.25), MCS25 (626)	MCS4 (i_{MCS} = 5)	MCS4 (i_{MCS} = 5)
−63 dBm	MCS6 (1540), MCS15 (1386)	MCS6 (i_{MCS} = 6)	MCS6 (i_{MCS} = 6)
−62 dBm	MCS5 (1251.25), MCS7 (1925), MCS16 (1732.5)	MCS7 (i_{MCS} = 7)	MCS7 (i_{MCS} = 7)
−61 dBm	MCS8 (2310)	MCS8 (i_{MCS} = 8)	MCS8 (i_{MCS} = 8)
−60 dBm	MCS17 (2079), MCS26 (834)	—	—
−59 dBm	MCS9 (2502.5)	MCS9 (i_{MCS} = 9)	MCS9 (i_{MCS} = 9)
−58 dBm	MCS18 (2772)	—	MCS18 (i_{MCS} = 10)
−57 dBm	MCS27 (1112), MCS28 (1251), MCS29 (1668), MCS30 (2224), MCS31 (2503)	—	—
−56 dBm	MCS19 (3465)	—	MCS19 (i_{MCS} = 11)
−55 dBm	MCS10 (3080)	MCS10 (i_{MCS} = 10)	—
−54 dBm	MCS11 (3850), MCS20 (4158)	MCS11 (i_{MCS} = 11)	MCS20 (i_{MCS} = 12)
−53 dBm	MCS12 (4620), MCS21 (4504.5)	MCS12 (i_{MCS} = 12)	MCS12 (i_{MCS} = 13)
−51 dBm	MCS22 (5197.5)	—	MCS22 (i_{MCS} = 14)
−49 dBm	MCS23 (6237)	—	MCS23 (i_{MCS} = 15)
−47 dBm	MCS24 (6756.75)	—	MCS24 (i_{MCS} = 16)

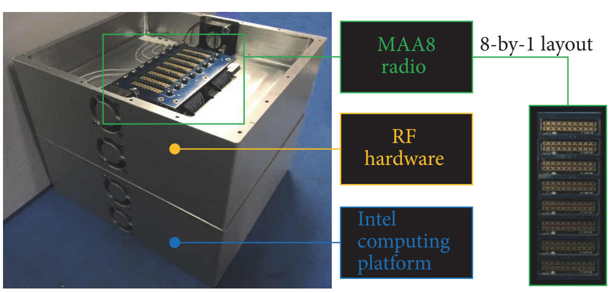


Figure 2: Integrated 60 GHz mmWave MAA architectures and snapshots.

Table 1 by reordering MCS values in terms of receiver sensitivity values. Moreover, if multiple MCS values are supportable in a specific receiver sensitivity value, the MCS value which can provide the highest achievable rate will be obviously used. Note that the reproduced Table 1 includes MCS Table Index values denoted as i_{MCS}. In addition, single carrier (SC) based MCS features are mandatory (from MCS0 to MCS12) and orthogonal frequency division multiplexing (OFDM) based MCS features (from MCS13 to MCS24) and low-power SC-based MCS features (from MCS25 to MCS31) are optional in WiGig/IEEE 802.11ad [10].

If the calculated received signal strength at an Rx-MAA by (1) is higher than the receiver sensitivity of an MCS Table Index i_{MCS} and lower than the receiver sensitivity of MCS Table Index $i_{MCS}+1$, the 60 GHz WiGig/IEEE 802.11ad wireless communication link should use MCS Table Index i_{MCS}. Therefore, if the distance of the wireless communication link is getting longer, $P^{Rx}_{dBm}(d)$ becomes lower due to attenuation factors (i.e., path-loss, oxygen, and rain) as shown in Figure 3; then the index of supportable MCS becomes lower as well. This lower MCS introduces more robust modulation and coding schemes; however, it also introduces lower physical data rates. This calculation procedure is summarized in Algorithm 1. In addition, the following sections include the detailed calculation procedures of EIRP (refer to Section 3.1), path-loss (refer to Section 3.2), mmWave specific attenuation (refer to Section 3.3), and receiver antenna gain (refer to Section 3.4).

3.1. EIRP

In (1), EIRP_{dBm} can be calculated as follows:

$$\mathrm{EIRP}_{dBm} = G^{Tx}_{dBi} + P^{Tx}_{dBm}, \quad (2)$$

where G^{Tx}_{dBi} and P^{Tx}_{dBm} are a transmit antenna gain and a transmit power at a Tx-MAA. In 1-module Tx-MAA (Tx-MAA1), G^{Tx}_{dBi} and P^{Tx}_{dBm} are 15 dBi and 10 dBm. In addition, G^{Tx}_{dBi} in 8-module MAA (Tx-MAA8) and P^{Tx}_{dBm} in Tx-MAA8 are 24 dBi and 19 dBm, respectively.

3.2. 60 GHz mmWave Path-Loss Models

Two different 60 GHz path-loss models are considered in this link budget estimation study: (i) LoS scenario and (ii) street canyon scenario.

The 60 GHz *LoS* path-loss is [11, 12]

$$\mathrm{PL}(d) = 92.44 + 20\log_{10}(f) + 10n\log_{10}(d) \quad (3)$$

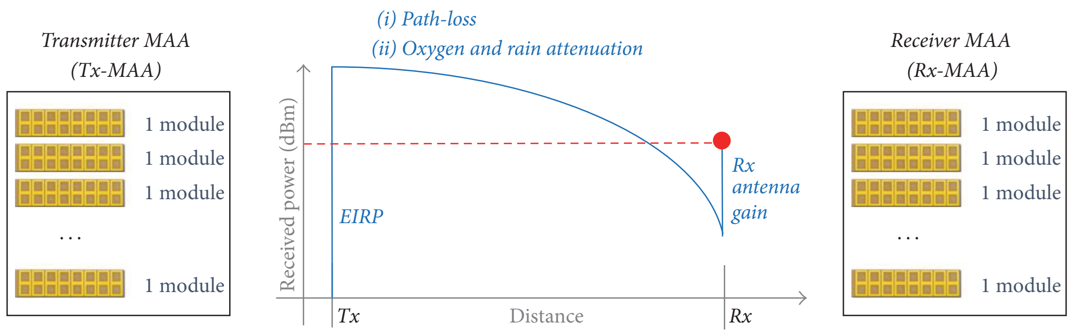


FIGURE 3: Link budget calculation procedure.

Parameter Definition
(i) i_{MCS}: MCS Table Index in Table 1;
(ii) $i_{\text{MCS}}^{\max}$: maximum MCS Table Index, i.e.,
$i_{\text{MCS}}^{\max} \leftarrow 12$ if SC-based MCS is used and
$i_{\text{MCS}}^{\max} \leftarrow 16$ if Full MCS is used;
(iii) $P_{i_{\text{MCS}}}^{rs}$: Receiver sensitivity of i_{MCS};
(iv) M^*: Supportable MCS;
(v) R^*: Supportable data rate;
Algorithm Description
(i) $\alpha \nleftarrow 1$
(ii) Received signal strength calculation with (1) and d: P^*
if $P^* < P_1^{rs}$ **then**
(a) P^* is too low, i.e., $M^* \leftarrow$ N/A and $R^* = 0$ Gbps
(b) $\alpha \leftarrow 1$
end
if $P^* \geq P_{i_{\text{MCS}}^{\max}}^{rs}$ **then**
(a) P^* is good enough for maximum MCS and rates, i.e.,
$M^* \leftarrow 12$ and $R^* \leftarrow 4.62$ Gbps in SC-based MCS; and
$M^* \leftarrow 24$ and $R^* \leftarrow 6.75675$ Gbps in Full MCS
(b) $\alpha \leftarrow 1$
end
if $\alpha \neq 1$ **then**
(a) $i_{\text{MCS}} \leftarrow 2$
while $i_{\text{MCS}} \leq i_{\text{MCS}}^{\max}$ **do**
if $P^* < P_{i_{\text{MCS}}}^{rs}$ **then**
(1) $k \leftarrow i_{\text{MCS}} - 1$
(2) M^* is the MCS where $i_{\text{MCS}} \leftarrow k$
(3) R^* is the rates of MCS level M^*
end
(b) $i_{\text{MCS}} \leftarrow i_{\text{MCS}} + 1$
end
end

ALGORITHM 1: Link budget estimation when the distance between Tx-MAA and Rx-MAA is d m.

and the 60 GHz *street canyon* (illustrated in Figure 4) path-loss is as follows [11]:

$$\text{PL}(d) = 82.02 + 10n\log_{10}\left(\frac{d}{d_0}\right)\Big|_{d_0=5}, \quad (4)$$

where d is a distance between Tx-MAA and Rx-MAA (unit: meter); f is a carrier frequency in a GHz scale; n is a path-loss coefficient, where

$$n = \begin{cases} 2.00, & \text{in an LoS scenario } [11, 12], \\ 2.36, & \text{in a street canyon scenario } [11]. \end{cases} \quad (5)$$

Table 2: Rain rates (unit: mm/h, i.e., millimeter per hour) and their corresponding attenuation factors (unit: dB/Km, i.e., decibel per kilometer) at 60 GHz depending on rain climatic zones (especially for ITU Regions D, P, and Q) [14].

ITU region	99.0% availability	99.9% availability
ITU Region D	2.1 mm/h	8 mm/h
(Northern CA, OR, WA)	(1.2 dB/Km)	(3.5 dB/Km)
ITU Region P [heavy rain areas]	12 mm/h	65 mm/h
(Brazil and so on)	(5 dB/Km)	(21 dB/Km)
ITU Region Q [heavy rain areas]	24 mm/h	72 mm/h
(Middle Africa and so on)	(9 dB/Km)	(25 dB/Km)

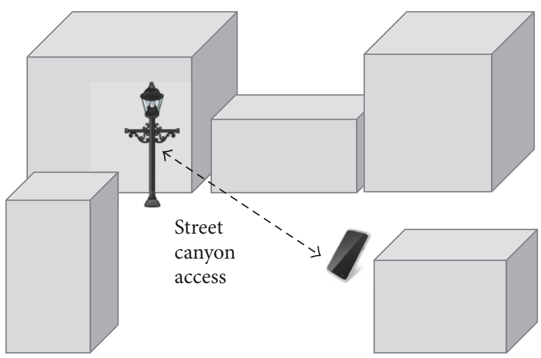


Figure 4: Illustration of street canyon access [11].

3.3. mmWave Specific Attenuation Factors. As explained in [12], attenuation by atmospheric gases (i.e., oxygen attenuation) and by rain must be considered in millimeter-wave propagation.

The oxygen attenuation $O(d)$ is observed as 16 dB/Km [13]: that is, $O(d) = 16 \cdot d/1000$, where d is a distance between Tx-MAA and Rx-MAA in a meter scale.

The rain attenuation factors depend on the rain climatic zones that are segmented and measured by the International Telecommunication Union (ITU) [14]. Table 1 in [14] presents rain rates depending on the segmented areas (from ITU Region A to ITU Region Q). In this paper, ITU Region D (Northern California (CA), Oregon (OR), and Washington (WA)), ITU Region P (heavy rain areas such as Brazil), and ITU Region Q (heavy rain areas such as Middle Africa) are of interest. Table 2 presents the rain rates of ITU regions D, P, and Q (unit: mm/h) and their corresponding rate attenuation factors (unit: dB/Km) based on [15] and Figure 5.

3.4. Receiver Antenna Gain. The receiver antenna gain $G_{\text{dBi}}^{\text{Rx}}$ is equal to $G_{\text{dBi}}^{\text{Tx}}$ in Section 3.1 because equivalent MAA antenna systems are used for both Tx-MAA and Rx-MAA. Therefore,

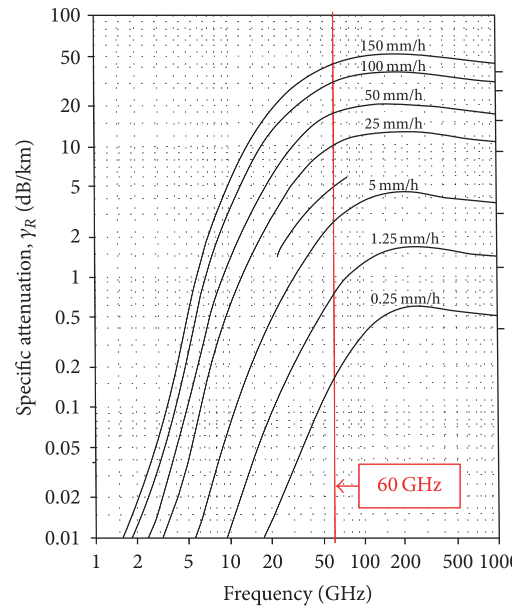


Figure 5: Rain attenuation factor estimation from FCC measurement results [15].

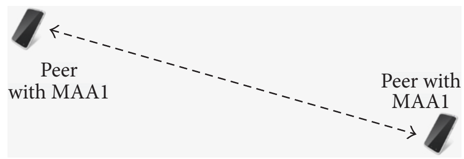
$G_{\text{dBi}}^{\text{Rx}}$ values are 15 dBi and 24 dBi in Rx-MAA1 and Rx-MAA8, respectively.

4. Link Budget Estimation Results

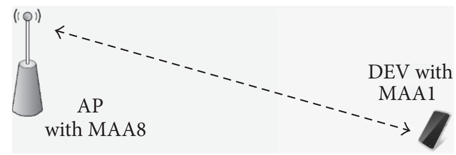
The link budget estimation performs with three different network scenarios as illustrated in Figure 6, that is, (i) peer-to-peer (P2P) links where each peer has MAA1 (i.e., MAA1-MAA1 link); (ii) AP-to-DEV (device) links where each AP and each DEV have MAA8 and MAA1 (i.e., MAA8-MAA1 link); and (iii) backhaul links where each backhaul base station (BS) has MAA8 (i.e., MAA8-MAA8 link). Note that the scenario of AP-to-DEV links is equivalent with the scenario of cellular links where a BS has MAA8 and a mobile user has MAA1.

4.1. Link Budget Estimation. With the given three scenarios, link budget estimation performs depending on two different path-loss models, different ITU regional segments (no rain case, ITU Region D, ITU Region P, and ITU Region Q), and different availability probabilities in each regional segments (99.0% or 99.9%). After performing all possible combinations of link budget estimation, various achievable distances depending on various target data rates (1 Gbps, 2 Gbps, 3 Gbps, and 4 Gbps for mandatory SC-based MCS; and 1 Gbps, 2 Gbps, 3 Gbps, 4 Gbps, 5 Gbps, and 6 Gbps for full MCS) are calculated as presented in Table 3. From Table 3, some remarkable facts are as follows:

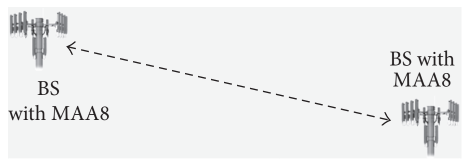
(i) In an MAA1-MAA1 link, 1 Gbps rates are achievable up to maximum 56.80 m (in LoS scenario and no rain) and minimum 36.84 m (in a street canyon scenario and ITU Region Q with 999% availability).



(a) Peer-to-peer link (MAA1-MAA1)

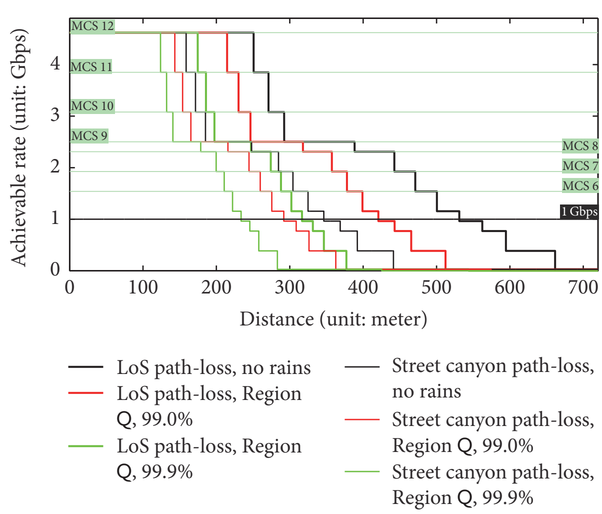


(b) AP-DEV link (MAA8-MAA1)

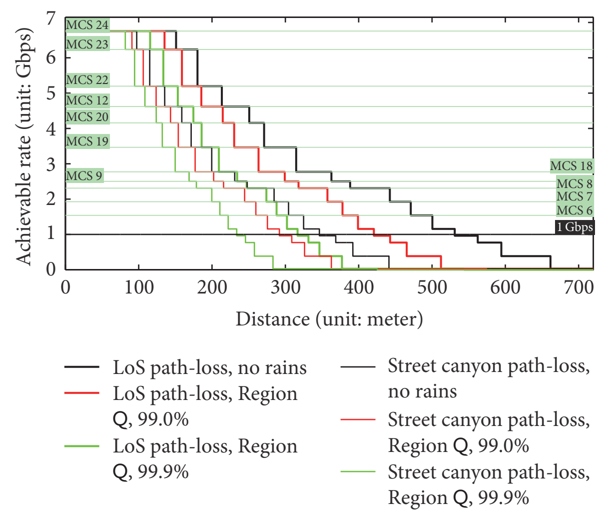


(c) Backhaul link (MAA8-MAA8)

FIGURE 6: Link budget analysis scenarios with MAA.



(a) SC-based MCS



(b) Full (SC-based and OFDM-based) MCS

FIGURE 7: Link budget estimation for backhaul link (MAA8-MAA8, as illustrated in Figure 6(c)) with various path-loss models and rain rates.

(ii) In an MAA8-MAA1 link, 1 Gbps rates are achievable up to maximum 292.37 m (in LoS scenario and no rain) and minimum 140.76 m (in a street canyon scenario and ITU Region Q with 999% availability).

(iii) In an MAA8-MAA8 backhaul link, 1 Gbps rates are achievable up to maximum 530.97 m (in LoS scenario and no rain) and minimum 233.62 m (in a street canyon scenario and ITU Region Q with 999% availability).

4.2. Performance Reduction due to Various Rain Attenuation Factors. Table 4 presents the performance degradation ratio due to various rain attenuation factors. The data in Table 4 can be calculated as follows:

$$\gamma = \frac{\delta_{\text{no-rain}} - \delta^*}{\delta_{\text{no-rain}}} \times 100, \quad (6)$$

where $\delta_{\text{no-rain}}$ stands for the achievable distance (from Table 3) when there is no rain and δ^* stands for the achievable distance (from Table 3) for specific thresholds, regions, and availability probabilities. By calculating γ (presented in Table 4), we can determine how much rain attenuation affects the achievable distance reduction.

As shown in Table 4, the performance degradation is mainly observed in LoS scenario and the ITU Region Q with 99.9% availability. The most significant performance degradation can be observed in the MAA8-MAA8 link when its target rate is 1 Gbps in an LoS scenario and the ITU Region Q with 99.9% availability, that is, about 40.36%.

4.3. Case Study for Backhaul Link Budget Estimation in Heavy Rain Areas (ITU Region Q). The presented 60 GHz MAA platform is originally designed for wireless backhaul networks, that is, MAA8-MAA8 link. Therefore, the link budget estimation for MAA8-MAA8 link is performed and plotted as shown in Figure 7. If service providers want to deploy these MAA boxes for constructing ad hoc mesh backhaul networks with the threshold of 1 Gbps, the following distances

Table 3: Achievable distances (unit: meter) for target data rates.

Scenario	Path-loss	ITU region	SC-based MCS				Full (SC-based and OFDM-based) MCS					
			4 Gbps	3 Gbps	2 Gbps	1 Gbps	6 Gbps	5 Gbps	4 Gbps	3 Gbps	2 Gbps	1 Gbps
MAA1-MAA1 (Figure 6(a))	LoS	No rains	17.22	21.51	41.37	56.80	10.99	13.76	19.25	24.02	41.37	56.80
		D (99.0%)	17.17	21.44	41.15	56.40	10.98	13.74	19.20	23.94	41.15	56.40
		P (99.0%)	17.05	21.25	40.48	55.19	10.92	13.66	19.04	23.71	40.48	55.19
		Q (99.0%)	16.93	21.06	39.81	53.99	10.87	13.57	18.89	23.46	39.81	53.99
		D (99.9%)	17.10	21.33	40.74	55.66	10.94	13.69	19.10	23.80	40.74	55.66
		P (99.9%)	16.56	20.50	37.98	50.80	10.71	13.34	18.43	22.78	37.98	50.80
		Q (99.9%)	16.44	20.33	37.42	49.84	10.66	13.26	18.29	22.57	37.42	49.84
	Street canyon	No rains	14.27	17.26	30.38	40.09	9.73	11.78	15.70	18.98	30.38	40.09
		D (99.0%)	14.25	17.23	30.27	39.92	9.71	11.77	15.67	18.94	30.27	39.92
		P (99.0%)	14.17	17.12	29.96	39.38	9.68	11.72	15.58	18.81	29.96	39.38
		Q (99.0%)	14.10	17.01	29.63	38.83	9.64	11.67	15.49	18.68	29.63	38.83
		D (99.9%)	14.20	17.17	30.08	39.59	9.69	11.74	15.62	18.86	30.08	39.59
		P (99.9%)	13.88	16.70	28.71	37.31	9.54	11.51	15.23	18.30	28.71	37.31
		Q (99.9%)	13.81	16.60	28.43	36.84	9.51	11.46	15.14	18.18	28.43	36.84
MAA8-MAA1 (Figure 6(b))	LoS	No rains	114.37	137.89	231.53	292.37	77.27	94.28	125.68	151.01	231.53	292.37
		D (99.0%)	112.91	135.83	226.49	284.95	76.56	93.25	123.95	148.60	226.49	284.95
		P (99.0%)	108.59	129.86	212.29	264.38	74.42	90.18	118.86	141.62	212.29	264.38
		Q (99.0%)	104.51	124.30	199.65	246.46	72.34	87.25	114.08	135.17	199.65	246.46
		D (99.9%)	110.24	132.13	217.61	272.03	75.24	91.36	120.80	144.27	217.61	272.03
		P (99.9%)	94.43	110.85	171.11	207.23	66.97	79.82	102.41	119.75	171.11	207.23
		Q (99.9%)	91.62	107.18	163.74	197.36	65.42	77.71	99.19	115.58	163.74	197.36
	Street canyon	No rains	75.17	89.36	146.70	185.14	52.68	63.01	81.98	97.29	146.70	185.14
		D (99.0%)	74.58	88.55	144.69	182.10	52.39	62.59	81.29	96.34	144.69	182.10
		P (99.0%)	72.80	86.11	138.80	173.30	51.47	61.32	79.21	93.50	138.80	173.30
		Q (99.0%)	71.06	83.74	133.27	165.20	50.56	60.05	77.18	90.76	133.27	165.20
		D (99.9%)	73.48	87.04	141.05	176.63	51.83	61.81	80.01	94.59	141.05	176.63
		P (99.9%)	66.48	77.62	119.73	145.95	48.08	56.66	71.88	83.71	119.73	145.95
		Q (99.9%)	65.13	75.84	115.98	140.76	47.33	55.65	70.32	81.68	115.98	140.76
MAA8-MAA8 (Figure 6(c))	LoS	No rains	250.75	292.37	442.46	530.97	180.17	213.37	271.03	314.78	442.46	530.97
		D (99.0%)	244.99	284.95	428.17	512.15	176.89	208.98	264.48	306.42	428.17	512.15
		P (99.0%)	228.85	264.38	389.66	462.05	167.48	196.54	246.21	283.35	389.66	462.05
		Q (99.0%)	214.59	246.46	357.37	420.70	158.92	185.39	230.19	263.39	357.37	420.70
		D (99.9%)	234.87	272.03	403.78	480.32	171.03	201.21	253.01	291.90	403.78	480.32
		P (99.9%)	182.72	207.23	290.28	336.60	138.93	159.94	194.77	220.11	290.28	336.60
		Q (99.9%)	174.57	197.36	274.10	316.68	133.63	153.30	185.78	209.30	274.10	316.68
	Street canyon	No rains	158.73	185.14	284.64	346.38	115.03	135.43	171.54	199.57	284.64	346.38
		D (99.0%)	156.41	182.10	278.27	337.57	113.73	133.69	168.88	196.10	278.27	337.57
		P (99.0%)	149.66	173.30	260.36	313.14	109.90	128.57	161.16	186.12	260.36	313.14
		Q (99.0%)	143.35	165.20	244.49	291.87	106.23	123.73	154.00	176.98	244.49	291.87
		D (99.9%)	152.23	176.63	267.06	322.22	111.37	130.52	164.08	189.89	267.06	322.22
		P (99.9%)	128.08	145.95	208.85	245.33	96.99	111.76	136.82	155.47	208.85	245.33
		Q (99.9%)	123.89	140.76	199.68	233.62	94.37	108.43	132.15	149.72	199.68	233.62

TABLE 4: Performance reduction depending on various regions and rain rates (calculated based on the data from Table 3).

Scenario	Path-loss	ITU region	SC-based MCS				Full (SC-based and OFDM-based) MCS					
			4 Gbps	3 Gbps	2 Gbps	1 Gbps	6 Gbps	5 Gbps	4 Gbps	3 Gbps	2 Gbps	1 Gbps
MAA1-MAA1 (Figure 6(a))	LoS	D (99.0%)	0.29%	0.33%	0.53%	0.70%	0.09%	0.15%	0.26%	0.33%	0.53%	0.70%
		P (99.0%)	0.99%	1.21%	2.15%	2.83%	0.64%	0.73%	1.09%	1.29%	2.15%	2.83%
		Q (99.0%)	1.68%	2.09%	3.77%	4.95%	1.09%	1.38%	1.87%	2.33%	3.77%	4.95%
		D (99.9%)	0.70%	0.84%	1.52%	2.01%	0.45%	0.51%	0.78%	0.92%	1.52%	2.01%
		P (99.9%)	3.83%	4.70%	8.19%	10.56%	2.55%	3.05%	4.26%	5.16%	8.19%	10.56%
		Q (99.9%)	4.53%	5.49%	9.55%	12.25%	3.00%	3.63%	4.99%	6.04%	9.55%	12.25%
	Street canyon	D (99.0%)	0.14%	0.17%	0.36%	0.42%	0.21%	0.08%	0.19%	0.21%	0.36%	0.42%
		P (99.0%)	0.70%	0.81%	1.38%	1.77%	0.51%	0.51%	0.76%	0.90%	1.38%	1.77%
		Q (99.0%)	1.19%	1.44%	2.47%	3.14%	0.92%	0.93%	1.34%	1.58%	2.47%	3.14%
		D (99.9%)	0.49%	0.52%	0.99%	1.25%	0.41%	0.34%	0.51%	0.63%	0.99%	1.25%
		P (99.9%)	2.73%	3.24%	5.50%	6.93%	1.95%	2.29%	2.99%	3.58%	5.50%	6.93%
		Q (99.9%)	3.22%	3.82%	6.42%	8.11%	2.26%	2.72%	3.57%	4.21%	6.42%	8.11%
MAA8-MAA1 (Figure 6(b))	LoS	D (99.0%)	1.27%	1.49%	2.18%	2.54%	0.92%	1.09%	1.38%	1.60%	2.18%	2.54%
		P (99.0%)	5.05%	5.82%	8.31%	9.57%	3.69%	4.35%	5.43%	6.22%	8.31%	9.57%
		Q (99.0%)	8.62%	9.86%	13.77%	15.70%	6.38%	7.46%	9.23%	10.49%	13.77%	15.70%
		D (99.9%)	3.61%	4.18%	6.01%	6.96%	2.63%	3.10%	3.88%	4.46%	6.01%	6.96%
		P (99.9%)	17.43%	19.61%	26.10%	29.12%	13.33%	15.34%	18.52%	20.70%	26.10%	29.12%
		Q (99.9%)	19.89%	22.27%	29.28%	32.50%	15.34%	17.58%	21.08%	23.46%	29.28%	32.50%
	Street canyon	D (99.0%)	0.78%	0.91%	1.37%	1.64%	0.55%	0.67%	0.84%	0.98%	1.37%	1.64%
		P (99.0%)	3.15%	3.64%	5.39%	6.40%	2.30%	2.68%	3.38%	3.90%	5.39%	6.40%
		Q (99.0%)	5.47%	6.29%	9.15%	10.77%	4.02%	4.70%	5.86%	6.71%	9.15%	10.77%
		D (99.9%)	2.25%	2.60%	3.85%	4.60%	1.61%	1.90%	2.40%	2.78%	3.85%	4.60%
		P (99.9%)	11.56%	13.14%	18.38%	21.17%	8.73%	10.08%	12.32%	13.96%	18.38%	21.17%
		Q (99.9%)	13.36%	15.13%	20.94%	23.97%	10.16%	11.68%	14.22%	16.04%	20.94%	23.97%
MAA8-MAA8 (Figure 6(c))	LoS	D (99.0%)	2.30%	2.54%	3.23%	3.54%	1.82%	2.06%	2.42%	2.66%	3.23%	3.54%
		P (99.0%)	8.73%	9.57%	11.93%	12.98%	7.04%	7.89%	9.16%	9.98%	11.93%	12.98%
		Q (99.0%)	14.42%	15.70%	19.23%	20.77%	11.79%	13.11%	15.07%	16.33%	19.23%	20.77%
		D (99.9%)	6.33%	6.96%	8.74%	9.54%	5.07%	5.70%	6.65%	7.27%	8.74%	9.54%
		P (99.9%)	27.13%	29.12%	34.39%	36.61%	22.89%	25.04%	28.14%	30.07%	34.39%	36.61%
		Q (99.9%)	30.38%	32.50%	38.05%	40.36%	25.83%	28.15%	31.45%	33.51%	38.05%	40.36%
	Street canyon	D (99.0%)	1.46%	1.64%	2.24%	2.54%	1.13%	1.28%	1.55%	1.74%	2.24%	2.54%
		P (99.0%)	5.71%	6.40%	8.53%	9.60%	4.46%	5.07%	6.05%	6.74%	8.53%	9.60%
		Q (99.0%)	9.69%	10.77%	14.11%	15.74%	7.65%	8.64%	10.23%	11.32%	14.11%	15.74%
		D (99.9%)	4.10%	4.60%	6.18%	6.97%	3.18%	3.63%	4.35%	4.85%	6.18%	6.97%
		P (99.9%)	19.31%	21.17%	26.63%	29.17%	15.68%	17.48%	20.24%	22.10%	26.63%	29.17%
		Q (99.9%)	21.95%	23.97%	29.85%	32.55%	17.96%	19.94%	22.96%	24.98%	29.85%	32.55%

should be maintained: that is, 530.97 m (no rains), 420.70 m (ITU Region Q with 99.0% availability), and 316.68 m (ITU Region Q with 99.9% availability).

5. Conclusions and Future Work

This paper presents practical link budget estimation results with IEEE 802.11ad standard-defined parameters and 60 GHz mmWave specific attenuation factors. In addition, the used system parameters are obtained from the real-world prototypewhich is currently developing for 60 GHz wireless backhaul networking. Based on the link budget estimation results, achievable distances between a transmitter and a receiver are determined depending on various thresholds of data rates in various regions, availability probabilities, and path-loss models.

For future research direction, the link budget estimation withthe other mmWave frequencies can be considerable for next-generation cellular and access systems.

Additional Points

More details about path-loss and radio propagation measurements are presented in [11]. The presented MAA radio platform in Section 2 and Figure 2 is the real-world prototype developed by Intel Corporation and was demonstrated at Mobile World Congress (MWC), 2015.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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