Empirical Characterization of mm-wave Communication Links in Realistic Indoor Scenarios

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***Abstract*—The large contiguous bandwidths available in the mm-wave frequency bands have recently started to gain significant attention due to the growing belief that it can alleviate the spectrum shortage at lower frequencies and meet the increasing high data rate demands. While some commercially available mm-wave transceivers in the 60 GHz and 70 GHz bands have been developed, only a few studies exist on the achievable data rates in realistic deployment scenarios. Moreover, practical issues such as interference and coexistence of heterogeneous applications have not been investigated. In this paper, we present our empirical study on the bit error ratio and throughput for realistic indoor application scenarios in 60 GHz and 70 GHz using orthogonal frequency division multiplexing based physical layer on various commercially available transceivers. Furthermore, we analyze the effects of interference on the performance characteristics of the mm-wave frequency links in different deployment setups.**

I. Introduction

Wireless communication has become an integral part of our daily life. While new applications and wireless services are becoming ubiquitous, our dependency on fast, reliable and readily available information content is posing an increasing demand for high data rates [1]. There is a common perception today that the currently available wireless spectrum will soon be insufficient to serve the growing data rate demands and therefore alternative solutions for better spectrum allocation have been intensively discussed in a wide community of engineers, regulators, policy makers and business stake-holders [2]. As digital transceiver designs for existing wireless systems are being pushed closer to their theoretical performance limits, investigating alternate frequencies with high communication bandwidths becomes an evident choice in order to effectively address the onslaught of emerging applications with high data rate demands. In this context, the mm-wave frequency bands of 60 GHz and 70 GHz have gained significant popularity in recent years. Studies indicate that the contiguous multi-GHz frequency band in the mm-wave frequency spectrum could potentially be utilized in small cells and home networking scenarios to support a number of future applications [3]. Besides theoretical studies, some researchers have also investigated the propagation characteristics and channel models experimentally in both outdoor urban environments and indoor deployments [4]–[7]. Although some transceiver prototypes in mm-wave frequencies have been demonstrated [8], so far very few empirical results on the packet- and link level characterization exist. Notable difference is experienced on Local Multipoint Distribution Systems (LMDS) systems developed for 28 GHz bands such as [9]. Moreover, the implications of heterogeneous network deployment scenarios have not been investigated by wireless researchers. We argue that empirical understanding of mm-wave communication in realistic deployment scenarios is of paramount importance for making the mm-wave communication systems a reality.

While mm-wave communication in the 60 GHz ISM band has a great push from industrial consortia through WiGig alliance promoting IEEE 802.11ad WLAN standard [10] and WirelessHD backing the high definition media content distribution, our major concern is that certain fundamental questions regarding the reliability of links and coexistence of terminals in realistic deployment scenarios are still not adequately addressed. In this paper, we present our experimental study to highlight some of the key challenges that need to be addressed before mm-wave communication for future networks could be realized. Our empirical study on diverse transceiver technologies, deployment setups and traffic patterns gives a broad overview of the achieved data rates on the currently available commercial-of-the-shelf (COTS) devices. We believe that our experimental analysis on heterogeneous deployment scenarios also gives an idea on estimating how far we stand today from embracing the mm-wave communication technology for indoor broadband applications. Moreover, our empirical investigation on the spectral interference highlights the practical issue of coexistence of multiple devices in the mm-wave frequencies that would inevitably be the case in future networking scenarios. While many theoretical studies exist on the propagation characteristics (cf. Section II) besides channel sounding measurements [6], this paper focuses on the system level experimental performance studies. The obtained results provide insights into the achievable mm-wave link characteristics in practical deployments. These link level metrics are very important for understanding the benefits and feasibility of different mm-wave systems.

The rest of the paper is organized as follows. Section II presents the related work towards characterizing mm-wave communication. Section III presents the realistic deployment scenarios and communication patterns in mm-wave communication networks. It further gives an overview on the various heterogeneous transceivers used in our experiments. Section IV presents the empirical performance evaluation results and key lessons learnt in our studies. Finally, Section V concludes the paper.

II. Related Work

WiGig and WirelessHD industrial consortia have been founded to push applications for future networks based on

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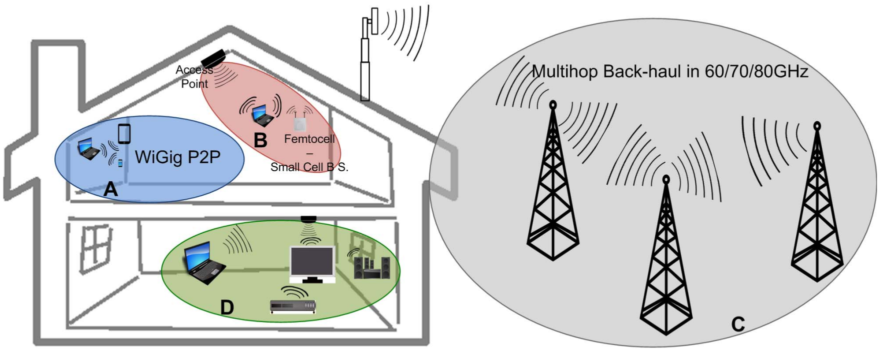

Fig. 1. Various communication interaction scenarios for networks based on mm-wave frequencies.

mm-wave frequencies. Standardization efforts especially IEEE 802.11ad [10] and IEEE 802.15.3c [11] are currently underway. ECMA international has published a standard for the physical- and MAC layers [12]. Earlier analytical studies characterize the properties of the mm-wave frequencies related to the atmospheric absorption, penetration and propagation [13], [14]. Recent experimental measurement campaigns in the mm-wave frequencies [4], [15], [16] mainly focus on channel modeling and propagation characteristics, and lack experimental studies on link level throughput evaluation in realistic indoor and outdoor environments.

As the coming era of wireless communication is moving towards massive and dense deployment of devices, having multi-Gbps of terminal connectivity in the context of small sized cells becomes one of the apparent choices [15]. High propagation losses in mm-wave frequency bands naturally favor short communication distances and high degree of spatial frequency re-use. Besides personalized short distance communication in the cellular context and broadband WLANs [17], longer wireless connectivity with media servers and inside data centers would be possible through directed antenna beams. Especially, beam-steering techniques appear to be highly desirable in the context of mm-wave frequencies [18], [19] because of the possibility of fabricating small sized phase antenna arrays [20]–[22]. Narrow beam transmissions will naturally help in reducing the amount of spectral interference [23], [24]. A number of schemes have been proposed on the premise of efficient beam-steering capability. Before steerable narrow beam transmissions could become economically viable and integrate into terminal devices, major technical hurdles have to be overcome. These include accurate 3D beam formation and control, mechanisms for suppressing angular gain degradation and minimizing the effects of side lobes. The ability of mm-wave frequencies to be reflected from smooth surfaces allows non-line-of-sight (non-LOS) propagation, especially for indoor coverage enhancement. This property of mm-wave frequencies can further be exploited for their potential use in data centers [25], [26] and other stationary deployment setups. Some commercially available mm-wave convertor boards with standard baseband interfaces have been manufactured in recent years and while standardization efforts are still underway, few early baseband chipsets and silicon intellectual property (IP) cores have been developed [27], [28]. Surprisingly, only a little attention has so far been given to empirical performance studies of mm-wave links in realistic deployment conditions.

III. Application Scenarios and Measurement Setup

Fig. 1 illustrates the common communication interactions and deployment scenarios for mm-wave systems. These include the following. Scenario A: peer-to-peer (P2P) communication, including wireless kiosk, wireless cable and in-vehicle communication applications. Scenario B: access or offload through access point (AP) or femto-cell base stations. Scenario C: back-haul over mm-wave wireless links. Scenario D: media and entertainment oriented content transport over mm-wave frequencies.

One of the prospects of the mm-wave frequencies is the possibility of fabricating small sized antenna arrays for beam-forming and beam-steering [29]. Although a number of schemes have been proposed based on the idea of flexible beam-steering capability in the mm-wave frequencies, no commercial product is yet available in the market. In our experiments, we use 10 dBi horn antennas to mimic application scenarios requiring short-distance broad coverage and 25 dBi horn antennas for longer directed links. Our empirical study focuses on the achievable bit-error-ratio (BER) and throughput in realistic deployment setups (cf. Fig. 1) using state-of-the-art mm-wave transceivers. The mm-wave transceivers used in our experiments include the following.

Hittite Microwave HMC6000/1 with on-chip antenna is tailored towards applications with short coverage ranges. These transceiver boards are interfaced through differential in-phase and quadrature (I/Q) signal components, and can support a baseband signal bandwidth of up to 1 GHz. A USB based configuration interface is used for setting various tunable parameters.

SiversIMA E & V band transceiver boards with flange waveguide interfaces for external antennas operate in the 60 GHz and 70/80 GHz frequency ranges. These boards are interfaced with I/Q signal components and support an intermediate frequency (IF) bandwidth of up to 5 GHz. These boards allow a USB based serial interface for configuration of various tunable parameters.

HXI GigaLink 6651 transceivers are primarily targeted for outdoor back-haul links using parabolic antennas. However,

TABLE I. MM-WAVE TRANSCEIVERS AND THEIR PARAMETER SETTINGS USED IN OUR EMPIRICAL STUDY.

Transceiver	Operating Frequency	Transmit Power	Antenna Type	Transmission Technology	Input Signal
Hittite Microwave HMC6000/1	57-64 GHz (Tunable)	Max. 12 dBm (Tunable)	On-chip (Max. gain 38dB)	Custom OFDM with 4-QAM	Differential I/Q
SiversIMA FC1005V/00	58-63 GHz (Tunable)	Max. 16dBm (Tunable)	External (Horn: 10dBi,25dBi)	Custom OFDM with BPSK,QPSK and 4,16,32,64,128,256,512-QAM	I/Q
SiversIMA FC1003E/02	71-76 GHz (Tunable)	Max. 16dBm (Tunable)	External (Horn: 10dBi,25dBi)	Custom OFDM with BPSK,QPSK and 4,16,32,64,128,256,512-QAM	I/Q
HXI GigaLink 6651	58.2 GHz,61.9 GHz (Not tunable)	Max. 0.5dBm (Not tunable)	External (Horn: 10dBi,25dBi)	Single Carrier with ON-OFF keying	Ethernet

we test them for indoor scenarios (base station/base station and terminal/base station links) using external horn antennas with transmit power of 0 dBm. HXI GigaLink 6651 provides fiber optic 1000Base-SX input/output interfaces which are connected to 1000Base-T Ethernet. In our experiments, we use *iperf* network traffic monitoring tool with HXI GigaLink 6651 to carry out performance measurements.

Table I summarizes the list of 60 GHz and 70/80 GHz transceivers used in our experiments. Our work analyzes the achieved performance characteristics in various mm-wave network deployment scenarios ranging from coverage distances of as little as 20 cm for near-field communication to longer coverage radii of over 15 m. However, most of our performance evaluation focuses on distances ranging from 3 m to 7 m – depicting typical indoor deployment setups of micro- and femto-cells. For back-haul communication, we study the feasibility of LOS traffic links and those involving reflection from mirrors [26]. We have used signal generator and spectrum analyzer operating in the mm-wave frequencies for various reference tests.

In this work, we have used our custom orthogonal frequency division multiplexing (OFDM) based physical layer, which is also being strongly favored on the standardization front [10], [11], and by WiGig Alliance and WirelessHD industrial consortiums. We have empirically studied different OFDM parameters including the number of sub-carriers, system bandwidth and the modulation order for data sub-carriers. We have used Agilent 81180A arbitrary waveform generator to generate wide bandwidth I/Q-baseband signals for our real-time measurements. These I/Q-baseband signal components are fed to Hittite Microwave and SiversIMA transmitters for over-the-air transmission in 60/70 GHz after necessary filtering and up-conversion processes. The mm-wave transmission is down-converted to baseband at Hittite Microwave and SiversIMA receivers. The corresponding baseband I/Q signal components at the receiver side are demodulated using Agilent 81960A Vector Signal Analysis software [30] running on the host 40 GSa/s Agilent 90804A Oscilloscope. A simplified scheme for the measurement setup is illustrated in Fig. 2. After the OFDM demodulation process, statistics on BER and goodput are gathered.

IV. Performance Measurements

In this section, we present the empirical performance results on link reliability and goodput. We also discuss the impact of spectral interference in realistic deployment setups and analyze the resulting performance degradation in this section.

A. Achievable Link Distances on COTS Transceivers

In order to cover different communication scenarios as depicted in Fig. 1, we have selected three different antennas in our experiments. Hittite Microwave HMC6000/1 transceivers are one of the first commercial products in 60 GHz with on-chip antennas. These transceiver boards primarily target WiGig applications and personal area scenarios with near field communication patterns (cf. Scenario A in Fig. 1). Two types of external horn antennas have been considered: 1) antennas with gain of 25 dBi for directed and longer distances (cf. Scenario C in Fig. 1) and 2) antennas with 10 dBi gain for traffic offloading (through AP or small cell base station) type of scenarios with wider coverage requirements (cf. Scenarios B and D in Fig. 1). Moreover, terminal/terminal and terminal/base station connectivity links have also been studied using hybrid combination of external horn antennas. Please note that in this paper, we do not report results on the other well-known issues of deafness and blockage in the mm-wave frequencies.

Hittite Microwave HMC6000/1 boards using our custom

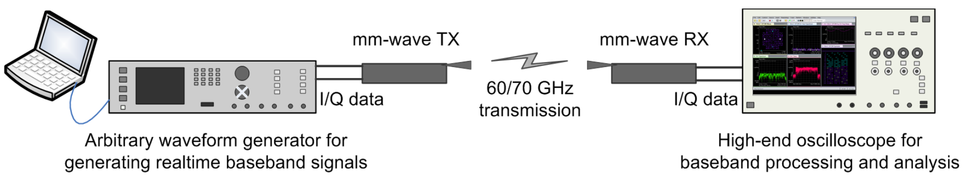

Fig. 2. Basic experimental setup for a single mm-wave link measurement.

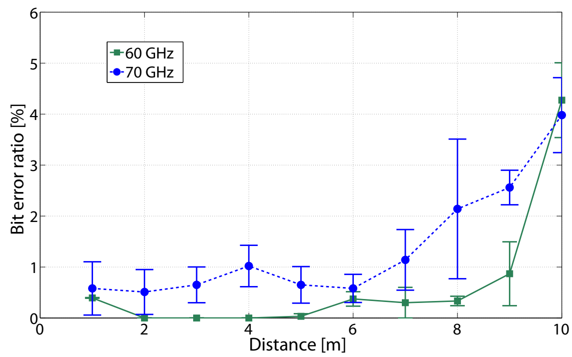

Fig. 3. Bit error ratio comparison of SiversIMA transceivers operating in 60 GHz and 70 GHz in identical deployment conditions using our 64-QAM OFDM implementation with 250 MHz of signal bandwidth.

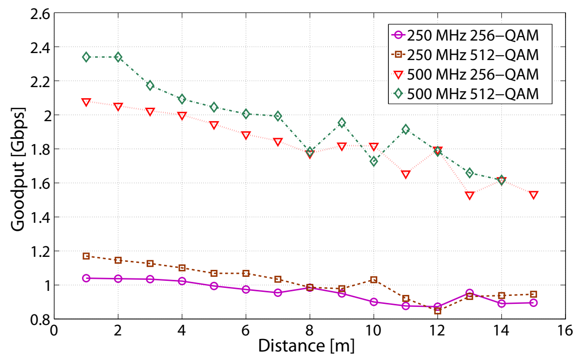

Fig. 5. Achieved goodput over different link distances for our custom OFDM implementation in 60 GHz on SiversIMA transceivers. Standard horn antennas with 25 dBi gains are used in these experiments.

OFDM implementation (without channel coding) have shown to achieve over 1 Gbps transmission links up to a distance of ca. 50 cm with the maximum supported transmit power level of 12 dBm. Our measurements indicate that HXI GigaLink 6651 transceivers can be used for back-haul communication links with reliable throughput of over 850 Mbps. Our measurements on a wide variety of base station/terminal and terminal/terminal communication patterns in micro- and femto-cell context on the SiversIMA transceivers using different settings for our custom OFDM implementation confirm that reliable Gbps links are realizable for indoor applications involving coverage distances of 1 m to 7 m. We have also observed that BER and goodput of 60 GHz and 70 GHz links suffer negligible loss due to reflections from mirrors, i.e., the performance characteristics of LOS and reflected (non-LOS) mm-wave links over the same distances are very similar. For instance, at distances of 5 m to 10 m, the maximum throughput degradation in mirror reflected paths stays lower than 0.2 %. Our throughput results for mirror reflection are in line to the earlier observations reported only for the received signal strength characteristics [26]. Moreover, our studies confirm the belief that 60 GHz transmission could be used in application scenarios relying on reflected signal paths.

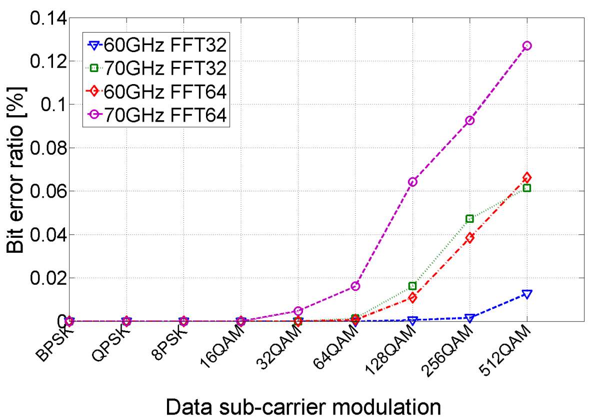

Fig. 4. Bit error ratio comparison of SiversIMA transceivers operating in 60 GHz and 70 GHz in identical deployment setups at a link distance of 3 m using our OFDM implementation with 250 MHz of signal bandwidth.

We have compared the achieved throughput and BER on a SiversIMA FC1005V/00 transceiver link operating in 60 GHz with a SiversIMA FC1003E/02 transceiver link operating in 70 GHz with identical parameter settings of our custom OFDM implementation using the same transmit power levels. We have used external horn antennas with 25 dBi gain in these experiments. Fig. 3 shows that BER of the OFDM based transmission links stay comparable for the 60 GHz and 70 GHz mm-wave frequencies. Moreover, due to decrease in the signal to noise ratio, BER starts to gradually increase at longer distances.

We have studied the effects of data sub-carrier modulation order and OFDM system bandwidths on BER. As expected, at the same transmit power level, BER increases with higher modulation order due to decrease in the signal to noise ratio. Moreover, we have observed that the increase in BER becomes more significant at longer transmission distances. We have also noticed a slight increase in BER with increasing system bandwidth of our custom OFDM implementation. This is because of sending more data sub-carriers per OFDM burst. Fig. 4 shows BER at a typical indoor distance of 3 m for the 60 GHz and 70 GHz SiversIMA transceiver links with 250 MHz of bandwidth using our custom OFDM implementation. We have also observed that BER increases with increasing depth of Fast Fourier Transform (FFT), i.e., number of carriers per OFDM burst and increasing modulation order for data sub-carriers.

Fig. 5 shows the achieved goodput over different distances with a SiversIMA FC1005V/00 transmission link using 25 dBi antennas. The figure shows that the achieved goodput is considerably higher for 500 MHz bandwidth compared to 250 MHz wide transmission. Higher throughput results have been achieved with larger bandwidths in the mm-wave frequencies supported by SiversIMA transceivers. Due to the large baseband processing delays at the receiver, we could not carry out experiments with higher than 1 GHz of bandwidths. This, however, would be possible using a dedicated baseband processing unit such as the recently developed chipsets [27], [28]. We have also observed that with the same parameter settings of the OFDM implementation, due to lower atmospheric absorption 70 GHz transmission links show a slightly higher goodput as compared to 60 GHz transmissions at longer distances.

B. Interference Effects on Performance Characteristics

As discussed before, there are a number of perceived mm-wave communication scenarios both indoor and outdoor applications. Some of the mm-wave communication deployments require narrow beamed longer links, others aim at short ranged wider coverage such as in near field communication applications, wireless LANs and cellular systems [15]. It is expected that due to dense deployment of devices and overlapping antenna radiation patterns, mm-wave applications will suffer from interference and need to coexist with one another in future. The effects of interference in mm-wave communication have been significantly down-played primarily because of potentially having highly directed transmission links through accurate beam-steering antenna arrays. As of today there is no commercially viable antenna array solution for beam-steering in the mm-wave frequencies. Moreover, inaccuracies in antenna beams and side lobes are expected in practical systems in future. We argue that the wide range of application requirements on link distances and antenna beamwidths, and massive deployments of terminals in the mm-wave frequencies would lead to far stronger wireless interference than what is currently estimated. We also argue that technological advancements towards consumer products for antenna arrays and beam-steering mechanisms in future will mitigate the interference problem but to a certain limit. We point out that at longer coverage distances, dense deployment of devices, inaccuracies in antenna radiation patterns and device mobility would certainly lead to degradation in performance characteristics due to interference. We think that efficient medium access control and link layer mechanisms would become essential for mm-wave communication to ensure transmission reliability, allow spectral coexistence and circumvent the effects of sudden disappearance of links due to antenna coverage problems of deafness and blockage.

We have carried out the initial interference study and analyzed the performance degradation caused by simultaneous transmissions in realistic deployment setups of mm-wave communication networks. In particular, we have analyzed the effects of transmit power levels, antenna directivity gains, interfering distances and spectral overlaps of the interfering transmissions on BER and throughput.

We have evaluated a scenario where an existing small-cell deployment in the mm-wave frequency range interferes with a mm-wave application requiring near-field communication, i.e., Scenario A suffering interference from Scenarios B and D (cf. Fig. 1). Our measurements show that the transmission links on Hittite Microwave HMC6000/1 transceivers are highly susceptible to external interference. We have observed that the Hittite Microwave HMC6000/1 transmission link breaks due to interference produced by HXI GigaLink 6651 and SiversIMA FC1005V/00 transmitters placed at a distance of 2 m using 10 dBi horn antennas.

We have analyzed the mutual interference resulting from nearby small cell deployments. Our investigation suggests that the spatial separation of two adjacent cells must ensure that the interference levels stay considerably low in order to avoid degradation in the link throughput. With dense deployment of mm-wave devices, controlling transmission power levels and spatial separation of devices in a precise manner would become unpractical. We have measured the amount of degradation in throughput of two SiversIMA transceiver pairs with a link distance of 2 m using wider beamwidth 10 dBi antennas. The spatial separation of the two transceiver pairs has been kept 5 m to mimic an adjacent cell scenario. Our results indicate that the link throughput degrades significantly due to spectral interference. We have also noticed that BER increases with increasing modulation order. At the OFDM system bandwidth of 500 MHz with 128-QAM modulation, we have observed that the mutual interference in the adjacent cell scenario becomes so high that the receiver is unable to demodulate the signal. Inability of correctly detecting the OFDM pilots and null subcarriers leads to unsuccessful demodulation. The reader should note that due to unavailability of antenna arrays commercially, our experiments mimic them by using horn antennas. For the directivity of the array antennas, our setup is a good practical approximation but due to absence of the side lobes, it represents substantially lower interference situation especially for shorter distances.

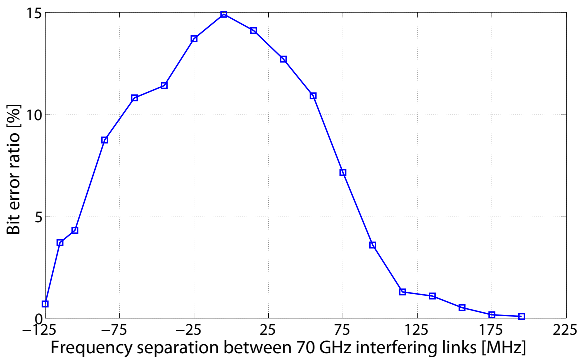

Fig. 6. Average bit error ratio of two interfering SiversIMA transceiver pairs at a distance of 5 m both using 64-QAM OFDM with 250 MHz transmission bandwidth in the 70 GHz frequency band. The center frequency of one of the links is sweeped with a step of 20 MHz.

We have experimented with deployment of adjacent cells in different frequencies. We have designed a scheme of using a relatively narrow bandwidth (250 MHz) 64-QAM custom OFDM transmission of two 70 GHz transceiver pairs with a transmitter-receiver distance of 2 m using the wider beamwidth 10 dBi antennas. The spatial separation of the two transceiver pairs has been kept to be 5 m as in the scenario described above. The center frequency separation of the two transceiver pairs has been varied and correspondingly the average BER has been measured. Fig. 6 shows that as the two transceivers coincide with their center frequencies, interference becomes maximum leading to the highest BER. The average BER decays gradually as the frequency separation of the two interfering transmissions increases. We have noticed that as the spectral interference increases, the ability of the receiver to decode the transmission decreases. Please note that the measured BER results are for the case when the receiver is able to decode the transmission. Our results suggest that channelization (frequency separation) will be necessary for coexistence of mm-wave communication applications. Our study further implies that appropriate medium access and link layer mechanisms combined with practical beam-steering techniques would become essential for mitigating the spectral interference problem in future.

V. CONCLUSION

In this paper, we have presented our empirical results on the bit error ratio and throughput for the 60 GHz and 70 GHz links in indoor environments. Our experimental study focuses on the OFDM based physical layer for mm-wave communication owing to its adaptation by standardization bodies. We have analyzed the effects of transmission bandwidth, modulation order for data sub-carriers, and link distances on the achieved throughput and bit error ratio for multi-Gbps communication in 60 GHz and 70 GHz bands. Our study considers the typical application scenarios and realistic deployment setups for mm-wave communication. We believe that our empirical results provide significant insights on the mm-wave link characterization especially when only a few experimental studies have so far been conducted and these mainly focus on the channel and propagation characteristics.

Our experimental results indicate that the interference due to dense deployment of devices and inaccuracies in spatial separation of antenna beams will be far stronger in real application environments than what is currently anticipated for mm-wave communications in literature. Therefore, besides channelization and beam-steering mechanisms, coexistence and scheduling techniques using efficient media access mechanisms would become essential in order to mitigate spectral interference and ensure communication reliability.

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