60 GHz Millimetre-Wave Channel Characterisation for Indoor Office Environments

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***Abstract*—A 60 GHz swept-tone channel sounder with 1 GHz measurement bandwidth has been developed. The sounder has been used to analyse millimetre-wave propagation in a compact indoor office environment. Profiles of the power angle-of-arrival have been measured for a number of different transmitter and receiver configurations to identify the dominant propagation paths. It was found that the power carried on specular single- and double-bounce reflections from objects in the office (e.g., door frames and whiteboards) are typically 15–20 dB below that carried on the line-of-sight (LOS) path. A further experiment with an absorber phantom (representing the human body) showed the LOS path can be readily shadowed at 60 GHz. However, the attenuation introduced by an internal wall consisting of drywall mounted on timber frames was measured to be between 11–22 dB, leading to the conclusion that internal walls may be insufficient to isolate co-channel systems if the LOS path is otherwise occluded.**

***Index Terms*—Millimetre-wave, propagation, indoor channels.**

I. Introduction

The high capacity requirements for fifth-generation (5G) wireless communication systems will likely be met by utilising (currently) unallocated millimetre-wave spectrum [1], [2]. In particular, the 57–67 GHz band is seen as a promising candidate for 5G systems, as up to 5–7 GHz of contiguous bandwidth is available in many countries [3], [4]. However, the propagation characteristics of 60 GHz channels are significantly different from sub-6 GHz channels, and are not well understood at this time, particularly for highly cluttered environments, e.g., within buildings. Contemporary wireless systems operating in sub-6 GHz frequency bands typically rely on diffraction and reflection mechanisms to propagate radio frequency energy into shadowed regions. However, at millimetre-wave frequencies, propagation is dominated by the line-of-sight (LOS) path and diffraction is virtually non-existent. Furthermore, penetration losses through typical building materials can be significant [5], [6].

Accordingly, characterising the indoor 60 GHz channel is important for the successful deployment of 5G wireless systems within buildings. In particular, accurately predicting the shadow regions is important to establish the placement of millimetre-wave access points, antenna specifications, and beam-steering requirements to ensure sufficient coverage can be achieved. However, previous measurements of the indoor 60 GHz channel have largely focused on developing distance-dependency models for the path-loss in outdoor and indoor environments [5], [7], [8], [9], and on estimating the delay spread [8], [10]. There has been limited investigation of millimetre-wave propagation in compact office environments, where the presence of local 'clutter', (e.g., office furniture) and people may occlude the LOS paths, leading to coverage holes [11]. Similarly, there has been little investigation of potential co-channel interference arising from millimetre-wave systems deployed in close proximity, i.e., in an adjacent office and/or separated by internal walls within a building.

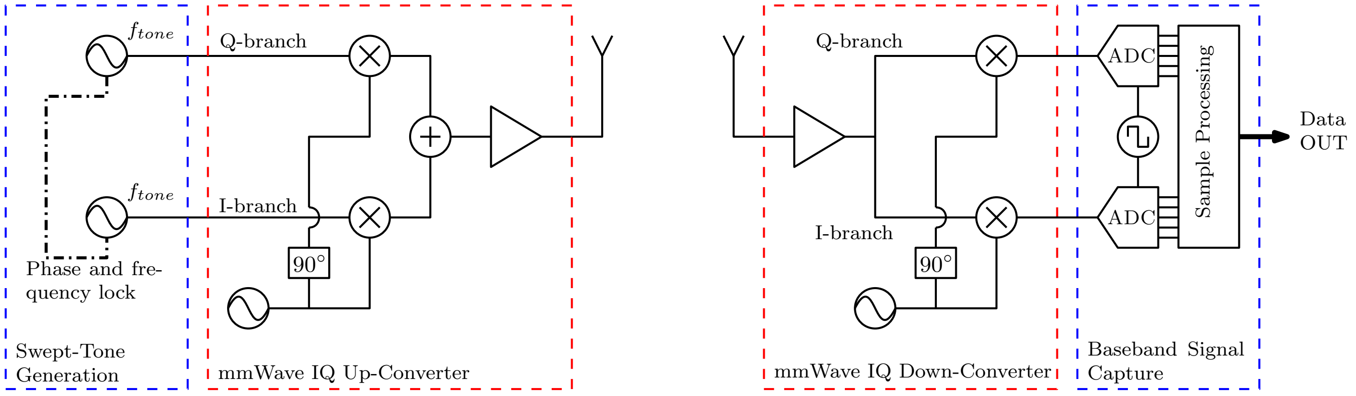
Contributions: This paper reports on a detailed propagation study within an office in the 60 GHz band using a swept-tone channel sounder built from off-the-shelf components. A particular focus of investigation is the contribution of specular reflections from metal objects in the offices (e.g., door frames and whiteboards) to the overall received power. Power angle-of-arrival measurements for the 60 GHz indoor channels have been reported previously, e.g., [12], which focused on large 'empty' rooms, where specular reflections from the wall surfaces dominated. Our paper also considers the impact of propagation from adjacent offices, through 'soft' internal partitions.

An overview of the channel sounder and the indoor environment investigated are presented in Section II. Section III describes the experimental measurement procedure and presents the results for the office measurements. Section III also discusses the implications of these results for the deployment of millimetre-wave systems within buildings. Conclusions are made in Section IV.

II. Indoor Millimetre-Wave Channel Measurements

A. 60 GHz Channel Sounder Architecture

Fig. 1 shows a block diagram of the channel sounder which is based around a pair of 60 GHz direct-conversion up- and down-converters (Sivers IMA FC2121V/01 and FC2221V/01 respectively [13], [14]). The inputs to the up-converter are the I- and Q-components of a narrowband tone generated from two phase and frequency locked signal generators. This baseband tone is swept from -500 MHz to $+500$ MHz in 10 MHz steps to perform a wideband channel characterisation in the passband from 59.5 GHz to 60.5 GHz. The received baseband IQ signals are sampled and captured using a dual-channel analog-to-digital-converter [15]. The implementation of the channel sounder is described in more detail in [6], and was verified by comparing measurements on an flat optical table with a two-ray geometrical optics model. Good agreement was found over the entire 59.5–60.5 GHz frequency range. In this



(a) Transmitter

(b) Receiver

Fig. 1. Block diagram of the millimetre-wave channel sounder. Not shown are the connections between the modules and a computer used control the hardware and generate/collect the data.

paper, we are interested in identifying the dominant 60 GHz propagation paths within a office environment, accordingly, directional horn antennas [16] were used and the receiver was mounted on a rotating platform. To remove multipath fading the received power is averaged in the frequency-domain across the 1 GHz measurement bandwidth.

B. Description of the Environment Investigated

A floor plan of the office environment is shown in Fig. 2. Three transmitter locations (TX A, TX B and TX C) and two receiver locations (RX 1 and RX 2) are considered. All transmitter locations are 1.6 m above the floor and are representative of typical deployments for indoor wireless access points. Similarly, both receivers are positioned 1.2 m above the floor and represent typical user locations in an indoor office. To examine the impact of interference arising from co-channel millimetre-wave systems, TX B and TX C are located in an adjacent office. Both offices are relatively compact (3×3.75 m) and contain typical office furniture, including desks, chairs, tables, bookshelves, whiteboards and filing cabinets. The offices have concrete floors and ceiling, while three of the surrounding internal walls are constructed from drywall mounted on timber frames. There is one glass-panelled internal wall, which also contains metal frames around a wooden door.

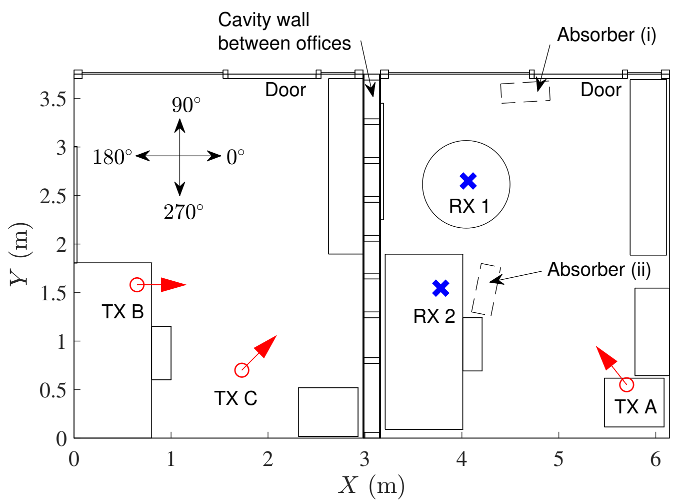


Fig. 2. Floor plan of the indoor office environment considered, with the transmitter and receiver locations identified by ∘ and × respectively. The boresight of the transmitting antenna horns are indicated by an arrow. The location of the flat microwave absorber panels (representing the human body) are also shown.

III. Experimental Results

To account for the transmitter power amplifier and gain stages in the receiver front-end, the measurement results presented in this section are normalised to a 'free-space' measurement when the boresight of the transmitter and receiver antennas are aligned with a separation distance of 2.5 m. This allows us to make comparisons between different transmitter/receiver locations and orientations of the antennas. The nominal transmit power was 23.7 dBm, and the gains of the horn antennas were 17 dBi. In all cases the transmitting and receiving antennas were vertically polarised.

A. In-Office Measurements

1) Case I: TX A, RX 1: Fig. 3 shows a polar plot of the normalised received power (in dB units) at receiver position RX 1, with the transmitter located at TX 1. It is observed that the majority of the received power at this location arrives on the LOS path, i.e., at an arrival angle of 310°, which represents the case where the transmitting and receiving antennas are boresight aligned. Three additional components, at 70°, 130° and 220° are also observed. However, the power carried on these components are between 13–20 dB below the LOS path, and arise from reflection/scattering in the environment, as no appreciable back- or side-lobes were measured using the

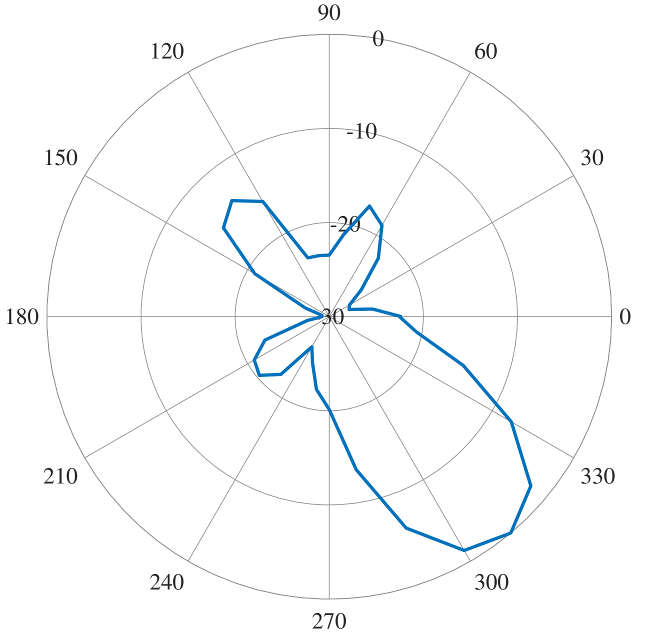


Fig. 3. Polar plot of the normalised received power (in dB units) when the transmitter and receiver are located in the same office (TX A, RX 1).

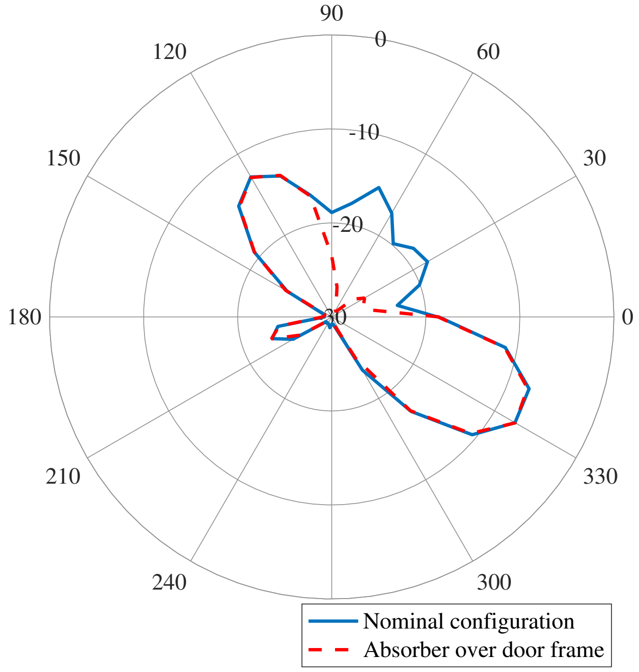


Fig. 4. Polar plot of the normalised received power (in dB units) at location RX 2, when the transmitter is placed in the same office (TX A). A comparison is made between the nominal office configuration and when a microwave absorber placed over the metal door frame.

channel sounder in an anechoic chamber.

2) Case II: TX A, RX 2: In this configuration, the receiver is moved off-boresight, while the orientation of the transmitting horn antenna is not changed. Fig. 4 shows the power received on the LOS path (between 330°–340°) is reduced by approximately 8 dB, as expected, since the horn antennas have a relatively narrow 15° 3 dB beamwidth. However, the magnitude of the power carried on the reflected/scattered paths has not changed significantly compared to Case I.

Microwave absorbers were used to determine the objects in the environment responsible for the reflected components observed in Fig. 4. For example, the dashed curve in Fig. 4 shows the impact of placing a microwave absorber to cover the metal door frame. In particular, it is observed the strong components between 30° and 70° arise from a specular reflection from the metal door frame. The location of the reflection point on the metal door frame is also consistent with that predicted by geometrical optics. Similar results were obtained for the component at 120°, which arises from a double-bounce specular reflection at the metal door frame and whiteboard. It should be noted that while the metal door frame is 'only' 6 cm wide, it is electrically large (12λ) at 60 GHz.

B. Adjacent Office Measurements

Two transmitter locations (TX B and TX C in Fig. 2) in an adjacent office have been also considered, and the boresight orientation of the horn antennas is indicated by an arrow. Fig. 5 shows the normalised received power at receiver location RX 2 for both transmitter positions. It is observed that the internal wall between the offices introduces attenuation in the range 11–22 dB (depending on the transmitter position), relative to the free-space case in Fig. 3. In particular, for transmitter position TX B, the attenuation on the main 'beam' is approximately 11 dB. In this case, the transmission path passes between the vertical timber supporting studs[1] and is only blocked by two layers of 1 cm thick drywall. While 11 dB is higher than previously measured for drywall attenuation at millimetre-wave bands [6], it should be noted that the drywall in the offices is painted, which may have trapped additional moisture. For transmitter position TX C, the wall attenuation is approximately 22 dB, and more lobes are observed in Fig. 5. In this case the timber studs now shadow the direct path and introduce an additional 10–15 dB attenuation.

C. Impact of Blocking the LOS Path

A 15 cm thick block of microwave absorber is used as a phantom to mimic the behaviour of the human body on the propagation of the 60 GHz signals. Fig. 6 shows the received power measured at RX 2 when the absorber is placed to block the LOS path from TX A, as depicted in Fig. 2. This configuration represents the case where a user is holding a millimetre-wave device in their hand and has turned their back to the access-point. Compared to the nominal case, the absorber introduces a 25 dB reduction in power on the LOS path (between 300° and 350°). It should be noted that the absorber generally does not affect the magnitude of the reflected components, which all remain approximately the same as previously measured.

[1]The locations of the timber studs were determined using a stud finder and have been accurately drawn on Fig. 2.

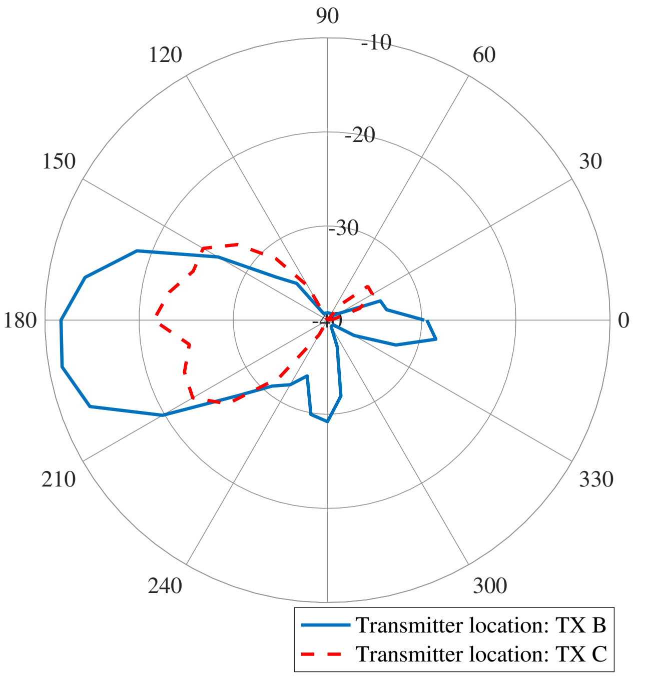


Fig. 5. Polar plots of the normalised received power (in dB units) at location RX 2, when the transmitter is placed at two locations (TX B and TX C) in an adjacent office.

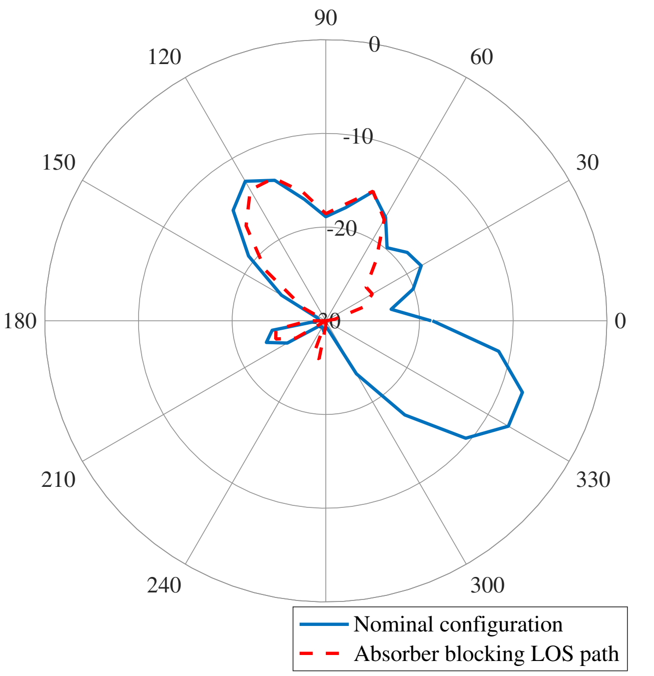


Fig. 6. Polar plots of the normalised received power (in dB units) at location RX 2, when the transmitter is located in the same office (TX A) comparing the nominal configuration to the case when the LOS path is blocked by an absorber phantom.

D. Implications for Millimetre-wave System Deployments

The results shown in Fig. 3 and 4 indicate that at 60 GHz, within an office, power is generally carried on the LOS path. Specular reflections from objects in the environment are present, but are typically 15–20 dB below the LOS path. In this case, the attenuation introduced by internal walls is sufficient to isolate co-channel systems located in adjacent offices and limit the impact of interference. However, as shown in Fig. 6, the LOS path can be easily blocked by the human body, and energy from the 'desired' access point now tends to be carried by the specular reflection paths. In particular, the desired power levels are now comparable to the co-channel interference from adjacent offices.

IV. Conclusions

Indoor environments represent a challenge for the successful deployment of millimetre-wave systems. In particular, millimetre-waves encounter significantly more diffraction loss and are readily shadowed by objects in the environment. This paper has focused on experimentally characterising the 60 GHz millimetre-wave channel in a compact office environment, with the aim of identifying the dominant propagation paths. A swept-tone channel sounder with 1 GHz measurement bandwidth has been developed and used to measure angular profiles of the received power. The results show the power carried on single- and double-bounce specular reflections from relatively small objects in the environment are typically 15–20 dB below the LOS path. Similarly, penetration through drywall (on timber frames) introduces 12–25 dB attenuation, with greater attenuation experienced if a timber stud occludes the direct path. This result is particularly relevant when the LOS path within an office is blocked, e.g., by the human body, as signals from co-channel access points in adjacent offices have the potential to create significant levels of interference.

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