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Indoor Millimetre Wave Channel Measurements for 5G Wireless Systems

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***Abstract*—A hardware testbed to characterise propagation for wideband indoor millimetre-wave channels in the 57–60 GHz band is described. The testbed is based on a direct conversion architecture and uses commercial-off-the-shelf components to transmit and receive the millimetre-wave signals and generate/capture the corresponding baseband waveforms. Tone-test measurements have been used to quantify the impact of hardware impairments in the testbed, and indicate that compensation for the IQ-imbalance arising from the mixers is required. The attenuation introduced by common building materials has also been experimentally investigated using a vector network analyser over the 33–50 GHz millimetre-wave bands. Pine wood was found to introduce approximately 25 dB attenuation, while the attenuation due to drywall was approximately 1.4 dB. These results suggest that internal partitions made from drywall may not be sufficient to isolate co-channel systems in a building. Measurements using sponge material also indicate materials with high water content experience increased attenuation.**

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

I. INTRODUCTION

Fifth-generation (5G) wireless communications services will utilise millimetre-wave spectrum in the ISM band at 67 GHz. The availability of bandwidth at these frequencies is anticipated to significantly alleviate capacity issues experienced by existing wireless services, particularly in areas of high user density (e.g. indoors). Contemporary wireless systems operating at less than 6 GHz can typically rely on diffraction and reflection to propagate their transmissions into regions of geometrical shadow. However, at millimetre-wave frequencies propagation is dominated by line-of-sight (LOS) paths, diffraction is virtually non-existent and wall penetration losses can be very appreciable. Accordingly (and in contrast to systems operating at less that 6 GHz) co-channel interference from access points (APs) in adjacent rooms is usually insignificant, and the key deployment challenge is to obtain sufficient coverage within a given office space.

Unfortunately, coverage from APs can be significantly influenced by small-scale obstacles within the indoor environment (e.g. office furniture, bookshelves, filing cabinets and people) which can cast sizeable geometrical shadows. If coverage is desired within these shadow regions, some strategy must be adopted to provide some sort of alternative illumination (e.g. additional antenna(s), artificial reflectors, etc). Any system deployment strategy will therefore require propagation model(s) which can adequately quantify these effects.

Propagation models based on the high-frequency asymptotic techniques of geometrical optics and the associated geometrical and uniform theories of diffraction (GTD/UTD) have been extensively adopted, even at frequencies below 6 GHz. The assumptions inherent in these techniques suggest that they should work even better in the analysis of propagation problems at millimetre-wave frequencies. However, the presence of complex inhomogeneous obstacles in typical indoor environments suggests that their applicability should not automatically be assumed. Although alternative numerical approaches (such as FDTD) might be entertained, the very large (electrical) scale of typical indoor geometries at millimetre-wave frequencies usually precludes their application as a consequence of computational domain size. Given this limitation the only remaining alternative is to revert to measurements of actual environments.

The aim of this paper is to report on the development of a millimetre-wave measurement testbed for characterising indoor wireless channels of relevance to 5G systems. An historical perspective of wireless channel characterisation is presented in Section II, followed by an outline of the proposed investigative strategy in Section III. The measurement system architecture is discussed in Section IV and then an experimental investigation of the attenuation characteristics of several common building materials is presented in Section V. Conclusions are made in Section VI.

II. INDOOR WIRELESS CHANNEL CHARACTERISATION — AN HISTORICAL PERSPECTIVE

Wireless propagation in indoor environments has been extensively studied at frequencies below 6 GHz. Early research has focussed on experimental characterisation from which simple empirical models have been derived for use in system planning applications (e.g. [1]). The general complexity of the indoor environment has led some authors to undertake comprehensive measurement campaigns to investigate the effects of co-channel interference on system performance (e.g. [2], [3], [4]). With the improved accessibility of computational resources with significant amounts of memory in recent times, some attention has been given to using computational electromagnetic techniques (such as the FDTD) to gain insight into how radiowaves propagation in indoor environments (e.g. [5], [6]). There as also been some attention focussed on the use of environmental modifications (e.g. [7]) and shielding solutions implemented using frequency selective surfaces (e.g. [8], [9]). Ultimately, a characterisation of the propagation can be used to assess system performance (e.g. [10]).

Given this body of existing work it is natural to question to what extent it is applicable to propagation at millimetre-wave frequencies. There is presently significant interest in the characterisation of millimetre-wave channels [11], and it is quite evident that there is considerable scope for research in this area. Most of the attention to date has been focussed on narrowband channels and the prediction of path loss. Relatively little attention has been directed at the characterisation of wideband channels.

III. PROPOSED STRATEGY

Given the established research corpus, it is now appropriate to propose a strategy for characterising propagation at millimetre-wave frequencies. There are essentially four aims, namely

1) To identify what sort of obstacles encountered in typical indoor environments are likely to significantly influence propagation;
2) To quantify the effects of these obstacles on path losses and integrate this with an associated propagation (coverage) model (probably ray-based);
3) To identify what sorts of antennas and environmental modification structures might be appropriate; and
4) To determine typical wideband parameters (e.g. delay spread) to allow for proper equaliser dimensioning.

To address these aims, a two-stage investigative procedure has been adopted. Firstly, a millimetre-wave measurement testbed is currently being developed to experimentally characterise both narrowband and wideband channels in the indoor environment. Secondly, a vector network analyser is being used to characterise the electromagnetic properties of common building materials.

IV. MEASUREMENT SYSTEM ARCHITECTURE

Fig. 1 shows the block diagram for the millimetre-wave channel measurement testbed. A direct-conversion (homodyne) transceiver architecture is used to modulate and demodulate the in-phase and quadrature components. The system is designed to operate over the 57–66 GHz frequency range, with a maximum bandwidth of 1.0 GHz and is based on commercial-off-the-shelf (COTS) components. As shown in Fig. 1, the testbed consists of four main modules:

- a baseband signal generator: Texas Instruments DAC38J84EVM [12];
- V-band IQ up- and down-converters (with tuneable local oscillators between 57–66 GHz): SiversIMA FC2121V/01 and FC2221V/01 respectively [13], [14];
- two 15 dBi V-band horn antennas: Sage Millimeter SAR-1725-15-S2 [15]; and
- a baseband signal capture unit: Texas Instruments ADC12D1X00RFRB [16].

The hardware components are configured and controlled by a computer running MATLAB®, which is also used to generate the baseband transmit signals and perform post-processing on the received samples. The maximum transmit power from the testbed is 20 dBm. The dual-channel 12-bit analog-to-digital converter (ADC) in the receiver has a maximum sampling rate of 1.8 GSa/s [16], which is sufficient to capture the entire 1.0 GHz bandwidth of the baseband signal. However, a limited number of contiguous samples (16384 complex samples) can be captured; the short duration necessitates precise synchronisation and triggering between the digital-to-analog converters (DACs) and ADC.

It is proposed to use the testbed to characterise millimetre-wave channels in the 60 GHz band by transmitting a 'known' wideband complex-baseband signal as a training frame. By applying frequency-domain equalisation to received signal the complex channel time- and frequency-response can estimated.

To identify the sources of non-linearity in the testbed a single tone-test was performed. Fig. 2 shows the received magnitude spectrum from the testbed when the input signal is a single (complex) tone at $+400$ MHz. The frequency of the carrier was 60 GHz and in this case the antennas were pointed toward each other and placed approximately 0.80 m apart. To reduce transmit non-linearities and quantify the influence of the millimetre-wave mixers, two phase-locked signal generators (Agilent E4438C and 8648B) were used to provide the in-phase and quadrature components of the $+400$ MHz complex tone. The strong component at -400 MHz observed in Fig. 2 is thought to arise from IQ imbalance in the millimetre-wave mixers in the up- and down-converters, and timing offsets between the in-phase and quadrature ADCs. Local oscillator leakage is suppressed by filtering in post-processing. Although other components are observed (including harmonics at twice the tone frequency), the result in Fig. 2 suggests that without additional calibration the dynamic range of the testbed is limited by the IQ imbalance to approximately 26 dB.

In addition to this testbed, a vector network analyser has also been used. However this approach is not as versatile as the proposed testbed as both transmitter and receiver subsystems are physically located in the same 'box', imposing a restriction on the maximum separation achievable between the transmitting and receiving antennas. However, the vector network analysis approach is still extremely versatile and can achieve a much greater bandwidth than the proposed testbed, so long as the propagation path lengths are short. The measurement of the attenuation properties of common building materials is a good example of how a vector network analyser can be used in characterising millimetre-wave channels.

V. ATTENUATION STUDY OF COMMON BUILDING MATERIALS

To illustrate the efficacy of using a network analyser in characterising millimetre-wave channels, a study into the attenuation performance of common building materials (as might be found in typical indoor environments) has been undertaken at Q-band (33–50 GHz). An Agilent E8364A Performance Network Analyzer (PNA) was fitted with standard coax-to-rectangular waveguide adapters (Agilent Q281A/B) at the ends of the standard test port cables which were then placed

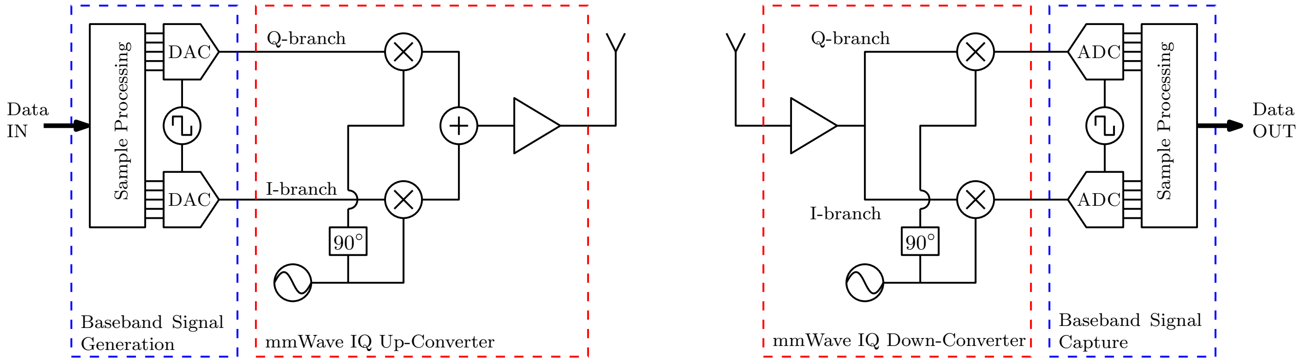

Fig. 1. Block diagram of the millimetre-wave measurement testbed. Not shown are the connections between the modules and a computer used control the hardware and generate/collect the data.

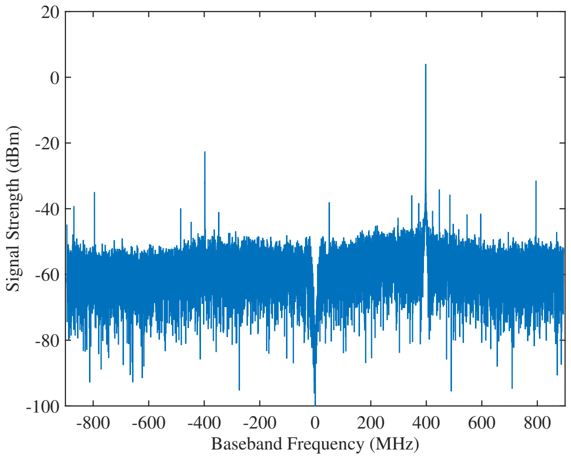

Fig. 2. Received magnitude spectrum for a single tone transmitted through the millimetre-wave testbed at +400 MHz.

TABLE I

MEAN PATH GAINS (RELATIVE TO FREE-SPACE) FOR COMMON BUILDING MATERIALS.

Material	**Mean gain relative to free-space (dB)**
Free-space (reference)	0
Drywall (10 mm)	-1.35
Perspex (5 mm)	-0.715
Plywood (12 mm)	-6.89
Pine (70 × 35) mm (through 70 mm)	-25.2
Pine (70 × 35) mm (through 35 mm)	-25.2
Sponge (dry)	-0.433
Sponge (wet)	-6.41

250 mm apart. The system was calibrated using a standard 2.4 mm ‘Response’ calibration for S21, and a 1.5 ns gate applied to remove unwanted echos. No additional antennas were attached to the open-ended Q-band waveguide apertures. A total of five building material samples were measured as listed in Table I.

Each material sample was placed at approximately mid-path (125 mm from each of the rectangular waveguide aperture) and normal to the direction of propagation. The gain relative to free-space was calculated from measurements of S21 for each material sample by subtracting the ‘reference’ measurement of free-space from each sample measurement. Results for drywall (10 mm), perspex (5 mm), plywood (12 mm) and two orientations of a pine sample (dimensions (70×35) mm) as an example of a typical wall stud are shown in Fig. 3 and Table I. The results for the drywall and perspex samples demonstrated little additional attenuation over free-space (on average -1.35 dB and -0.175 dB respectively). However, the plywood and pine samples exhibited significant additional attenuation, which is thought to be due to the (likely) greater water content of these samples. To test this hypothesis a sponge sample was also measured as shown in Fig. 4 and Table I. These results show little in the way of attenuation when the sample is dry, but a significantly increased average attenuation (6.41 dB) when wet (it should be added that moisture in the wet sample was barely detectable when squeezed).

These results suggest that significant variability in path loss might be observed if a range of building materials were to be encountered in an office deployment. Furthermore, significant wall attenuation might be expected if non-drywall partitions are encountered — especially if they are fabricated from a material (such as timber) which possesses hygroscopic properties. The results also suggest that it might not be possible to assume *a priori* that drywall is sufficiently good an attenuator to provide adequate isolation between co-channel services in (physically) adjacent offices.

VI. CONCLUSIONS

A hardware testbed for characterising indoor millimetre-wave channels in the 57–60 GHz band has been implemented using commercial-off-the-shelf components. The baseband IQ waveforms are generated using a dual-channel DAC and are fed a millimetre-wave up-converter. Directional V-band horn antennas are used to achieve appreciable separation distances and the received signals are down-converted and sampled using a high-speed dual-channel ADC. The bandwidth of

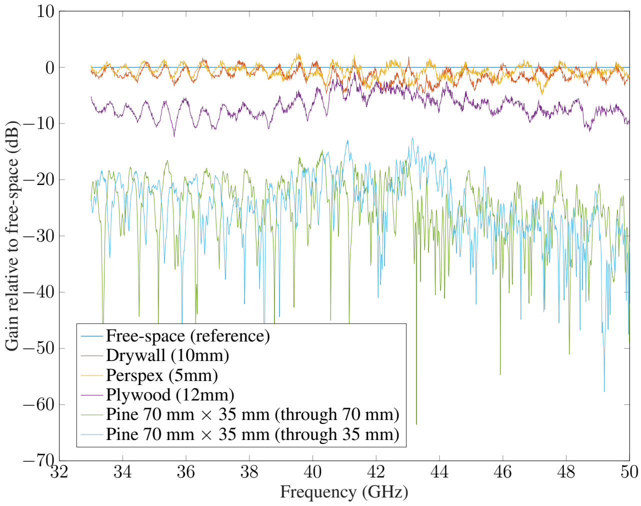

Fig. 3. Gain (relative to free-space) vs frequency for common building materials.

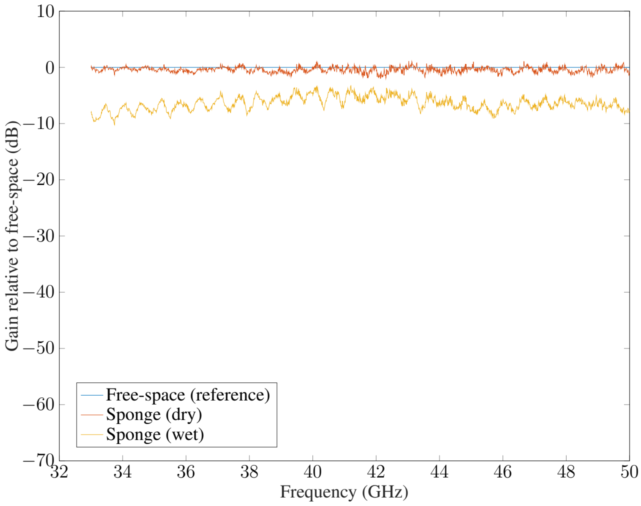

Fig. 4. Gain (relative to free-space) vs frequency for dry and wet sponges.

the system is 1 GHz, with a maximum transmit power of 20 dBm. Tone-test measurements show that without additional calibration the dynamic range is approximately 26 dB due to the IQ-imbalance arising from the mixers. Additionally, the attenuation introduced by various common building materials—drywall, pine wood, plywood and perspex—have been measured over the 33–50 GHz band using a vector network analyser. Results indicate that the high water content of pine wood and plywood can introduce significant attenuation (between 6 to 25 dB). However, the attenuation of the drywall was approximately 1.4 dB, indicating internal partitions made from drywall may not be sufficient to isolate co-channel systems in a building.

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