Development of a Multiple-Input Multiple-Output Ultra-Wideband System Emulator

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Abstract— An experimental testbed is described for the characterization of indoor channels with sufficient spatial resolution and sufficient bandwidth to study the practical capacities of MIMO-UWB systems. UWB measurements have been made in both frequency and time domains for mutual validation. The opportunity has been taken in this paper to extract narrowband transmission loss models from the resulting UWB database. The extraction of a UWB channel model is work in progress.

Keywords-component: UWB, MIMO, channel impulse response, channel frequency response

I. INTRODUCTION

Ultra-Wideband (UWB) and multiple-input multiple-output (MIMO) communications both have the potential to increase wireless channel capacities markedly over those conventionally realizable. The combining of these two technologies provides a route for extremely high data-rate communication within short-range indoor environments [1]. To take full advantage of such a system requires a detailed knowledge of the wireless channel. Measurements have been undertaken by several groups aimed at securing such knowledge for MIMO [2, 3, 4] and UWB [5, 6, 7] systems. A MIMO-UWB System Emulator (MUSE) is currently being developed in the Radio Science and Wireless Communications laboratory of the University of Strathclyde in order to establish the practical channel capacities available from this combination of technologies.

Ultra-Wideband (UWB) communication is defined as communication using signals that exceed a fractional bandwidth of 20% or exceed a -10 dB bandwidth of 500 MHz. The large bandwidth may be realized by using pulse position modulation (PPM) of impulses in impulse radio (IR), conventional spread spectrum methods, OFDM or combinations and variations of all of these.

Ultra-wide bandwidths create channel effects not present in systems with conventional bandwidths. Distortion arises, for example, as different frequency components are affected differently by the environment [8]. As with all wireless systems regulations govern UWB usage. Such regulations dictate the frequency bands that can be used for UWB transmission and limitations on radiated power spectral density. These regulations are primarily to avoid interference with other wireless communication devices and users.

MIMO employs multiple antennas to take advantage of multipath propagation, thereby realizing multiple decorrelated channels. Spatial and/or polarization diversity can be used in such environments to increase signal-to-noise ratio (SNR). Alternatively, spatial multiplexing can be used to increase channel capacity [9]. The smaller the correlation between multiple channels the higher is diversity gain and/or channel capacity. As correlation approaches unity then the MIMO system performance approaches that of a conventional single-input single-output (SISO) system [10].

This paper principally presents narrowband transmission loss models extracted from the UWB measurements. Close agreement between the frequency responses of sample UWB channels measured in time and frequency domains provide confidence in the measurements approach which will be used extensively in a future UWB - MIMO measurement campaign. The paper is divided into the following sections. Section 2 describes the MIMO-UWB System Emulator. Section 3 addresses into measurement validation. Section 4 presents some example narrowband transmission loss models derived from the UWB database and section 5 draws some conclusions.

II. MEASUREMENT METHODOLOGY

The frequency domain measurement system is based around an Agilent N5230 Vector Network Analyzer (VNA) [11] with a frequency sweep maximum span from 10 MHz to 20 GHz. The VNA measures the frequency response of the radio channel between a pair of biconical antennas. Three pairs of biconical antennas (Schwarzbeck Mess-Elektronik SBA 9112 [12], SBA 9113 [13], and SBA 9119 [14]) are available covering the frequency ranges 0.5 – 3 GHz, 1 – 6 GHz, and 3 – 18 GHz. The antennas have low gain (approximately 0 dBi) and omni-directional radiation patterns. They have approximately constant amplitude response and linear phase response over their design bands and thus good (narrow) impulse response. One of the 1 – 6 GHz band antennas is shown in Fig. 1.

The antennas are connected to the VNA with high-quality low-loss flexible (MegaPhase, EM18 [15]) coaxial cable. A (Picosecond, 5867 [16]) linear, broadband, low-noise amplifier (LNA) with a typical gain of 15 dB and a bandwidth of 15 GHz is used to increase the dynamic range of the channel measurements.

A typical channel measurement setup for UWB in the frequency domain is show in Fig 2.

The LNA-VNA combination yields sufficient dynamic range to make useful channel measurements over path lengths of up to 17 m. For shorter paths (up to 8 m) the measured channel frequency response can be validated by a measurement of the time-domain impulse response using a Picosecond

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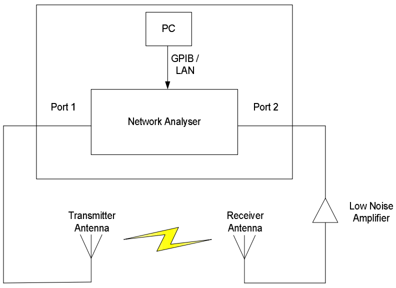
10,060A pulse generator [17] as a source and a LeCroy SDA 9000 Serial Data Analyzer [18] with two, cascaded, Picosecond 5866 LNAs [19] as a receiver, Fig. 3.

Figure 1. SBA 9112 antenna



(a)

(b)

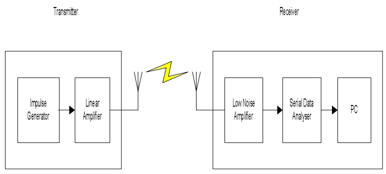
Figure 2. Typical frequency-domain measurement setup: (a) schematic diagram, (b) physical realisation

The pulse generator has a minimum-duration pulse capability of 10 ps and the serial data analyzer, which is operated as a conventional digital storage oscilloscope (DSO), has a maximum sampling rate of 40 GS/s and an analogue bandwidth of 9 GHz.

The primary purpose of the MUSE is to emulate channels that would be realized by arbitrary antenna configurations in a MIMO-UWB system. To do this transmit and receive antennas are scanned in discrete steps over a required line, surface or volume. A UWB frequency response (or impulse response) measurement is made for every discrete combination of transmit and receive antenna locations. The spatial resolution of the discrete scanning process is half a wavelength or less at the highest frequency of interest (i.e. the highest frequency of band being investigated). The number of channel measurements can be large so this spatial sampling must be done automatically. Two robotic arms (ST Robotic R17, [20]) under the control of a PC are therefore used to position the antennas, Fig. 4. The robotic arms provide a repeatable spatial accuracy of 0.2 mm.

The positioners allow scanning of antennas over any arbitrary space within the maximum volume swept out by the robotic arm. The robotic arms are themselves mounted on precision linear tracks, Fig. 4, which extends the volume in one dimension by up to 1.66 m. (The location repeatability of the linear track is much better than the robotic arm so the spatial accuracy of 0.2 mm quoted above is not significantly degraded.)

A simple, but important, measurement would involve scanning the antennas over a 1m × 1m plane surface with half-wavelength spatial sampling as illustrated in Fig. 5.



(a)

(b)

Figure 3. Typical time-domain measurement system setup: (a) schematic diagram, (b) physical realisation

Figure 4. Robotic arm mounted on track

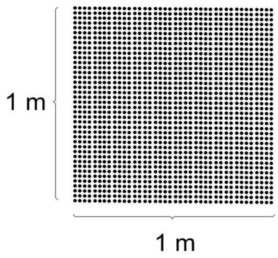


Figure 5. Spatial sampling for emulation of arbitrary MIMO antenna configuarations in 1m × 1m planes

(Fig. 5 assumes a highest frequency of interest of 6 GHz.) Since the spatial sampling of the field is at the Nyquist rate or greater, an appropriate analysis of the resulting database can predict the practical channel capacity available for the frequency band measured (or any frequency sub-band) with arbitrary antenna number, spacing and polarizations (within the measurement planes) at transmitter and receiver. Many such measurements for links of different lengths and orientations will allow the optimum arrangements of MIMO antennas in each case to be identified. This in turn will allow practical rules for MIMO-UWB system design to be established and physical and/or empirical models to be derived for the prediction of the practical channel capacities that can be realistically expected. When measurements are extended to rooms of different sizes and different degrees of clutter etc. it is reasonable to hope that simple design rules for indoor MIMO-UWB systems specific to different environment types will be derivable.

III. UWB MEASUREMENT VALIDATION AND NARROWBAND TRANSMISSION LOSS

A preliminary proof-of-principal measurement is presented here to validate the proposed approach to channel emulation. These measurements were taken in the Mobile Communications Laboratory of the University, a rectangular space 19.2 m long, 8.4 m wide and 4.5 m high. The furniture is dominated by wooden laboratory benches, Fig. 6.

The 1 - 6 GHz transmit and receive antennas were mounted on movable stands (not the robotic arms). The antennas were spaced by 1.5 m at a height of 1.55 m and their polarization adjusted to horizontal. The stands were shrouded in flexible microwave absorber. The VNA-LNA combination was calibrated by cascading the two antenna feeds with a through connector. The frequency response (S_{21}) of the channel was then measured between transmit and receive antenna ports, Fig. 7. The response in the reverse direction (S_{12}) could not be measured due to the inclusion of the LNA.

Figure 6. Mobile Communications Laboratory

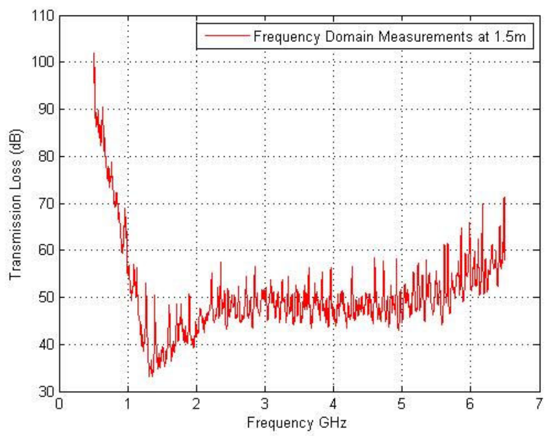


Figure 7. $|H(f)|$ measured using the VNA

The VNA was replaced with the pulse generator and DSO. The pulse height and width were set to 10 V and 50 ps and the pulse repetition frequency was set to 50 kHz. The impulse response of the channel between the two antenna ports was then measured using DSO averaging over 100 measurements, Figure 8.

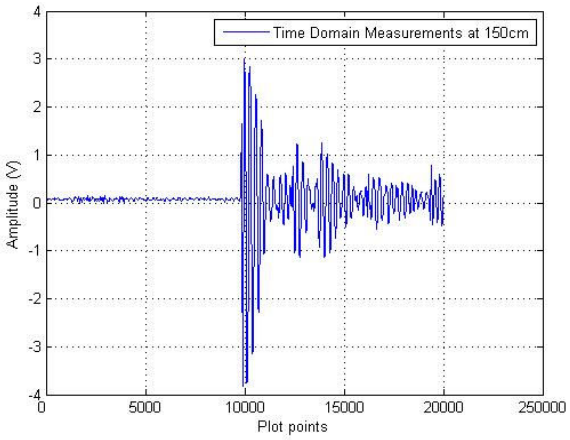


Figure 8. $h(t)$ measured using the pulse generator and DSO

The impulse response was converted to a frequency response by applying an FFT. The two measurements are compared in Fig. 9.

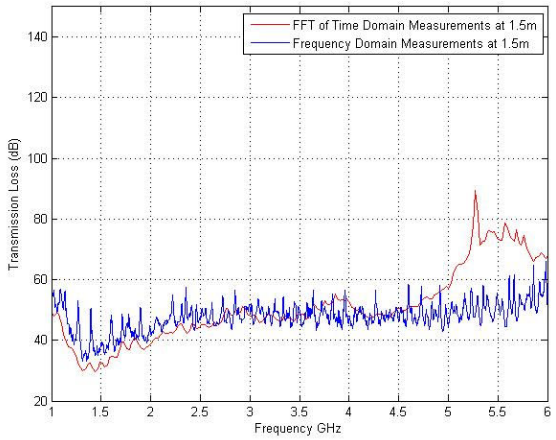
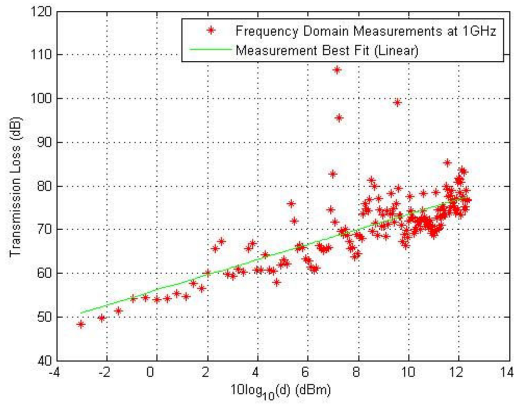


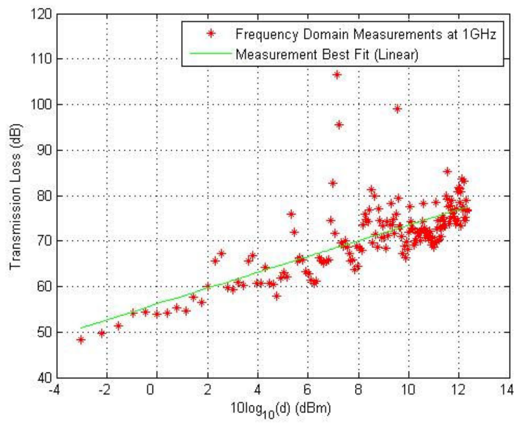
Figure 9. Comparison of channel amplitude response measured in frequency- and time-domains

The close agreement (up to 4.5 GHz) between the two frequency responses in Fig. 9 is interpreted as good evidence that the measurement approach is fundamentally reliable. The difference of the two results above 4.5 GHz is, as yet, unexplained. This will be investigated further before the system is used to construct a MIMO-UWB measurement database.

Whilst the measurement system described is intended primarily for the investigation of MIMO-UWB channels the opportunity has been taken, whilst gaining experience with the instrumentation, to make some narrowband transmission-loss measurements. The resulting scattergrams of transmission loss against link length are shown in Fig. 10.



(a)



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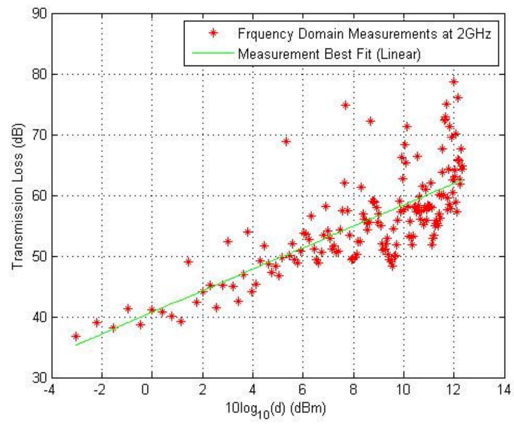

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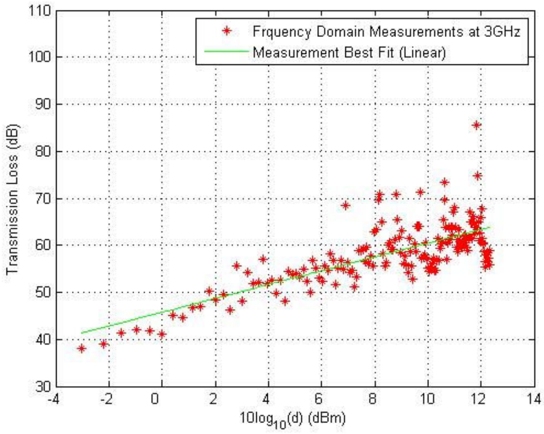

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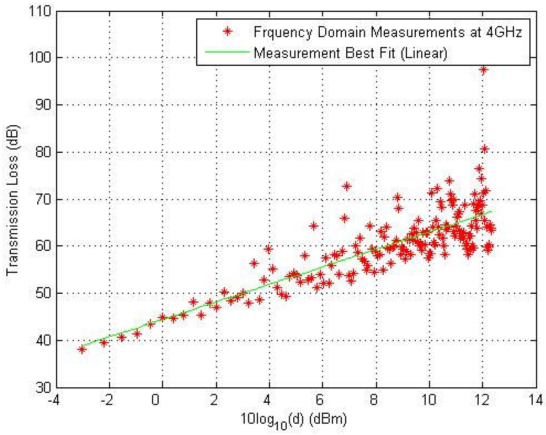

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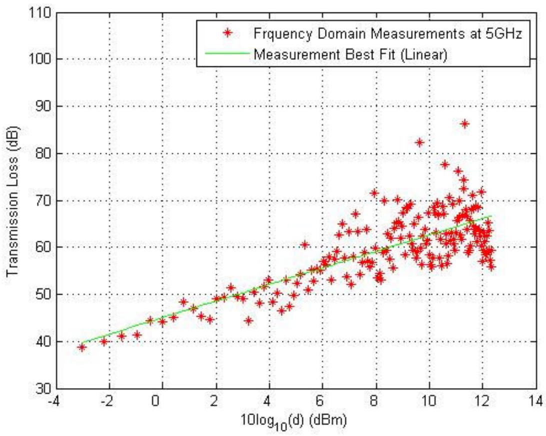

(f)

Figure 10. Transmission loss vs. link length scattergrams and associated minimum mean square error regression lines for (a) 1 GHz, (b) 2 GHz, (c) 3 GHz, (d) 4 GHz, (e) 5 GHz, (f) 6 GHz

Table 1 shows the parameters of the transmission loss law:

$$L_T = L_0 + 10n\log_{10} d \tag{1}$$

corresponding to the regression lines in Fig. 10 where L_0 is the transmission loss for a path length of 1 m, n is the transmission loss index and d is the distance between transmitter and receiver in metres.

TABLE I. 1M INTERCEPTS AND GRADIENTS CORRESPONDING TO REGRESSION LINES

Frequency (GHz)	**L_0 (dB)**	***n***
1.0	56.1	1.74
2.0	40.7	1.77
3.0	45.7	1.47
4.0	44.4	1.86
5.0	45.1	1.75
6.0	50.3	1.77

The variation of L_0 with frequency in Table 1 reflects the variation of antenna gain.

The transmission loss laws represented by the values in Table 1 are close to the free-space law (n = 2) as might be expected for short link lengths in a relatively large room. This is because multipath reflections from walls, ceiling and floor are likely to be long compared with the direct line-of-sight path and therefore relatively weak.

IV. CONCLUSIONS

A measurement system for MIMO-UWB indoor channel characterization has been described. The system is built around a vector network analyzer and omni-directional antennas having good (narrow) impulse response designed for EMC measurement applications. The system has been part validated by replicating a channel frequency response using a time-domain impulse response measurement. Some narrowband SISO transmission loss measurements have been presented for frequencies across part of the UWB band as a precursor to MIMO UWB channel measurements.

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