Experimental Determination of Room Parameters, Signal Distortion and Interference for Indoor UWB Communications

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Abstract

We report on signal distortion and room characteristics for UWB signals inside an office environment between 500 MHz and 3 GHz, for fields sampled across a scanned volume inside the room. The quality factor and input impedance of the room are deduced experimentally. A measure for signal distortion caused by the room and antenna mismatch is given. The distortion of a synthesized UWB signal is calculated based on the measured set of S-parameters. A signal-to-interference ratio for adjacent bands is defined and calculated from the measured data.

1 Introduction

Indoor electromagnetic environments (EMEs) pose considerable challenges in the estimation of signal integrity and propagation conditions for wireless communication devices and networks. For wide-band communication signals, signal distortion occurs as a result of frequency-selective indoor propagation, fading, and antenna mismatch. The accurate prediction of signal distortion levels and associated uncertainties is a prerequisite for estimating signal degradation of a single communication link, as well as in quantifying interference levels between different signals employed by multiple devices based on different protocols.

Physically, the complexity of accurately characterizing indoor environments is caused by scattering and diffraction characteristics of objects, partial transmission and absorption by distributed scatterers and reflectors (joined walls, windows, floors, etc.), frequency dispersion (particularly for ultra-wideband (UWB) communications), and the large variety of types of propagation environments in existence. In recent years, large efforts have been expended on the characterization of indoor environments, e.g., [1]–[3], both theoretically and experimentally. Here, we report on experimental work, which is aimed at providing a systematic procedure and framework for quantifying distortion and interference of arbitrary periodic signals using a physics-based experimental characterization of indoor signal propagating. In [4], we reported on determination and statistical field models for characterizing of the extent of signal variation that may be expected at various locations across a modern office room. Some of the aims of the experimental work reported here are:

1. investigating whether the effect of the room and building can be captured by a single metric for classification of the energy characteristics inside this EME;
2. defining and experimentally assessing a metric for linear distortion of an UWB signal inside a room;
3. defining and experimentally assessing the signal-to-interference ratio for UWB signals inside a room.

2 Measurement Set-Up and Procedure

2.1 Room and FAR Measurements

Measurements were performed in an unoccupied office of quasi-parallelepiped shape with dimensions 5.895 m $\times$ 4.427 m $\times$ 2.685 m, located on the first floor in a two-storey office building. A floor plan, photographs, and configurational details and positionings are given in [4]. The room contains swivel chairs, a surround desktop, and a few metal floor-standing under-desk drawer units. During measurements, the room contained all measurement instrumentation. The adjacent corridor runs along a full-length glass wall of the room, while all other interior walls are made of plasterboard separating this office from adjacent ones. A small double-glazed window gives acces to the outside world. The floor is concrete and carpeted. The suspended ceiling has a 0.6 m square grid of ribs.

Single-input-single-output (SISO) S-parameter measurements were taken using two identical biconical antennas at different antenna locations inside the room. Antenna "1" was mounted on a glass fibre shaft and was moved, at constant height, by a planar automated XY-scanner. Antenna "2" was fixed and mounted at 65.4 cm from the glass wall and the same distance from one plasterboard wall. Both antennas were parallel and vertically polarized. A measurement grid with cell size 5 cm $\times$ 5 cm $\times$ 5 cm was adopted across a horizontally scanned area of 0.750 m $\times$ 0.750 m, at 25 different heights between 0.500 m and 1.700 m, yielding 256 spatial sample points per frequency at each scanned height. Measurements were performed across the frequency band 500 to 3000 MHz, in steps of 12.5 MHz.

The measurement set-up in the office room was carefully replicated inside a 9 m $\times$ 6 m $\times$ 6 m fully-anechoic chamber (FAR) with the aim to extract the line-of-sight (LoS) component for CW wave transmission and reflection in the office room. The residual, i.e., scattered field then provides an EM signature of the room and its contents, relative to ideal free-space conditions. In order to avoid near-field effects compromising the performance of the absorbers, the antennas were placed not closer to the floor than in the office measurements. The use of a FAR as a reference site avoids difficulties due to frequency dispersion in connection with determining the power delay profile per spectral component when using time-domain characterization of multiple reflections.

2.2 Extraction of Scattered Field

The use of a vector network analyzer enables coherent subtraction of FAR data from the room data, i.e., corresponding complex-valued S-parameter values between the office room (subscript 'R') and the FAR (subscript '0') may be subtracted for each scanned position at each frequency. This presumes that the input power (excitation field) injected into both environments is identical, i.e., that the input impedance seen by either antenna is the same in both the FAR and in the room. This is a reasonable, but finite approximation: since the office room is not impedance matched, the input power will be somewhat different from that for the FAR ($\eta_0 = 120\pi\ \Omega$) and varying with antenna positions. Under this idealized assumption, $\{E_j\}_{mn} = \{E_{j,\mathrm{R}}\}_{mn} = \{E_{j,0}\}_{mn}$ for the excitation field E_j, so that $\Delta S_{ij\,mn} \equiv S_{ij,\mathrm{R}\,mn} - S_{ij,0\,mn} \approx (E_{i,\mathrm{R}\,mn} - E_{i,0\,mn})/E_{j\,mn}$ with $i, j = 1, 2$ and $m, n = 1, \ldots, 16$ represents the non-line-of-sight (NLoS) field (i.e., scattered & diffracted field in/by the office room.) Analysis of the scattered field enables the effect of the room on the propagation characteristics to be quantified. The assumption of constant input power was tested by also measuring the reflection parameters S_{ii} at each location and frequency. This parameter was found to vary by a relatively small amount across the scanned volume.

3 Quality Factor of Room

The Q-factor provides a single parameter for estimating the effect of the room on the magnitude of the average received power, compared to free space. For scattering by walls and artefacts that is sufficiently close to ideal isotropic, we can use results from the theory of highly resonant enclosures with volume V, in the absence of direct illumination ($S_{ij} = \Delta S_{ij}$). For this case, theory predicts the effective quality factor of such enclosures to be

$$Q(f) = \frac{16\pi^2 V f^3}{c^3} \frac{\langle|\Delta S_{21}(f)|^2\rangle}{1 - \langle|\Delta S_{11}(f)|^2\rangle}, \tag{1}$$

where $\langle\cdot\rangle$ denotes an ensemble average over realizations and $c = 2.9979 \times 10^8$ m/s. Since a static room produces only one realization of this ensemble, no ensemble averaging can be performed unlike, e.g., in a mode-stirred or mode-tuned reverberation chamber. However, a spatial average across a scanned volume can be taken instead, on the premise that – at sufficiently high frequencies – spatial averages of the scattered field should approximate ensemble averages. Fig. 1(a) shows results of $Q(f)$ for measurement data aggregated across nine heights between 1.300 m and 1.700 m as a function of frequency. Since the scattered field shows considerable deviations from a χ^2_2 distribution function below about 1.3 GHz [4], the idealized diffuse properties and, hence, the accuracy of the values for Q are limited below this frequency. The Q oscillates with frequency, because the scattered field is not statistically homogeneous, which leads to fluctuations of the local energy density. Because our office was measured empty (thus minimizing the absorption), an occupied office in use is expected to have a somewhat smaller Q.

4 Input Impedance of Room

From the S-parameter measurements in the FAC and the office room, the room input impedance can be calculated and compared with the ideal value of free space, $\eta_0 = 120\pi\ \Omega$, as follows.

We calculate the change in the antenna impedance evoked by moving the antenna from the FAR to the office room. This change does not only depend on the difference between $\eta_{\rm R}$ and η_0, but also on the antennas. Each CW frequency of the channel sounder excites just one mode of the room, because the Q-bandwidth of the modes varies between 2.5 MHz and 5 MHz, which is smaller than the spacing of frequency samples (12.5 MHz) in our measurements. After some calculations, the wave impedance inside the office room follows as

$$\eta_{\rm R} = \frac{A-B}{C-D} Z_0, \quad \text{where} \tag{2}$$

$$\begin{aligned}
A &= Z_0\,(1-S_{11,\rm R})\left[\eta_0 Z_0\,(1-S_{11,0}) - Z_c Z_0\,(1+S_{11,0})\right], && (3)\\
B &= Z_c\,(1+S_{11,\rm R})\left[\eta_0 Z_c\,(1+S_{11,0}) - Z_0^2\,(1-S_{11,0})\right], && (4)\\
C &= Z_c\,(1+S_{11,\rm R})\left[\eta_0 Z_0\,(1-S_{11,0}) - Z_c Z_0\,(1+S_{11,0})\right], && (5)\\
D &= Z_0\,(1-S_{11,\rm R})\left[\eta_0 Z_c\,(1+S_{11,0}) - Z_0^2\,(1-S_{11,0})\right], && (6)
\end{aligned}$$

where Z_c and Z_0 are the characteristic impedance of the coaxial cable and antenna, respectively, and $S_{11,0}$ and $S_{11,\rm R}$ represent the reflection coefficients in the FAR and office room, respectively. Fig. 1(b) shows the measured $\eta_{\rm R}$ as a function of frequency, after spatial averaging over all positions within the scanned volume. Some notable deviations from the free space value $\eta_0 \simeq 377\ \Omega$ occur, particularly at higher frequencies as effects of multiple scattering become more prevalent. At relatively low frequencies the values are, on average, slightly below the free-space value, which can be interpreted as limited effective dielectric loading by office furniture.

5 Distortion of Signal Transmitted Across Room

With the aid of both $S_{11}(f)$ and $S_{21}(f)$ data, one can investigate the distortion of (UWB) signals at launch into the transmitting antenna or after propagation and fading inside the room. In an ideal anechoic environment, S_{11} and S_{21} define baseline values that define the input to the transmitting antenna $(1 + S_{11,0})$ and the received signal $S_{21,0}/(1 + S_{11,0})$. For example, for incoherent detection, the distortion in the received signal caused by the room can be defined as

$$D_{21}(f) = \left(\frac{|S_{21,\rm R}(f)|^2}{1-|S_{11,\rm R}(f)|^2}\right) \Big/ \left(\frac{|S_{21,0}(f)|^2}{1-|S_{11,0}(f)|^2}\right). \tag{7}$$

Fig. 2(a) compares the envelope of received signal $Y_{\rm R}(t)$ at a single location in the office room (blue curve) with that in a reflection-free environment $Y_0(t)$ (red curve), for an amplitude-plus-phase (hybrid) randomly modulated excitation $X(t)$ (black curve). The results indicate significant qualitative and quantitative differences between both environments. At launch into the room, the distortion level due to the room mismatch was found to be of the order of 5% compared to the level of the input signal at either port.

6 Signal-to-Interference Ratio Across Room

An external signal at $f_0 \pm \Delta f$ may cause interference to a wanted signal at f_0 if this disturbance is within the bandwidth of the filter. For incoherent detection at a given spatial location, we define a signal-to-interference ratio (SIR) as

$$\mathrm{SIR}_{21}(f_0, \Delta f) = \frac{2\,|S_{21}(f_0)|^2}{|S_{21}(f_0-\Delta f)|^2 + |S_{21}(f_0+\Delta f)|^2}. \tag{8}$$

Fig. 2(b) shows SIR (in dB) at 2.45 GHz (Bluetooth in ISM band) with $\Delta f = 12.5$ MHz. In practice, the filter bandwidth can be taken much smaller or wider than this value of Δf, leading to higher or smaller values of SIR, respectively. The SIR is seen to vary considerably with antenna location at a single center frequency.

7 Acknowledgement

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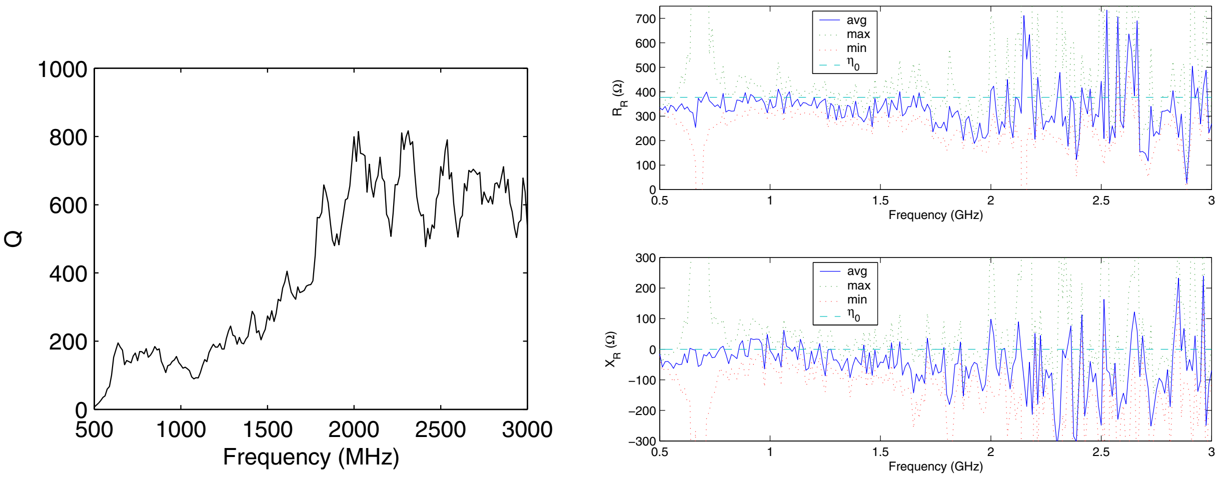
References

[1] D. Ullmo and H. U. Baranger, "Wireless Propagation in Buildings: a Statistical Scattering Approach", *IEEE Trans. Veh. Techn.,* vol. 48, no. 3, pp. 947–955, May 1999.

[2] J. Bach Andersen, J. O. Nielsen, G. F. Pedersen, G. Bauch, and M. Herdin, "Room Electromagnetics", *IEEE Ant. Propag. Mag.,* vol. 49, no. 2, pp. 27–33, Apr. 2007.

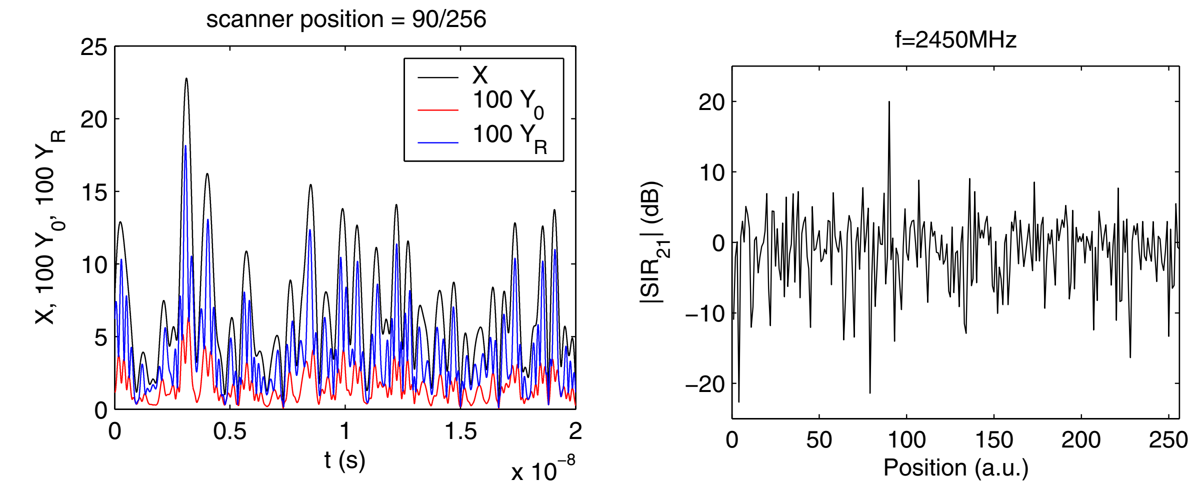
[3] R. Heddergott and P. Truffer, "Statistical Characteristics of Indoor Radio Propagation in NLOS Scenarios", COST 259, Report TD (00) 024, 19–21 Jan. 2000, Valencia, E.

[4] L. R. Arnaut, T. H. Loh, and B. O. Peters, "Statistical Experimental Characterization of Indoor Radio Wave Propagation in an Office Environment", COST 2100, Report TD (08) 403, 6–8 Feb. 2008, Wroclaw, PL.



(a) (b)

Figure 1: (a) Measurement based estimate of Q-factor of office room, based on spatial averaging of measured intensities. (b) Measured average, maximum and minimum room impedance $\eta_{\rm R} = R_{\rm R} - jX_{\rm R}$, compared to free-space impedance η_0.



(a) (b)

Figure 2: (a) Time-domain envelopes of randomly modulated UWB input signal $[X(t)]$ and corresponding received signals inside fully anechoic chamber $[Y_0(t)]$ and in office room $[Y_{\rm R}(t)]$ at an arbitrary scanner position. (b) Signal-to-interference ratio inside office room for receiver with bandwidth 25 MHz at f=2.45 GHz, as defined by (8), measured across a horizontal plane of area 0.75 m $\times$ 0.75 m at height 1.300 m above the office floor.