Room Electromagnetics in an Industrial Workshop

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***Abstract*—This work validates the theory of Room Electromagnetics (RE) for a small industrial workshop for shipping container restoration. Radio channel sounding measurements with a vector network analyzer and virtual antenna arrays were carried out. The specular and dense multipath components were estimated from channel sounding data by means of an iterative maximum-likelihood algorithm (RiMAX). In agreement with RE, the dense multipath is well-described by a single exponential decay as function of delay with a reverberation time that is nearly constant across the room. The dense multipath is found to have a longer reverberation time compared to office environments because of the highly reflective (metallic) nature of the industrial environment.**

***Index Terms*—room electromagnetics, dense multipath components, channel sounding, industrial environment.**

I. Introduction

The Room Electromagnetics (RE) theory borrows from the science of room acoustics and obtains an exponential decay for the diffuse electromagnetic field under these assumptions: the field's intensity does not depend on the direction (rich scattering environment) and its energy density is constant across the whole room (valid for rooms that are small enough) [1]. As with room acoustics, RE is a scalar theory and therefore does not account for more than one polarization at transmitter and receiver.

This work presents a validation of the RE theory in an industrial environment, specifically a workshop for shipping container restoration. The validation is based on narrowband channel sounding around a 3 GHz center frequency. The RiMAX framework is used to estimate the specular and dense multipath components from channel sounding data [2], [3]. For the purpose of this paper we will equate the definitions of dense multipath and diffuse multipath. Strictly speaking, the dense multipath estimated with RiMAX can, in addition to diffuse multipath, also contain low-SNR specular multipath. The idea is that these specular paths cannot be reliably detected among the diffuse multipath due to limitations of the estimator and/or the measurement system's aperture.

II. Channel sounding measurements

The industrial environment under consideration is a workshop for reparation of intermodal shipping containers, shown in Fig. 1. The workshop consists of a single room with dimensions 20.4 m (length) by 22.0 m (width) by 4.8 m (height). The building materials for the walls are a collection of bricks, concrete slabs, steel plates, steel industrial doors, and glass windows. The floor and ceiling are made up of concrete slabs and corrugated steel panels, respectively. The workshop's inventory consists largely of metal container parts, machinery, and small cranes.

Fig. 1. Measurement environment

Narrowband frequency-domain channel sounding measurements were performed inside the workshop. A vector network analyzer was used to probe the radio channel in a 100 MHz bandwidth centered around 3 GHz (in 256 uniformly spaced frequency points). At both link ends, a virtual antenna array was created by an automated positioning system. At both transmit and receive side, the virtual array was a planar horizontal Uniform Circular Array (UCA) consisting of eight antenna elements. The inter-element spacing was 0.45 times the wavelength at the largest measurement frequency of 3.050 GHz. As transmitting (Tx) and receiving (Rx) antenna, broadband omnidirectional discone antennas were used. Both antennas were 1.50 m above ground level during measurements.

In total, twelve Tx-Rx links were measured: the Tx remained at a fixed location while the Rx was moved to different locations between measurements. Measurements were done for three different Tx-Rx link shadowing conditions: Line-of-Sight (LoS, three measurements), Obstructed Line-of-Sight (OLoS, four measurements), and Non-Line-of-Sight (NLoS, five measurements).

III. Multipath estimation

The RiMAX maximum-likelihood multipath search algorithm is used to simultaneously estimate the Specular Multipath Components (SMC) and the Dense Multipath Components (DMC) from the channel sounding data [2], [3]. RiMAX's data model assumes DMC that is spatially white at transmit and receive side. The DMC power $\psi(\tau)$ is modeled as an exponential decay as function of delay τ,

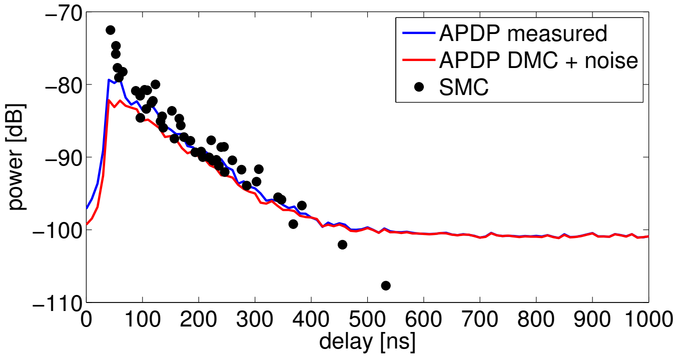

Fig. 2. SMC and DMC + noise in the delay domain for the Tx-Rx$_1$ link

$$\psi(\tau) = \alpha_1 \exp\left[-\frac{\tau-\tau_d}{\tau_r}\right] \qquad (\tau > \tau_d). \tag{1}$$

In (1), α_1, τ_d, and τ_r are the peak power, the onset time, and the reverberation time of the DMC, respectively. Fig. 2 shows the estimated multipath for an NLoS measurement. Shown are the measured Averaged Power Delay Profile (APDP), the estimated SMC, and the APDP of the DMC + measurement noise obtained after subtracting the SMC from the measured channel response.

IV. Discussion

Firstly, Fig. 2 shows that the single exponential decay (1) fits the DMC process very well. Secondly, the DMC reverberation time τ_r was found to vary between 64.6 and 84.5 ns across the twelve Tx-Rx links. It was observed that τ_r does not change noticeably between link shadowing categories and is even fairly constant across all Tx-Rx links. The former observation was backed by a Kruskal-Wallis analysis of variance test which found no difference in median τ_r between link shadowing categories (p-value = 0.55) [4].

The two observations made about DMC in the previous paragraph — a single exponential decay and a reverberation time that is independent of Rx location — is entirely in line with the theory of Room Electromagnetics (RE) [1]. The RE theory provides a simple relationship between the reverberation time τ_r, the room's geometry and a single constant describing the room's electromagnetic absorption qualities:

$$\tau_r = \frac{4V}{c\eta A} \tag{2}$$

In (2), V and A are the room's volume and area, respectively, c is the speed of light in vacuum, and η is the fraction of energy absorbed by the area A. Using the industrial workshop's dimensions, we obtain $V = 2154.2$ m^3 and $A = 1304.6$ m^2. The median τ_r across all Tx-Rx links equals 75.8 ns. Using (2), we then obtain the median absorption coefficient η as 0.29. Formula (2) for the reverberation time is also called Sabine's model [1]. We chose Sabine's model over Eyring's model, which replaces the factor $1/\eta$ in (2) with $-1/\ln(1-\eta)$, because the former is preferred for small values of η such as the one obtained in this study [5].

The parameter η is particularly interesting to compare the reverberation properties of different rooms: unlike the τ_r parameter, η is independent of room geometry and solely depends on the average electromagnetic absorption characteristics of the materials present. These materials in turn directly relate to the type of environment. For office environments and vertical polarization at both link ends [1], [6], and [5] found respectively $\eta = 0.51$, 0.45, and 0.47. In comparison, $\eta = 0.29$ in the industrial workshop for the same polarization conditions reveals that the materials of the latter are 16 to 22% less absorbent. This is easily explained by the highly reflective nature of the materials commonly found in an industrial environment.

V. Conclusion

This contribution presented a validation of the room electromagnetics theory for a small industrial workshop. The validation was based on channel sounding experiments with virtual antenna arrays and the RiMAX algorithm was used to estimate the specular and dense multipath from the sounding data.

The dense multipath reverberation time is nearly constant and thus independent of transmitter/receiver location, which is in line with room electromagnetics theory. Room electromagnetics is further used to calculate the average absorption of electromagnetic energy by the environment. The industrial workshop is found to be 16 to 22% less absorbent compared to office environments in literature. This is due to the metallic and thus highly reflective nature of the materials in the workshop.

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