Experimental Investigation of Electromagnetic Reverberation Characteristics as a function of UWB Frequencies

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***Abstract*—The electromagnetic reverberation time characteristics of indoor environments are experimentally investigated from 2 to 10 GHz with bandwidths up to 900 MHz. At a given frequency, the reverberation time is observed to be approximately constant up to 900 MHz. Moreover, the reverberation time decreases for increasing frequencies. Based on the theory of electromagnetic fields in cavities, a model to predict the room quality factor, reverberation time value, and average absorption coefficient is developed for the first time in indoor environments for the investigated frequency range. The validity and robustness of the model is investigated with data obtained for various environments, central frequencies, and bandwidths. The model is applied to another room over the whole 2-10 GHz frequency band and a maximum and average relative error of 22.30% and 8.80% were obtained, respectively, with an rms error of 1.90 ns. Furthermore, good agreement is obtained with measurements reported in the literature with settings falling into the model range; scenarios for which relative errors smaller than 10% were computed. The results demonstrate that this approach is not only an accurate alternative to the reverberation time measurements and computations of indoor environments in the 2-10 GHz frequency range but also a viable route to link propagation mechanisms in indoor scenarios with reverberation chambers.**

Keywords: Reverberation time, modeling, dense multipath components, power density, Ultra-Wideband.

I. INTRODUCTION

RECENT studies such as [1] have shown the importance of the Dense Multipath Components (DMC) in realistic indoor environments in terms of its contribution to the total power density. The DMC is usually considered as the remainder of the measurement data after removing all possible specular paths and includes the diffuse scattered fields plus weak specular components. The diffuse power density may represent up to 95% of the total power [1] in indoor environments and can be analytically expressed as a function of its reverberation time [2], [3]. This parameter, which characterizes the decay rate of the diffuse fields, is derived from the room electromagnetics theory [2], [4] and electromagnetic fields theory in cavities [5]. Hence, the reverberation time is the most important parameter regarding the diffuse absorption [2] and can be used, as an example, to predict the average power level in a room [6], [7].

The reverberation time has previously been investigated in office environments at a single frequency, i.e., 1.4, 2.3, 3.0, or 5.2 GHz [2]–[4], [7], [8]. However, the frequency dependence of the reverberation time or its characterization at higher frequencies have yet to be adressed to the best of the authors' knowledge. Currently, there are two approaches to determine the reverberation time in indoor environments, i.e., the measurement-based [3] and the computational-based methods such as the radiosity [9]. The former solution is time-consuming and difficult because it requires extensive measurement campaigns and post-processing steps, whereas the latter solution demands excessive time and memory resources, mainly at higher frequencies.

In contrast with indoor scenarios, the quality factor (Q) is more frequently used to describe the capacity of reverberation chambers to store electromagnetic energy. Several works [10]–[13] have addressed the determination of Q in reverberation chambers. Basically, Q can be obtained either from the power-ratio method (frequency domain) or the decay-time method (time domain). The power-ratio method is based on the received power of a receiving antenna located in the reverberation chamber whereas the decay-time method is based on the reverberation time of the considered environment. The decay-time measurement was reported to yield a better estimate of Q compared to the power-ratio method [5], [10], [13].

The novelty of this paper relies on the development of a frequency-dependent model for Q and the reverberation time for indoor scenarios, which can be considered as low-Q reverberation rooms. This aspect is clearly missing in the literature and this work aims at filling this gap. Furthermore, the proposed approach links the absorption properties in indoor scenarios, characterized by the average absorption coefficient independent of the room dimensions, with the power losses in reverberation chambers, characterized by Q. This approach is motivated by the fact that similar mechanisms should be observed in both environments but at different scales due to the electromagnetic complexity of each scenario. Finally, this approach aims to provide an alternative to both measurements and computational methods.

The paper is organized as follows: Q and the reverberation time approach from which the model is based on are presented in section II. The measurement scenarios and the methodology are also described. Section III presents the reverberation time dependency to the bandwidth as well as the frequency-dependent model for Q, the reverberation time, and average absorption coefficient. The validity of the reverberation time model is discussed in section IV. Finally, conclusions are drawn in section V.

II. MODEL, SCENARIOS, AND METHODS

A. Model for the Q-factor and reverberation time

1) Frequency domain: From the electromagnetic fields theory in cavities, the quality factor of a resonant environment requires that four types of losses are accounted for. Q is expressed as follows [5]:

$$Q^{-1} = Q_1^{-1} + Q_2^{-1} + Q_3^{-1} + Q_4^{-1} \tag{1}$$

where Q_1, Q_2, Q_3, and Q_4 are the quality factors due to the dissipated power in the walls (P_1), absorbed power in loading objects in the room (P_2), power lost in apertures (P_3), and dissipated power in the loads of receiving antennas (P_4), respectively.

The four quality factors exhibit frequency dependent behavior and are given by [5]:

$$\begin{aligned} Q_1 &= \frac{\omega U}{P_1} = h_1(f), \quad Q_2 = \frac{\omega U}{P_2} = h_2(f), \\ Q_3 &= \frac{\omega U}{P_3} = h_3(f), \quad Q_4 = \frac{\omega U}{P_4} = h_4(f^3), \quad \text{with } \omega\text{=}2\pi\text{f}, \end{aligned} \tag{2}$$

where U, and f, are the energy in the room, and the considered frequency, respectively.

Given the expressions in (2), Q is a cubic function with frequency as reported in [5], [10]. In particular, Q_1, Q_2, and Q_3 values are smaller compared to Q_4 at low frequencies such that their contribution to Q is greater at high frequencies [5]. However, in contrast with reverberation chambers, Q_1, Q_2, and Q_3 are expected to be smaller in indoor environments since the power losses in the walls, objects, and apertures are larger.

2) Time domain: In the time domain, Q is alternatively expressed as [5], [10], [13]:

$$Q = 2\pi f \tau, \tag{3}$$

where τ is the room reverberation time given by Sabine's law [4]:

$$\tau = \frac{4V}{c_0 \eta_{avg} A}. \tag{4}$$

V, c_0, η_{avg}, and A are the room volume, light velocity, average fraction of energy absorbed by the surfaces, and room total area (including the floor, walls, ceiling, and objects).

Substituting (4) in (3), Q becomes:

$$Q = \frac{8\pi f}{c_0 \eta_{avg}} \times \frac{V}{A} = Q_{density} \times \frac{V}{A}. \tag{5}$$

It is observed that Q is proportional to V/A in agreement with [14], [15]. This also implies that a Q-factor density $Q_{density}$ [m^{-1}] independent of the room dimensions can be introduced. $Q_{density}$ is the quality factor per volume per area and is expressed as follows:

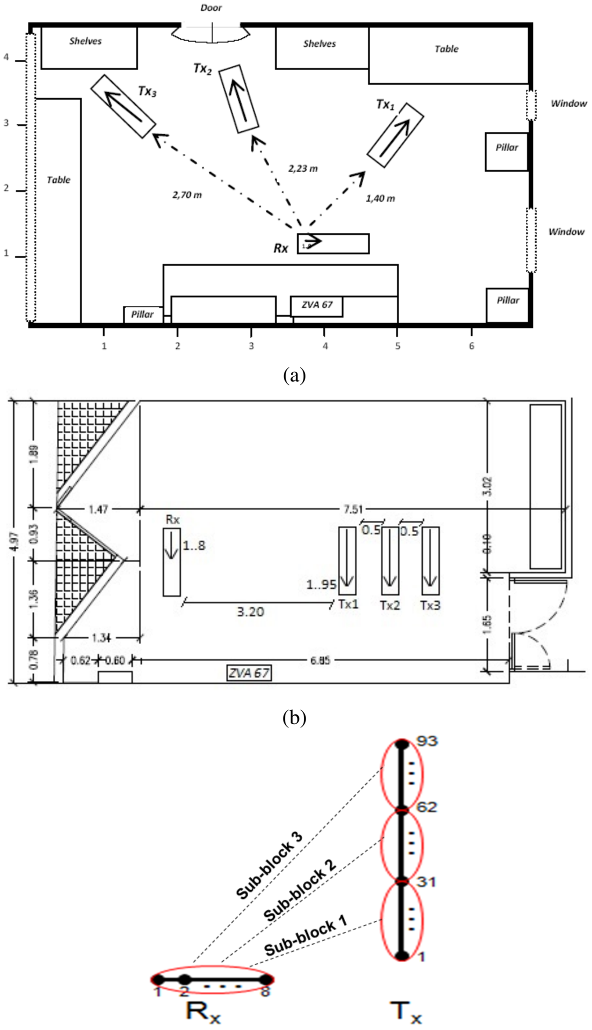
$$Q_{density} = \frac{8\pi f}{c_0 \eta_{avg}} = 2\pi f \tau \times \frac{A}{V}. \tag{6}$$

Consequently, the frequency dependence of the reverberation time is given by :

$$\tau(f) = \frac{Q_{density}}{2\pi f} \times \frac{V}{A}. \tag{7}$$

B. Scenarios

The measurements have been carried out in two laboratories located in the Universidad Politecnica de Cartagena, Spain. The laboratories are furnished by several closets, desktops, computers, shelves, etc. The first (resp. second) laboratory size is approximately 4.5 m × 7 m × 3 m (resp. 4.9 m × 8.8 m × 4.1 m) resulting in a volume of $\sim 94.5\ m^3$ (resp. $\sim 169\ m^3$). The measurements performed in laboratory 1 (Fig. 1a) are used to characterize Q and the reverberation time, as well as for modeling purposes, whereas the data from laboratory 2 (Fig. 1b) are used for the validation of the developed model (see section IV). The measurement scenarios and the channel sounder settings can be found in [16] but the main settings are recalled here for the reader: *i)* the frequency is ranging between 2 and 10 GHz with 2048 frequency points and *ii)* three transmitter (Tx) blocks were considered. Each block consists of 95 Tx positions along a linear segment of 95 cm, whereas the receiver (Rx) occupied 8 positions along a linear segment of 70 cm (see Fig. 1c).



(a)

(b)

(c)

Fig. 1. (a) Laboratory 1 ($V = 94.5\ m^3$ and $A = 132\ m^2$). The measurements are used to develop the Q-factor and reverberation time model. (b) Laboratory 2 ($V = 169\ m^3$ and $A = 195\ m^2$). The measurements are used to validate the developed model. (c) Tx-Rx sub-blocks.

C. Methods

Each block (or segment of 95 cm) is divided into 3 sub-blocks with 31 successive elements at the Tx side (in each sub-block) as shown in Fig. 1c (the 8 Rx positions are retained). The Tx and Rx have been re-arranged so that the spatial correlation between two received signals in different sub-blocks is lower than 0.5 for the whole frequency band. This criterion is set to obtain spatially uncorrelated signals. Then, an averaged impulse response per sub-block is obtained with 8 positions of the Rx and 31 positions of the Tx (248 impulse responses). This is sufficiently large to remove the small-scale fading effects. The reverberation time is then experimentally determined from the averaged Power Delay Profile (PDP) as follows [3]:

$$\tau = -\frac{10\log(e)}{\mathit{slope}}, \tag{8}$$

where *e* is Euler's number and *slope* is the slope of the PDP's linear tail. An example of the PDP is shown in Fig. 2. The reverberation time obtained from (4) is repeated for all sub-blocks. Finally, a single

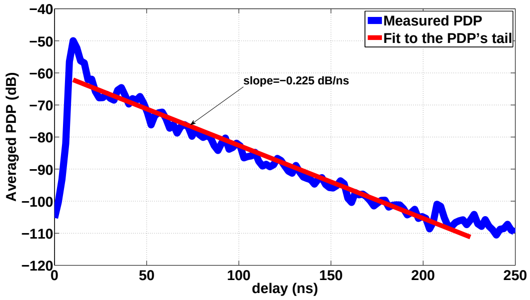


Fig. 2. A PDP averaged over all sub-blocks (in dB) in laboratory 1.

value of the reverberation time - characteristic of the room regarding the diffuse absorption - is obtained by averaging the reverberation time values over all sub-blocks.

III. RESULTS

A. Reverberation time as a function of bandwidth for laboratory 1

Frequencies ranging from 2.5 to 9.5 GHz with a step of 500 MHz are investigated. The bandwidth varies from 100 MHz up to 900 MHz with a step of 50 MHz. Figure 3 presents the reverberation time as a function of the bandwidth for different frequencies in laboratory 1. Only selected frequencies (legend of Fig. 3) are shown for the sake of clarity. The maximum relative standard deviation is about 2.2%. This insignificant relative deviation clearly indicates that the reverberation time can be considered as constant over bands up to 900 MHz. This is probably because the building materials (bricks, concrete, limestone) properties do not vary significantly even over a wide frequency range [17]. A bandwidth of 500 MHz is now considered for the rest of this study.

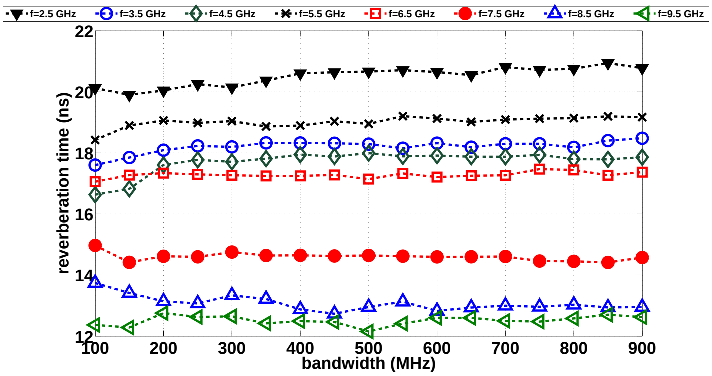


Fig. 3. Reverberation time as a function of bandwidth from 2.5 to 9.5 GHz (laboratory 1).

B. $Q_{density}$ and reverberation time model

At each frequency, the reverberation time values obtained for the 9 locations in laboratory 1 are averaged and used in (6) to obtain $Q_{density}$. Figure 4 presents the experimental $Q_{density}$ and cubic polynomial fit as a function of frequency. The model choice is motivated by the fact that Q is a cubic function with frequency as discussed previously in section II-A1. For the 2-10 GHz range, the $Q_{density}$ model is given by the following equation:

$$Q_{density}(f) = 0.473f^3 - 24.9f^2 + 321f - 254, \text{ with } R^2{=}0.96 \quad (9)$$

where $0 < f < 10$ is the frequency in GHz, and R^2 is the goodness of fit. The reverberation time is obtained by substituting (9) into (7):

$$\tau(f) = \frac{V(0.473f^3 - 24.9f^2 + 321f - 254)}{2\pi f A}, \quad (10)$$

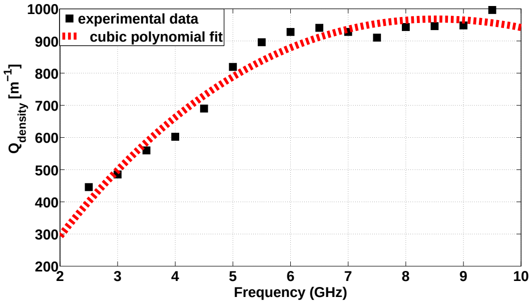
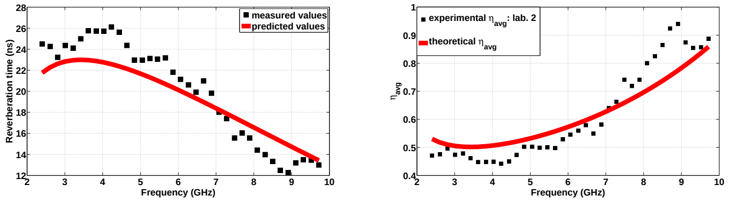


Fig. 4. Experimental (black squares) and model (red line) of $Q_{density}$ as a function of frequency for the laboratory 1. A 500 MHz bandwidth was considered and the x-axis data represent the central frequency.



(a)

(b)

Fig. 5. Experimental (black squares) and model (red line) of τ (a) and η_{avg} (b) in the laboratory 2 from 2-10 GHz. A 500 MHz bandwidth was considered and the x-axis data represents the central frequency.

where τ(f), V, A, and f are in nanoseconds, m^3, m^2, and GHz, respectively.

Finally, η_{avg} can be obtained either from (4) or (5) and is shown to be, like $Q_{density}$, independent of the room dimensions:

$$\eta_{avg}(f) = \frac{8\pi}{c_0(0.473f^2 - 24.9f + 321 - 254f^{-1})}. \quad (11)$$

The independence of η_{avg} of the environment is justified since it characterizes the absorption properties of the building materials and most of the buildings use the same materials.

IV. VALIDATION OF THE MODEL

In this section, the validity of the model is discussed by applying (10) to different environments. For the sake of comparison, it is applied to an other room measured in this work over the whole frequency range of the model. In addition, it is also applied to experimental data reported in the literature from various research groups. These data were measured at frequencies and bandwidths for which the model can be used.

A. Validation with Laboratory 2

First, the proposed model is applied to measurements performed in laboratory 2 (Fig. 1b) over the complete 2-10 GHz range. The experimental (*black squares*) and predicted (*red curve*) reverberation time values for laboratory 2 are presented from 2 to 10 GHz in Fig. 5a. A maximum (resp. average) relative errors between the predicted and the measured values are about 22.30% (resp. 8.80%) for the investigated frequency range. Moreover, the rms error is only about 1.90 ns for the complete frequency range. These low deviations show that the model accurately predicts the reverberation time values in the laboratory 2.

Figure 5a also shows the decrease of the reverberation time τ as the frequency increases. This indicates that the energy is fading faster away at higher frequencies compared to lower frequencies. This is confirmed by Fig. 5b which presents the frequency dependence of η_{avg}. A maximum (resp. average) relative error between the predicted and the measured average absorption coefficient are of about 22.40% (resp. 8.70%) for the investigated frequency range. When the frequency is low, the contribution of the dissipated power in the antenna loads to Q cannot be neglected and becomes the major source of absorption in the environment; thus explaining the observed plateau. In contrast, as the frequency is increased, the losses from the building materials (walls, objects, and apertures) become larger and the reverberation time decreases. Indeed, the surface roughness plays a major role in this effect at higher frequencies; effect included in the reflection coefficient as follows [18], [19]:

$$R_{rough} = \rho \times R_{smooth}. \tag{12}$$

R$_{smooth}$ is the Fresnel reflection coefficient for a smooth surface depending mainly on the surface dielectric properties [19], which in turn depends slightly of the frequency [17] and ρ is the roughness attenuation factor. The roughness attenuation factor decreases as the frequency increases [18], [19]. Eventually, the reflection coefficient of rough surfaces decreases when the frequency increases. Therefore, the building materials of indoor environments (brick for the walls, limestone (or wood) for the floor, concrete, etc.) absorb more electromagnetic energy at higher frequencies (assume that their surfaces are rough), which in turn results in a decrease of the reverberation time as a function of the frequency as observed in Fig. 5a.

B. Validation from literature

1) Reference [4]: First, the model is compared to experimental data obtained in a rectangular room located in Aalborg University, Denmark ($V = 522.5\ m^3$ and $A = 560\ ^2$) at 5.8 GHz with 100 MHz bandwidth. A reverberation time value of ∼22.10 ns was computed using (10) compared to the reported 24.10 ns resulting in a relative error of 9%.

2) Reference [7]: Measurement-based reverberation time values of 18.40 ns and 16.70 ns were reported in two rooms R4 ($V = 74.4\ m^3$ and $A = 111\ m^2$) and R3 ($V = 55\ m^3$ and $A = 90\ m^2$) at 5.20 GHz with 120 MHz bandwidth, respectively. In comparison, 16.70 ns and 15.30 ns are computed with (10) yielding a relative error of only 9.20% and 8.30%, respectively.

3) Reference [9]: Theoretical reverberation time values of 22.40 ns and 21.50 ns were obtained at 5.9 GHz in the same room than [4] from radiosity (numerical simulation method), and theory, respectively. Our model predicts a reverberation time value of 21.60 ns at the same frequency. The relative error between the model and the simulations and theory are 3.60% and 0.50%, respectively.

V. CONCLUSIONS

The frequency dependency of the electromagnetic Q-factor and reverberation time is experimentally investigated in indoor environments in the 2-10 GHz frequency range. The results demonstrate that, for a given frequency, the reverberation time is constant over a large bandwidth - up to 900 MHz. In addition, the reverberation time decreases smoothly as the frequency is increased, indicating that the diffuse fields fade at a faster rate at higher frequencies. This phenomenon is attributed to the absorption coefficient frequency dependence of the building materials.

Based on the theory of electromagnetic fields in cavities, a model is proposed to predict the Q-factor, reverberation time, and average absorption coefficient over the investigated frequency range in indoor environments. It is concluded that the presented model not only agrees well with the reverberation time values reported in the literature but also with additional values measured in this work over the complete frequency range of 2-10 GHz. The validity and robustness of the model with data obtained for various environments, central frequencies, and frequency ranges demonstrate that this approach is an accurate alternative to the reverberation time measurements and computations in the frequency range of 2-10 GHz in indoor environments. Future research consists in extending the model to the mmW range.

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