A Theory for Exposure Prediction in an Indoor Environment for UWB System

Aliou Bamba*, Emmeric Tanghe, Wout Joseph, Günter Vermeeren and Luc Martens

Ghent University / IBBT - Department of Information Technology

Gaston Crommenlaan 8 box 201, B-9050 Ghent-Belgium

Fax: +32 9 33 14 899, Tel: +32 9 33 14 908

*Email: aliou.bamba@intec.ugent.be

Abstract—A simple theory based on room electromagnetics theory is presented. It primarily modelizes the Diffuse Multipath Components (DMC) power density with a simple circuit model, and afterwards include the Line-Of-sight component (LOS) in order to determine the whole-body absorption rate for Ultra-Wide-Band (UWB) system. The model may be very useful for prediction tools in realistic environment.

Keywords: Ultra-Wide-Band, room electromagnetics, Diffuse Multipath Components, absorption rate

I. INTRODUCTION

EXISTING Specific Absorption Rate (SAR) values are derived from a set of plane wave(s) exposure [1], [2]. However, it has been proved that the diffuse multipath components (DMC) may contribute significantly in the total power density in an indoor environment [3]. Recall that the DMC is the remainder of the measured power delay profile (PDP) after removing all specular or discrete paths.

Our previous work has introduced a method to assess experimentally the whole-body SAR, while taking the DMC part into account [4]. This has been feasible thanks to the room electromagnetics theory [5]. Several works have used the Finite-Difference-Time-Domain (FDTD) method for the prediction of the coverage in an indoor/outdoor environment [6], [7]. Likewise, the exposure in an realistic indoor environment may be simulated by discretizing the Maxwell equations, however this solution is unlikely to be feasible as it would require a huge amount of memory in terms of computation resources.

A simple method to determine the exposure that takes the DMC power into account is necessary. Moreover, the UWB systems in indoor environment have gained interest these recent years. Simulating and forecasting the total exposure according to the room properties may be hence very useful in order to comply safely to the ICNIRP [8] restrictions values. A novel and simple method to achieve this purpose is to translate the room electromagnetics theory into a simple electrical circuit model. The source of an access point will be characterised by its impulse transmitted power P_0 and its duration Δ .

A room is characterized by its volume, its total area absorbing

Fig. 1. Principle of the circuit model

electromagnetics radiation, the properties of its materials (walls, floor, ceiling, etc...) and hence its reverberation time.

The objective of this paper is to use these parameters as the inputs of a R-C circuit model to forecast the exposure in a realistic indoor environment. The paper is organized as follows: in Section II, we

present the main idea necessary to build the model and Conclusion is drawn in Section III

II. MODEL FOR ULTRA-WIDE-BAND (UWB) SYSTEM

A. Modeling the DMC

Let $P(t)$ be the transmitted pulse signal in a room during Δ . $P(t)$ is balanced by the decrease of energy/second in the room and by the increase of the losses at the walls as follow [5]:

$$P(t) = V \frac{dW}{dt} + \frac{c_0 \eta A}{4} W \quad (1)$$

where V , W , c_0 , η and A are the room volume, the remaining energy density, the light velocity, the fraction of energy absorbed by the walls, and the total area absorbing electromagnetics radiation, respectively.

Let establish the relation involving the voltage in Fig. 2.

$$E(t) = U_c(t) + RC \frac{dU_c(t)}{dt} \quad (2)$$

where E , U_c , R and C are the input voltage, the voltage of the capacity, the resistor, and the capacity. This differential equation describes the charge/discharge of the capacitance.

Fig. 2. Circuit model equivalent to room electromagnetics theory

Assume that the circuit model is fed with E (in Volt) during the same Δ , a solution of (2) is :

$$\begin{aligned} U(t) &= E(e^{\frac{t}{RC}} - 1)e^{-\frac{t}{RC}} \\ &= U_0 e^{-\frac{t}{RC}} \end{aligned} \quad (3)$$

$U_c(t)$ looks like the classical expression of the voltage discharge in a RC circuit fed with U_0 .

Assume that the total energy in the room can be stored in the capacitance, the energy density in the room can be expressed as:

$$W_d(t) = \frac{C}{2V} U_0^2 e^{-\frac{2t}{RC}} \quad (4)$$

where $W_d(t)$ represent the energy density in watt.s/m³.

The room electromagnetics theory has determined the energy density for UWB systems [9]:

$$W_d(t) = P_0 \frac{\tau}{V} (e^{\frac{t}{\tau}} - 1) e^{-\frac{t}{\tau}} \quad (5)$$

where P_0 is the active value of $P(t)$. By comparing the energy density in the circuit model (4) and in the room electromagnetics theory (5) and assuming the same decay, the following relations are derived:

$$\frac{RC}{2} = \tau \quad (6)$$

$$R = \frac{U_0^2}{P_0(e^{\frac{\Delta}{\tau}} - 1)} \quad (7)$$

R is homogeneous to $\frac{V^2}{watt} = \Omega$ (Ohm). By choosing a value of U_0 and knowing P_0 , Δ and τ the R -value can be easily computed. We demonstrate further that the power density in the circuit is independent of its input voltage. Hence R is calculated, we use (6) to determine the value of the capacitance:

$$C = 2\tau \frac{P_0(e^{\frac{\Delta}{\tau}} - 1)}{U_0^2} \quad (8)$$

C is homogeneous to $\frac{s}{\Omega} = F$ (Farad). Assume complete diffuse field, the power density in the capacitance is then expressed as:

$$I(t) = \frac{c_0}{8\pi V} C U_0^2 e^{-\frac{2t}{RC}} \quad (9)$$

The average intensity (power density) I_D at t_0 is given by:

$$I_D(t_0) = \frac{1}{\Delta} \int_{t_0}^{\infty} I(t) dt \quad (10)$$

where t_0 is the arrival delay of the first DMC component. Taking (6) into account, a solution of (10) is:

$$I_D(t_0) = \frac{\tau c_0 C}{8\pi \Delta V} U_0^2 e^{-\frac{t_0}{\tau}} \quad (11)$$

The total power density can be expressed with different terms:

$$I_D(t_0) = \frac{\tau c_0 C}{8\pi \Delta V} U^2(t_0) \quad (12)$$

$$= \frac{\tau^2 c_0 P_0}{4\pi \Delta V} (e^{\frac{\Delta}{\tau}} - 1) e^{-\frac{t_0}{\tau}} \quad (13)$$

Note that in (12) the power density is expressed as a function of the voltage discharge in the capacity. Moreover, (13) proves that the power density in the circuit model is independent of the input voltage U_0 . Since the separation from a transmitter is more relevant than an electromagnetic wave arrival time regarding a prediction tool, the average power density is rewritten as:

$$I_D(d_0) = \frac{\tau c_0 C}{8\pi \Delta V} U^2\left(\frac{d_0}{c_0}\right) \quad (14)$$

$$= \frac{\tau^2 c_0 P_0}{4\pi \Delta V} (e^{\frac{\Delta}{\tau}} - 1) e^{-\frac{d_0}{c_0 \tau}} \quad (15)$$

where d_0 is the separation from the transmitter.

B. Including the LOS component in the model

The goal of the circuit model is primarily to model the power density of the DMC. However, if we want to use this circuit model to determine the SAR_{wb} , it should include the LOS component power density since the SAR_{wb} is induced by both sources. Consider now that an incident LOS component illuminates a person with an absorption cross section ACS_{LOS} , the power absorbed by that person is:

$$P_{abs}^{LOS} = \frac{P_0}{4\pi d_0^2} \times ACS_{LOS} \quad (16)$$

Notice that the absorbed power times the free space impedance is homogeneous to a square voltage. Since the voltage of the circuit model has not yet been set to a particular value, it can be defined as follows:

$$U_0 = \sqrt{Z_0 \times \frac{P_0}{4\pi d_0^2} \times ACS_{LOS}} \quad (17)$$

where Z_0 is the free space impedance (in Ω).

Finally, the LOS component power density in the circuit model is given by $I_L = \frac{U_0^2}{Z_0 \times ACS_{LOS}}$, which is only dependent on the circuit model input voltage, and the human body illuminated by the LOS plane wave. It is noteworthy to stress that the circuit model derived here determines the exposure (afterwards the SAR_{wb}) for only one person in one position. Actually, the ACS_{LOS} depends on the incident LOS component direction of arrival, but we do not aim to deal with these details.

C. Determination of the SAR from the exposure

Since the power densities for both sources (DMC and LOS components) are known via the circuit model, the whole-body SAR (SAR_{wb}) can be easily derived.

$$\begin{aligned} SAR_{wb} &= SAR_{DMC} + SAR_{LOS} \\ &= \frac{1}{m} (I_D \times ACS + I_L \times ACS_{LOS}) \\ &= \frac{1}{m} \left(\frac{\tau c_0 C}{8\pi \Delta V} U^2\left(\frac{d_0}{c_0}\right) ACS + \frac{U_0^2}{Z_0} \right) \end{aligned} \quad (18)$$

where m is the mass of the person in kg.

III. CONCLUSION

The present theory will permit to forecast the whole-body specific absorption rate of humans in a realistic room through a voltage discharge in a R-C circuit model. Its main contribution is the accounting of the diffuse multipath components (DMC) and the low computation burden since it does not need any discretization to model the DMC. The circuit elements (R and C) are calculated using the transmitter and the considered room characteristics. The simulations and the results will be discussed in the full paper.

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