Channel model for wireless communication around human body

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A channel model for a wireless body area network at 400 MHz, 900 MHz and 2.4 GHz is derived. The electromagnetic wave propagation around the body is simulated with a finite-difference time-domain simulator. Creeping waves were identified as the propagation path around the body. Its impact on the delay spread in an indoor environment is discussed.

Introduction: The next generation of wireless systems is evolving towards personal area networks. Among them, a very promising application is the wireless body area sensor network (WBAN) used for health monitoring. Indeed, if medical monitoring can be performed wirelessly, the patient is no longer constrained in his movements. This can shorten hospital stays, thereby reducing the convalescent period and patient costs. It can even lead to theranostics, where sensors and actuators monitor and control the patient's health autonomously.

The development of any communication link starts with a model for the channel. A plethora of models exist that characterise wireless communication channels in WANs and LANs. However, to our knowledge, very few attempts have been made to characterise electromagnetic (EM) propagation around the human body. This is probably because the properties defining EM propagation around the human body are complex, rendering the development of a simple mathematical model quite difficult. The human body has a complex shape consisting of different layers (e.g. tissues) each with its own permittivity and conductivity. Using a finite-difference time-domain EM simulator, XFDTD from REMCOM, we are able to simulate the field propagation in such an environment. Furthermore, this simulator uses an anatomically accurate model of the human body, derived from the Visual Human project of the National Library of Medicine. It accurately represents the shape of the human body as well as all the EM properties of its different tissue layers.

We derived a mathematical model in a number of industrial scientific and medical (ISM) frequency bands, in which such a network will most likely operate. In Europe, the ISM licence-free bands are at 433 MHz, 868 MHz and 2.4 GHz. In the US, they are at 315 MHz, 915 MHz or 2.4 GHz. Lower frequencies will require unacceptably large antennas, whereas at higher frequencies the propagation loss quickly becomes very high. We have therefore chosen three frequencies to study the propagation of radio-frequency waves around the human body: 400 MHz, 900 MHz and 2.4 GHz.

Variation around the body: EM waves can propagate around the body via two paths. One path is the penetration inside the body and the second path is the creeping wave that follows the surface of the body. Simulations with the software showed that the penetration resulted in a substantially higher loss.

In our study to characterise the propagation of the field around the human body, we analysed the field at eight different heights ranging from the shoulders down to the pelvis. The distance between two cuts was 7.5 cm. For each slice, we analysed the fields at 15 radial points following the shape of the body. The angle between two adjacent radial points was about 12°. At each slice, we placed a 5 cm long dipole oriented vertically on the front of the standing body. We then analysed the vertical component of the electric field around the slice.

The data points obtained at 400 MHz, 900 MHz and 2.4 GHz are plotted in Figs. 1, 2 and 3, respectively, (in normalised dB power units against the angle relative to the antenna position). We fitted two straight lines minimising the mean square error to model the path loss (each denoting an exponential decay in linear power). The proposed path loss model can then be expressed as:

$$P_{dB}(\theta) = P_{dB}(\theta_0) - \gamma_1(\theta - \theta_0) \quad \text{for } \theta_0 < \theta \le \theta_{bp}$$
$$P_{dB}(\theta) = P_{dB}(\theta_{bp}) - \gamma_2(\theta - \theta_{bp}) \quad \text{for } \theta_{bp} < \theta < \pi$$

This model corresponds to a classical EM diffraction phenomenon called creeping waves, which exhibits an exponential decay of the power [1]. Since the decaying factor depends on the loss in the dielectric, the attenuation is larger for 2.4 GHz where the conductivity is higher [2]. From a certain angle on, the propagation turns into an interference regime. The creeping wave that turned clockwise starts to interfere with the one that turned anticlockwise. In dual-slope models, this angle is classically called a breakpoint. In the interference region, the decay is smaller but the variability of the field is much larger. The width of that zone depends on the relative strength and on the wavelength of the creeping waves. It is then logically smaller at 2.4 GHz. The decay coefficients, γ_i, the breakpoint angle θ_{bp} and the standard deviations are detailed in each Figure.

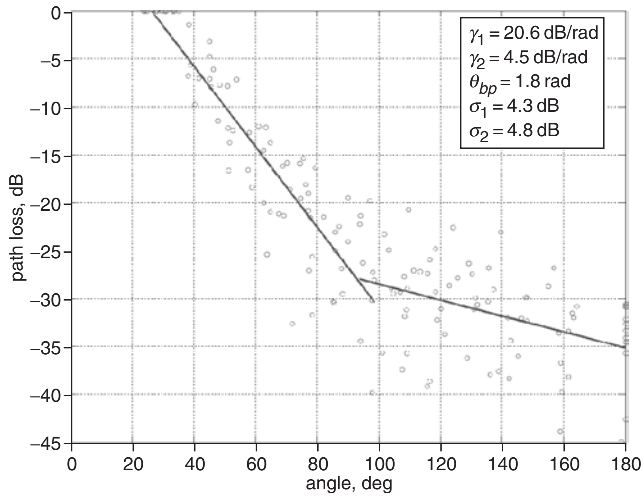

Fig. 1 *Propagation loss [dB] at 400 MHz*

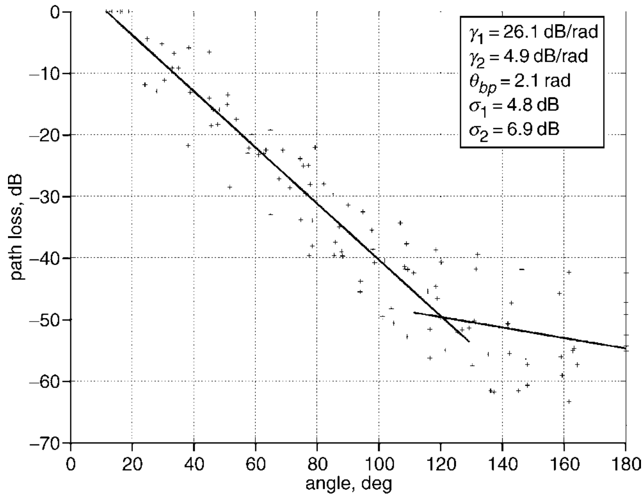

Fig. 2 *Propagation loss [dB] at 900 MHz*

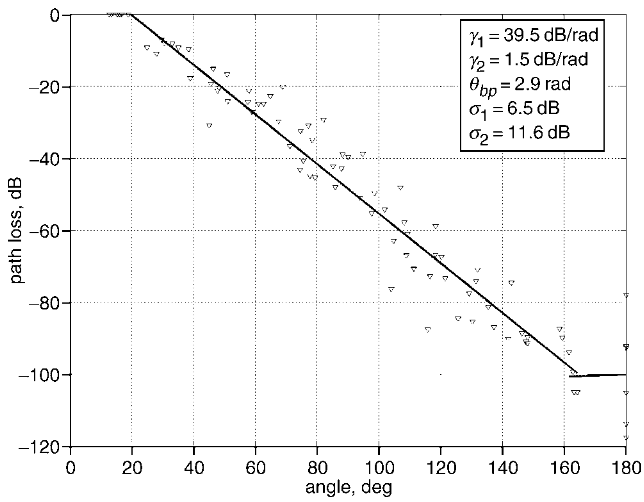

Fig. 3 *Propagation loss [dB] at 2.4 GHz*

We can finally compare these results to the penetrating wave path. The penetration loss can be estimated by defining an average conductivity and permittivity, and considering an insertion loss at the skin interfaces. We projected a path loss from the sternum to the spine to be as high as 90 dB at 400 MHz. This loss would probably be even higher due to the interfaces that exist between tissues inside the body. Compared to the 35 dB loss shown in Fig. 1, we conclude that the contribution of the penetrating wave can be neglected.

Variation along the body: After analysing the propagation around the body, we looked at the variation of the field along the vertical dimension of the standing body. The analysis is somewhat more complex since, for a given height difference, the propagation paths connecting different transmitter-receiver pairs have different shapes. One cannot therefore derive a generic model as a function of the relative height difference between the receiver and the transmitter. However, the maximal variation with the height is smaller than the variation around the body. For instance, we obtained a maximal variation of 14 dB along the spine at 400 MHz for a transmitter placed on the chest.

Delay spread: In the interference region, both creeping waves turning around the body may be considered temporally unresolvable at the receiver owing to the slight difference in path lengths. A single path model corresponding to the creeping wave is then adequate to estimate the propagation around the body. The delay for a creeping wave to travel from the sternum to the spine is simulated to be about 1.8 ns, which is close to the delay in free space as found in [3] for a dielectric-coated cylinder. If the body is placed in an indoor environment, some reflected rays would arrive at the receiver together with the creeping wave. For instance, a ray transmitted at the chest and reflected by a wall situated at a distance of a few metres will arrive at a receiver situated on the spine with about the same power as the creeping wave. This indicates that in the estimation of the delay spread of an indoor WBAN, the creeping wave is to be seen as an extra path in the impulse response of the channel. Since the delay of the creeping wave is very low, adding the creeping wave path to the impulse response of a typical indoor channel [4] results in an increase of the delay spread from 37 to 57 ns.

Conclusion: We have derived a channel model for a WBAN at frequencies at which these systems will most likely operate. We discovered that the main mechanism for the propagation of EM waves around the human body is via creeping waves. The order of magnitude of the path loss is close to the power of the multipath components for a medium sized room. However, the creeping wave reaches the receiver with a much smaller delay than the first multipath component, resulting in an increase of the delay spread.

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