Channel Modeling for UWB WBAN On-Off Body Communication Link with Finite Integration Technique

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ABSTRACT
Comprehensive knowledge of the channel and accurate channel models are essential in the optimized system design. In the Wireless Body Area Network (WBAN) applications, use of Ultra Wideband (UWB) transmission as well as close presence of human body, bring their own major challenges in the channel modeling. Several channel models have been proposed and numerous channel measurement campaigns have been performed for WBAN applications, but they are only approximations for certain situations. The main challenge in this field is to find a method to generate realistic channel models for new different purposes quickly and flexibly without excessive computational efforts. In this paper, applicability of Finite Integration Technique (FIT) is studied in the modeling the channel characteristics of WBAN on-off body communication link. The validity of the FIT-based channel modeling is verified by comparing the FIT simulation results with the measurement results using three different Ultra Wide Band (UWB) printed planar antennas. The analysis is performed both in frequency and time domains. It is shown that there is a clear agreement between the simulated and measured channel responses. Hence, FIT can be considered as a promising technique in the modeling of realistic on-off body communications channel characteristics for the cases where there is no analytical model available.

Categories and Subject Descriptors
H.4.3 [**Information Systems Applications**]: Communications Applications – *computer conferencing, teleconferencing, and videoconferencing.*

General Terms
Measurement, Verification

Keywords
Channel measurement, channel modeling, FIT, UWB, WBAN

1. INTRODUCTION
In the last few years, Medical Information and Communication Technology (ICT) related research topics have taken high-profile places in the research forums. Main target of the research is to find wireless solutions to increase quality of health care and efficiency in hospital administration, healthcare center, and home. Wireless Body Area Networks (WBAN), which includes communication within and around the human body, is one of the key concept in this development. The standard for WBAN has been developed by the study group IEEE802.15.6 and it has been published just recently [1]. [2]

Bodynets 2012, September 24-26, Oslo, Norway.

WBAN communication is classified into four different categories: in-in, in-on, on-on and on-off body communication links. *In-in* body communication covers the link between the internal medical implants. *In-on* body communication occurs between the internal implants and the sensors, which are attached on the body. *On-on* body communication is related to the communication between the sensors attached on the body. *On-off* body communication is related to the link between on-body device and an external gateway, e.g. hospital room access point. [3].

Intensive research has been going on in the channel modeling for medical applications [4]-[13]. Furthermore, study group IEEE802.15.6 has presented channel characteristics specified for different WBAN communication links in [14]. However, according to the studies presented e.g. in [10], there are measurement based channel models available which are more accurate than the IEEE802.15.6 channel models. Obviously, the use of measurement data in the simulations gives more realistic performance in a certain environment than the use of channel models, which, however, are always pure approximations of certain situations. Nevertheless, the use of measurement data is not always possible due to the laboriousness of the measurement campaigns. Besides, there are several challenges related to the inaccuracies and uncertainties of the measurements. [13]

One option for modeling electromagnetic propagation is to solve Maxwell's equations in the given scenario by using numerical approaches, such as Finite Integration Technique (FIT) [15] or Finite-Difference Time-Domain (FDTD) [16] technique. Both techniques are widely used in antenna simulations, also in Ultra Wide Band (UWB) context. Recently, some studies has been published about using FDTD and FIT in the modeling of WBAN communication link characteristics, mainly concentrating on the on-on body communication link, e.g. in [8], [9], [12]. A preliminary study for the usability of FIT in the modeling of UWB WBAN on-off body communication link was presented in [13]. The study was exploited comparing free-space measurement results and FIT-based simulation results conducted with Computer Simulation Technology (CST) Microwave Studio (MWS) software [17]. The results were based on the assumption that when there is a small gap between the human body and the antenna of the on-body device, the impact of human body on antenna performance can be decreased [13], [18]. This paper is a continuation for the research presented in [13] by including the human body in the experiments. FIT-simulation and measurements results are analyzed and compared in frequency and time domains for three different UWB antenna pairs.

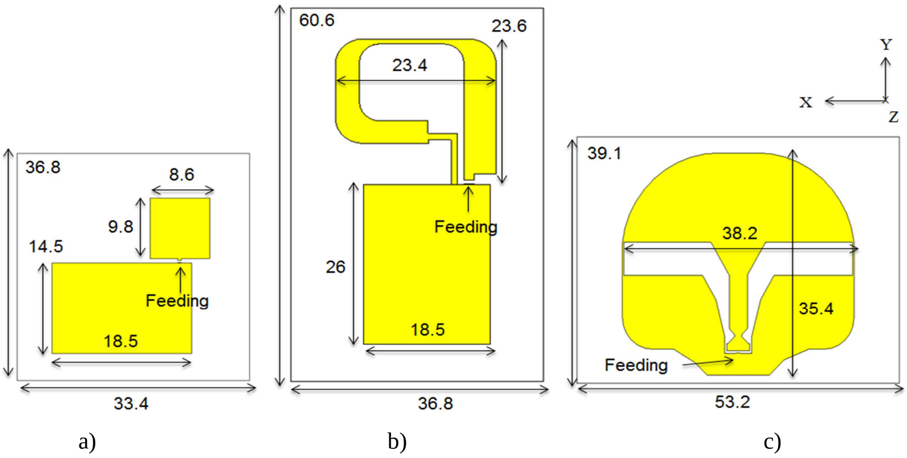


Figure 1. Planar UWB antennas in the investigations: a) Monopole, b) Loop, and c) Slot loop antenna.

The paper is organized as follows: Section II presents the UWB antennas used in this study. Simulation and measurement setups are presented in Section III and Section IV, respectively. In Section V, the simulation and measurement results are shown and analyzed. Summary and future works are discussed in Section VI.

2. UWB ANTENNAS

Three different planar UWB antennas targeted to be used for on-on and on-off body bcommunication links are exploited in this study. The antennas and their dimensions in millimeters are presented in Fig.1. Each antenna is fabricated on a 1.6 mm thick FR4 substrate with the material parameters of permittivity $\varepsilon_r = 4.3$ and loss tangent of $tan\delta = 0.025$. Monopole antenna in Fig. 1a is published earlier in [13]. Loop and slot loop antennas (Figs. 1b-c) are presented in [19] and [20], respectively.

Figure 2 presents simulated radiation patterns of the antennas at the frequencies of 3, 7, and 10 GHz in ZY- and XZ-planes. Presented monopole and loop antennas have corresponding polarization properties: their polarization is elliptical and it is rotated roughly 45º from the direction of y axis to the x axis. This is because antennas are asymmetric with respect to their feeding point. Slot loop antenna in Fig. 1c has its maximums in the +/- z direction and minimums in +/- y directions. The surface currents of this antenna start to travel from the feeding along the center line of the antenna such that in the lower frequencies, the currents are the most significant around the feed point and at the end of the slot area, and in the higher frequencies the currents travel constantly along the center line such that many consecutive waves can be observed simultaneously. Due to the polarization properties of the antennas, monopole and loop antennas will radiate more efficiently to the direction of y axis in comparison with the slot loop antenna (as in Fig. 2a). However, antennas radiate roughly equally to the direction of x axis, as presented in Fig. 2b. It should be noted that the radiation patterns of each antenna start to decompose slightly from the range of 7 GHz to 10 GHz. More results of the antennas are presented in [13],[19],[20].

3. SIMULATION SETUP

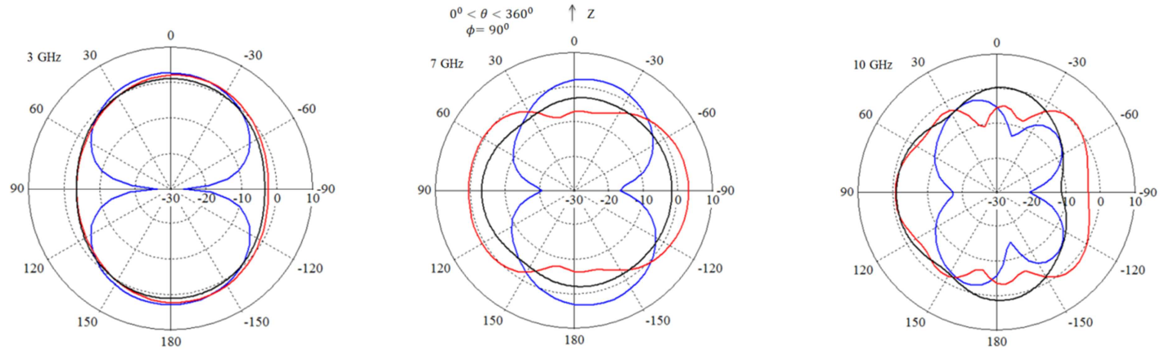
In this study, simulations are conducted with CST MWS Software [17], which uses FIT technique for modeling the electromagnetic propagation. Basically, FIT provides a discrete reformulation of Maxwell's equations in their integral form suitable for computer calculations [21]. Principle of FIT with more details as well as advantages of FIT in this context are explained e.g. in [13], [21].

The simulation setup for the studied on-off communication link is presented in Fig. 3. The setup consists of two identical antennas placed on the top of plastic stand perpendicularly against each other, epoxy cables and the CST human body model having the 2^{nd} order Debye dispersion with the material properties: high frequency limit permittivity (infinity) value $\varepsilon_\infty = 23$, low frequency limit permittivity (static) values $\varepsilon_{s1} = 3399$ and $\varepsilon_{s2} = 55.59$, and for the relaxation times $\tau_1 = 46.2$ ns and $\tau_2 = 0.091$ ns. The relaxation time τ corresponds to a relaxation frequency f_r ($f_r = 1/2\pi\tau$) and can be expressed in terms of molecular parameters [21]. The first antenna is attached on the human body model below the chest representing the antenna for an on-body device. The second antenna represents the antenna for the room access point device. The evaluations are performed using three different UWB antenna pairs presented in Section II. In the simulations, the sub-gridding scheme is used, which allows different levels of mesh to be used for different solids in the model. The number of Perfectly Matched Layers (PML), i.e, the amount of absorber layers enclosing the simulation model, were increased to the level of 20 to receive reliable channel operation. Furthermore, the simulations are conducted in two cases: a) the antenna is attached directly on the body surface and b) there is a gap of 20 mm between the body and the antenna. The results with the gap represents more realistic situation, since in practice the antenna of the on-off link device is not assumed to be directly on body surface. Simulation parameters are summarized in Table 1.

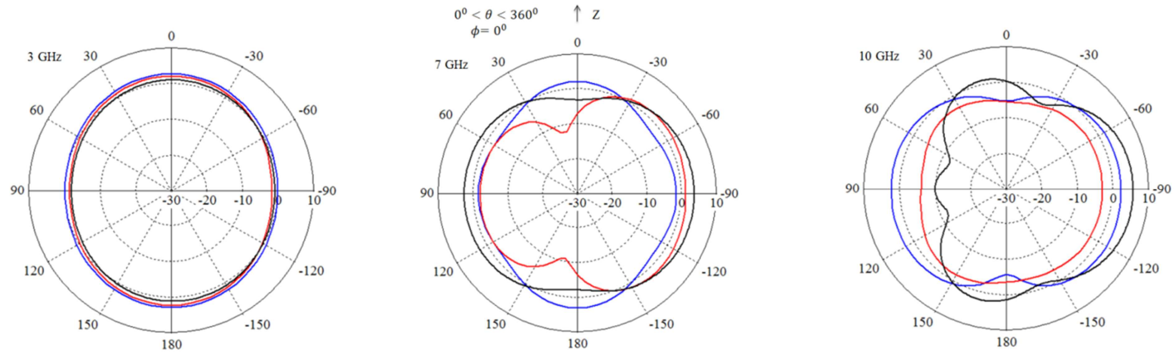
As simulations are carried out in frequency domain, we obtain reflection coefficient S_{11} for antenna 1 and channel transfer function S_{21} between the antennas. The channel response S_{21} can then be converted into time domain using Inverse Fast Fourier Transform (IFFT) function to obtain the channel impulse response.

Table 1. Parameters for Simulations

Parameter	Value
Frequency bandwidth	2-10 GHz
Number of frequency points	1601
Meshcells before subgridding	350 M
Meshcells after subgridding	75 M
Height of plastic stakes	2 m
Lines per wavelength for mesh density control	5
PML layers	20



a)



b)

Figure 2. Simulated radiation patterns (plots of realized gain) at the frequencies of 3 GHz, 7 GHz, and 10 GHz in a) ZY-plane, and in b) XZ-plane.

4. CHANNEL MEASUREMENT SETUP

The channel measurements were carried out using Agilent 8720ES Vector Network Analyzer (VNA) [22] in an anechoic chamber of the measurement laboratory at the University of Oulu. Three pairs of UWB antenna prototypes produced from the models described in the Section II were used in the experiments.

One of the authors acted as a test person in the measurements. The test person, height of 183 cm, was wearing a cotton T-shirt and jeans during the measurements. Figure 4 presents the measurement setup constructed in the anechoic chamber, having floor space 2.4 m x 3.85 m, and height of 3 m.

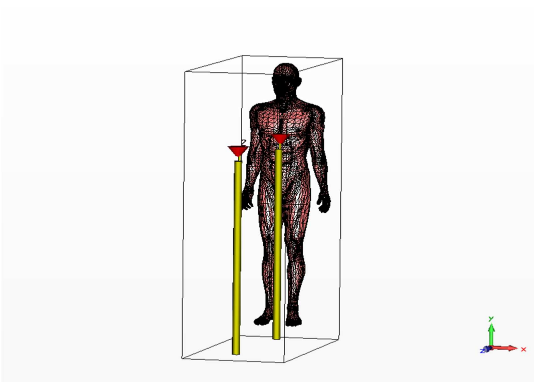


Figure 3. Simulation setup in CST environment with a body model, antennas and plastic stands.

Similarly to the simulation setup, the antenna prototypes were placed on the top of plastic stands, perpendicularly against each other at the same height having distance of 0.5 m from each other. The test person was standing behind the first antenna (on the absorber block in order to get the antenna on the desired level) so that the antenna was below his chest. Likewise in the simulations, the measurements were conducted both with and without the 20 mm gap between the antenna and body surface. The gap was obtained by setting a piece of rohacell between the body and antenna. Rohacell is assumed to be valid gap-material since it has corresponding material properties to air [23].

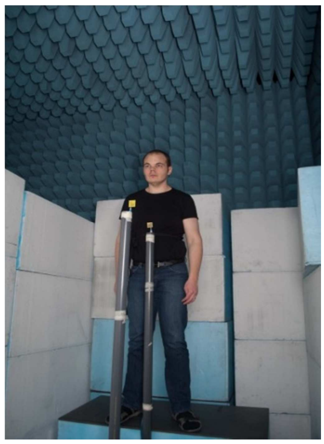


Figure 4. Measurement setup in an anechoic chamber.

5. RESULTS

5.1 Monopole

First the simulation and measurement results were examined both in frequency and time domains for the monopole antenna pair presented in Fig. 1a. Figure 5 presents the frequency response S_{21} obtained from the simulations (solid line) and measurements (dashed line) for the frequency range 2-11 GHz when there is no gap between the antenna substrate and the body. Furthermore, the measured and simulated S_{11}-parameters are included in Fig.6.

It is noted that the simulated S_{21} and S_{11} match well with the measurement results. The shape and the level of the curves are similar, though some small differences can be seen especially in the frequency range 2-4.5 GHz. The cable effect is presumably one of the factors affecting on the difference between the simulated and measured results. On the other hand, small differences in the results are natural due to the unidealities always present in the measurements. For instance, the simulation software uses two completely identical antennas, whereas in practice, it is not even possible to produce two antenna prototypes having exactly identical properties with exactly identical cabling. In the measurements, the antenna prototypes may also have an inexpedient minor tilt, which can slightly effect on the polarization and hence, on the channel transfer function. Furthermore, the human body used in the simulations is just a model with certain parameters; exact modeling of a human individual is infeasible. The impact of the unidealities in the measurements in this context is discussed in more details in [13]. It is also noteworthy that due to these known unidealities, the simulated and measured responses are compared merely visually in this study. Use of numerical comparison methods would not be appropriate in this case. The similarity in the simulated and measured results, i.e. the shape and level of the curves in the most significant area, is best seen by visual inspection of the responses in the figures.

Next, the simulated and measured frequency domain channel responses are converted into time domain using IFFT function. The obtained Impulse Responses (IR)s are presented in Fig. 6. The clear correspondence between the simulated and measured can be seen also in this case. As expected from the frequency domain results, the level of the simulated impulse response is slightly higher than that of the measured impulse response. The timing of the main peak of the impulse responses is same: approximately 1.8 ns. This is valid also in theory: Since the distance between the antennas is 0.5 m, the peak of the impulse response should start at the time instant.

$$t = \frac{d}{c} = \frac{0.5\,\mathrm{m}}{3.0 \cdot 10^{8}\,\mathrm{m/s}} = 1.7\,\mathrm{ns}$$

Next, the simulated and measured responses are compared when there is a gap of 20 mm between the body surface and the antenna. Interestingly, the difference between the simulated and measured responses is now smaller as seen from the frequency domain and time domain results presented in Figures 7-8, respectively. Especially the S_{11} parameters are almost equal. When there is a gap between the body and the antenna, the impact of unidealities in the simulation body model is less significant. This also confirms the claim that unideality of the body model has some impact on the level difference presented in Figs. 5-6.

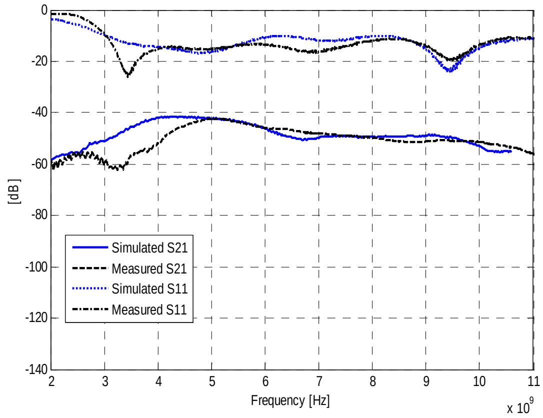


Figure 5. Simulated and measured S_{21} and S_{11} of the monopole antenna without a gap between the antenna substrate and the body surface.

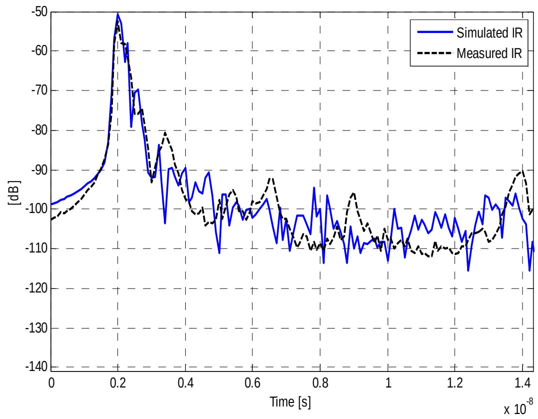


Figure 6. Simulated and measured impulse responses of the monopole antenna without a gap between the antenna and the body.

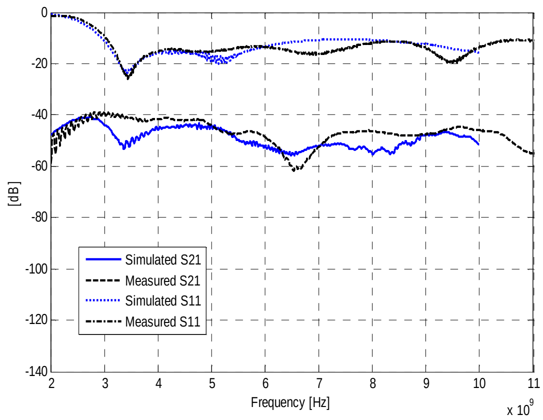


Figure 7. Simulated and measured S_{21} and S_{11} of the monopole antenna in the presence of a gap between the antenna substrate and the body surface.

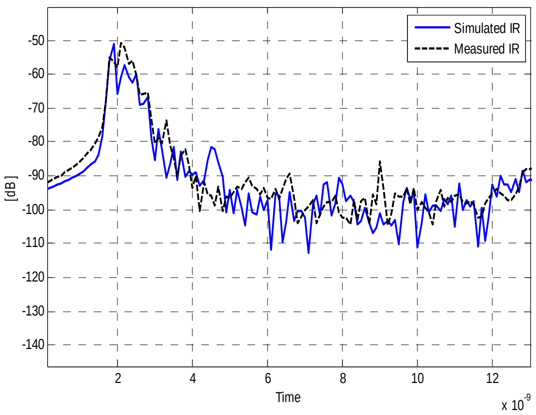


Figure 8. Simulated and measured impulse responses of the monopole antenna in the presence of a gap between the antenna and the body.

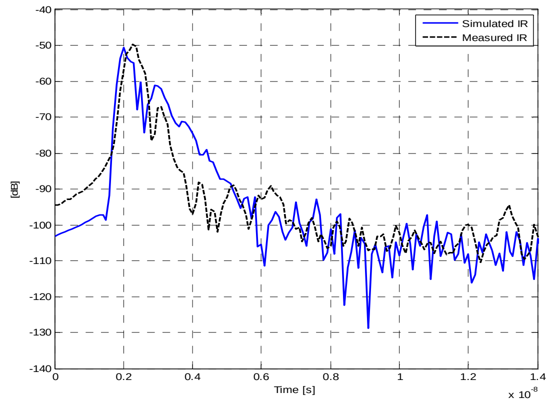


Figure 10. Simulated and measured impulse responses of the loop antenna obtained without a gap between the antenna and the body.

5.2 Loop antenna

Next, the loop antenna pair presented in Fig.1 b is used in the simulations and measurements. First we compare the results when there is no gap between the antenna substrate and the body surface. The frequency domain and time domain channel responses are presented in Figures 9-10, respectively.

The simulated and measured frequency domain responses seem to match excellently also with the loop antennas: the shape and strength of the curves are very similar. In time domain, the timing and strength of the main peak is rather similar, whereas somewhat difference can be seen in the levels at the time period 3-5 ns. The reasons causing the level difference is so far under investigation, since typical causes discussed in the previous section are normally seen in the frequency domain channel response as well. Nevertheless, the level difference is less significant in practice since the signal level is more than 10 dB below the main peak.

Figures 11-12 present the measured and simulated frequency and time domain results in the presence of a gap between the antenna and body surface. Similar tendencies can be observed also in these cases, expect the level difference in time domain results is remarkably minor.

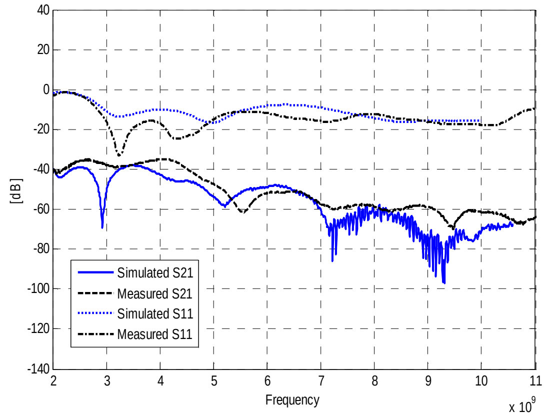


Figure 11. Simulated and measured S_{21} and S_{11} of the loop antenna in the presence of a gap between the antenna substrate and the body surface.

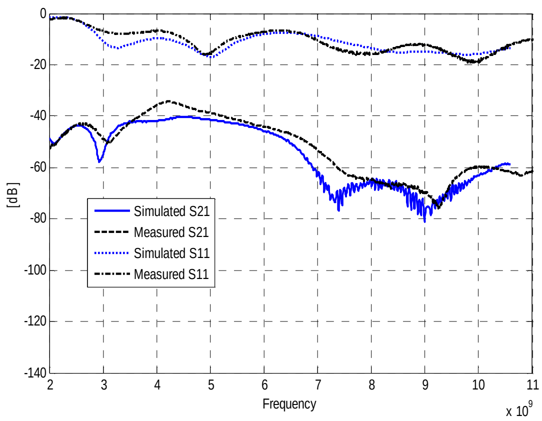


Figure 9. Simulated and measured S_{21} and S_{11} of the loop antenna without a gap between the antenna substrate and the body surface.

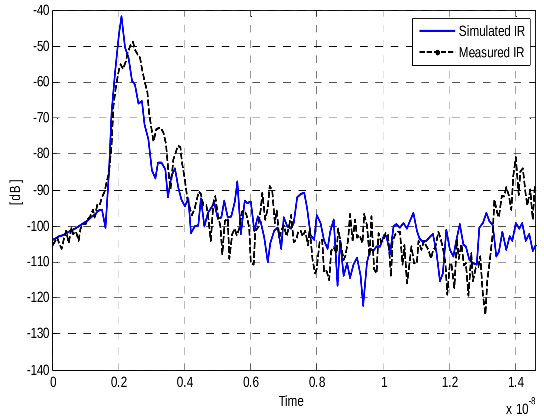


Figure 12. Simulated and measured impulse responses of the loop antenna in the presence of a gap between the antenna and the body.

5.3 Slot loop antenna

Finally, the slot loop antenna pair presented in Fig.1 c is evaluated by simulations and measurements. First we study the case without the gap between the antenna and the body. The frequency domain and time domain channel responses are presented in Figures 13-14, respectively. The shape and level of the simulated and measured channel transform functions are in fact similar from the beginning of 2.5 GHz upwards. Besides, the simulated and measured impulse responses match well, though some difference can be seen in the levels of the peaks following the main peak in the time period 5 ns. Instead, a clear frequency shift can be seen in the notches of the simulated and measured S_{11} parameter. Such differences are rather unavoidable as the antenna is located directly on the body surface. As expected, this difference diminishes as the gap between the antenna and the body surface is introduced, as shown in Figure 15. Furthermore, in the presence of the gap also the simulated and measured channel responses match well both in time and frequency domains as seen in Figures 15-16. However, tiny timing error can be noticed in the impulse responses; this is evidently due to small misplacement of the test person during the measurements. Despite of these small differences, one can observe a good match between the simulated and measured responses obtained with the slot loop antenna study.

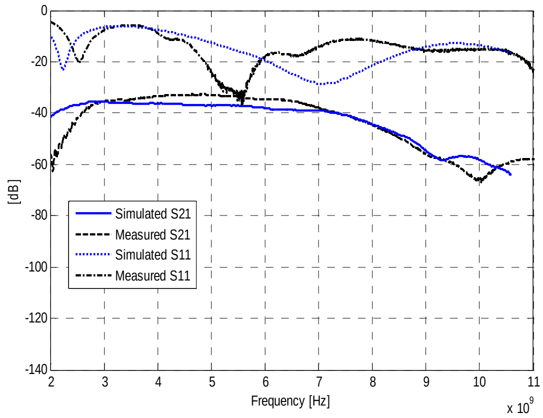


Figure 13. Simulated and measured S_{21} and S_{11} of slot loop antenna without a gap between the antenna substrate and the body surface.

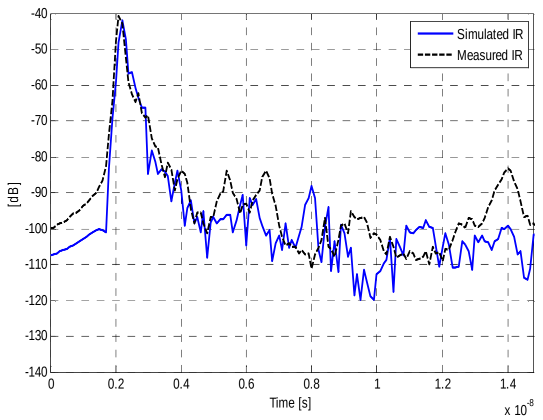


Figure 14. Simulated and measured impulse responses of the slot loop antenna without a gap between the antenna and the body.

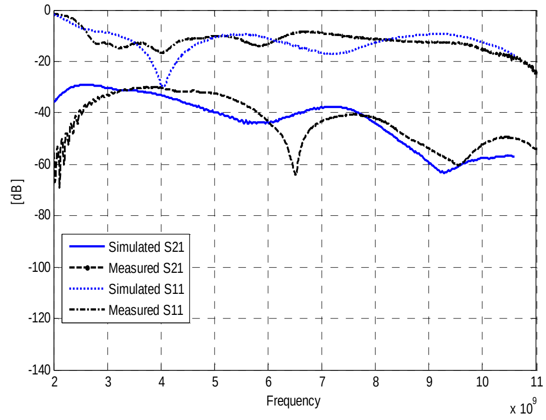


Figure 15. Simulated and measured S_{21} and S_{11} of the slot loop antenna in the presence of a gap between the antenna substrate and the body surface.

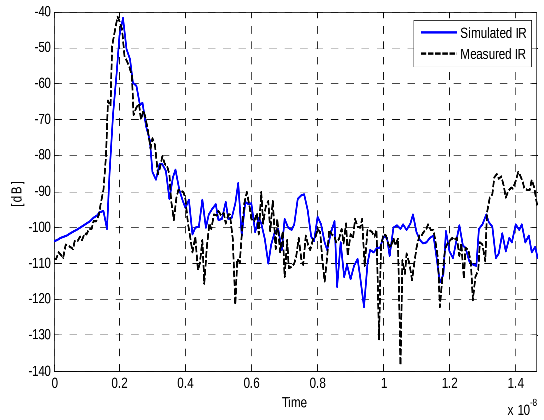


Figure 16. Simulated and measured impulse responses of the slot loop antenna in the presence of a gap between the antenna and the body.

6. SUMMARY AND CONCLUSIONS

In this paper, channel modeling for UWB WBAN on-off body communication link with Finite Integration Technique was studied. Three different UWB antenna pairs designed for on-on and on-off body communications were used in the experiments. The validity of the FIT is verified by comparing the simulation results with the measurement results in frequency and time domains. A clear visual agreement between the simulated and measured results was noticed with all of the evaluated antennas, especially when there was a small gap between the antenna and human body/model. The small differences in the results were explained to occur due to the unidealities always present in the measurements; such as unideal prototyping of antennas, unideal cabling, small errors in the placement of antennas, etc. Furthermore, the unidealities in the human body model used in the simulations have impact on the results. This was confirmed by showing that the simulated and measured responses are even more similar when there is a gap between the antenna and the human body.

One of the main advantages of FIT-based simulations in channel modeling is that the desired channel characteristics for a specific environment can be obtained simply by drawing the environment on the software and selecting proper parameters for the simulations. The frequency domain channel response resulting from the simulations can further be converted into time domain to get a realistic channel impulse response. The simulated channel impulse response was observed to be almost equal with the measured impulse response.

Main challenge in the use of FIT for modeling the on-off body communication link is that it requires huge computational and memory capacity when using a dispersive body model especially in a complex environment. As a next step of this work, we aim to reduce computational complexity by performing simulations piecewise, and hence enable on-off body communication link simulations in a more complex environment.

7. ACKNOWLEDGMENTS

This research has been performed in the project EWiHS (Enabling Future Wireless Healthcare System) which is partly funded by Finnish Funding Agency for Technology and Innovation (Tekes). We would also like thank CST help support, especially Ilari Hänninen, for his valuable advices with simulations.

8. REFERENCES

[1] IEEE P802.15 Working Group for Wireless Personal Area Networks (WPANs). TG6 Body Area Networks (BAN) standard IEEE P802.15-10-0245-06-0006. 2012.

[2] Hämäläinen M., Iinatti J.,Kohno R., "Wireless Communications in Healthcare, Recent and Future Topics", *4th International Symposium on Applied Sciences in Biomedical and Communication Technologies (ISABEL)*, Oct 2011. DOI=10.1145/2093698.

[3] Hall P.S., Hao Y., "*Antennas and Propagation for Body-Centric Wireless Communication*", Artech House 2006.

[4] Hämäläinen M., Taparugssanagorn A., Iinatti J., "On the WBAN Channel Modelling for Medical Applications", *in European Conference on Antennas and Propagation (EUCAP)*, p. 2967-2971, 2011. DOI=10.1.1.204.6283.

[5] Lu X., Chen X., Sun G., Jin D., Ge N., Zeng L.,"UWB-based Wireless body Area Networks Channel Modelling and Performance Evaluation", *7th International Wireless Communications and Mobile Computing Conference (IWCMC)*, p.1929-1934, 2011. DOI= http://dx.doi.org/10.1109/IWCMC.2011.5982829.

[6] Takizawa K., Aoyagi T., Kohno R., "Channel Modeling and Performance Evaluation on UWB-Based Wireless Body Area Networks", *IEEE International Conference on Communications, ICC'09*, Jun 2009. DOI= http://dx.doi.org/10.1109/ICC.2009.5198820.

[7] Ryckaert J., De Doncer P., Meys R., De Le Hoye A., Donnary S., "Channel Model for Wireless Communication around Human Body," *Electronics letters*, vol. 40, no. 9, Apr 2004. DOI= http://dx.doi.org/10.1049/el:20040386.

[8] Zhao Y., Hao Y., Alomainy A., Parini C. G., "Two novel FDTD Based UWB Indoor Propagation Model", *Proc. IEEE Inernationa. Conference on. Ultra-Wide-Band*, Sept. 2005. DOI= http://dx.doi.org/10.1109/ICU.2005.1569970.

[9] Aoyagi T., Kim M., Takada J., Hamaguchi K., Kohno R., "Numerical simulations for dynamic WBAN propagation channel during various human movements" *5th International Symposium on Medical Information & Communication Technology (ISMICT)*, 2011. DOI= http://dx.doi.org/10.1109/ISMICT.2011.5759798.

[10] Viittala H., Hämäläinen M., Iinatti J., "Different Experimental WBAN Channel Models and IEEE802.15.6 models: Comparison and Effects," *2nd International Symposium on Applied Sciences in Biomedical and Communication Technologies (ISABEL)*, Nov 2009. DOI=http://dx.doi.org/10.1109/ISABEL.2009.5373626.

[11] Viittala H., Hämäläinen M., Iinatti J., "Impact of difference in WBAN Channel Models on UWB System Performance", *In IEEE International Symposium on Spread Spectrum Techniques and Applications (ISITA)*, p. 175-180, Oct. 2010. DOI=http://dx.doi.org/10.1109/ISSSTA.2010.5651033.

[12] Uusitupa T., "Parallel FDTD Simulations for WBAN Channel Characterization using Different Body Models", 6th *European Conference on Antennas and Propagation (EUCAP)*, March 2012. DOI= http://dx.doi.org/10.1109/EuCAP.2012.6206558.

[13] Säreströniemi M., Tuovinen T., Hämäläinen M., Yekeh Yazdandoost K., Kaivanto E., Iinatti J., "Applicability of Finite Integration Techniques for the Modelling of UWB Channel Charaterization", The *6th International Symposium on Medical Information and Communication Technology (ISMICT2012)*, San Diego, CA. USA, Mar 2012. DOI= http://dx.doi.org/10.1109/ISMICT.2012.6203045.

[14] IEEE P802.15 (WPANs), Channel Model fo BAN, 2010

[15] Weiland T., "A Discretization Method for the Solution of Maxwell's equations for six-component fields," *Electronics and Communication (AEU)*, Vol. 31, p. 116, 1977.

[16] Yee K.S., "Numerical solution of initial boundary value problems involving Maxwell's equations in isotropic media," *IEEE Trans. on Antenna and Propagation*, Vol. 14, No. 3, pp. 302-307, May 1966.

[17] *CST Microwave Studio*, [Online]. DOI= http://www.cst.com.

[18] Tuovinen T., Berg M., Yekeh Yazdandoost K., Salonen E., Iinatti J., "The Radiation properties of Planar UWB Dipole Antenna in the Proximity of Dispersive Body Models", *7th International Conference on Body Area Networks (BodyNets)*, Sept 2012, Oslo, Norway.

[19] Tuovinen T., Yekeh Yazdandoost K., Iinatti J., "Ultra Wideband Loop Antenna for On-Body Communication in Wireless Body Area Networks", *6th European Conference on Antennas and Propagation (EuCAP)*, March 2012.DOI= http://dx.doi.org/10.1109/EuCAP.2012.6205811.

[20] Tuovinen T., Yekeh Yazdandoost K., Iinatti J., "Comparison of the Performance of the Two Different UWB Antennas for the Use in WBAN On-Body Communication", 6th *European Conference on Antennas and Propagation (EuCAP)*, March 2012.DOI= http://dx.doi.org/10.1109/EuCAP.2012.6206090.

[21] Barnes, F. S. and Greenebaum, B.. 2007. *Bioengineering and Biophysical Aspects of Electromagnetic Fields*. Taylor & Francis Group.

[22] CST User Manual,CST AG, Darmstadt, Germany

[23] Agilent, [Online]. DOI: http://www.home.agilent.com/agilent/home.jspx?cc=FI&lc=fin.

[24] Rohacell, DOI=www.rohacell.com