

Finite Integration Technique for Modelling of WBAN Communication Links in Complex Environments

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Abstract—Recently, finite integration technique (FIT) is shown to be promising method for modelling channel characteristics of wireless body area network (WBAN) on-off body communication links. One of the main advantages of FIT-based channel modelling is that channel characteristics for a specific environment can be obtained simply by drawing the environment on the software and selecting proper parameters for simulations. FIT-simulators face the same problem as the other corresponding simulators: large memory and computational capacity is required in complex environments. However, these requirements can be reduced significantly especially by using FIT with a careful planning of meshing for the simulation model and by proper selection for the critical parameters. The first aim of this paper is to depict and visualize how FIT-simulations should be conducted in complex scenarios taken into account the meshing, accuracy of simulation results, complexity, and simulation time. Further, this paper shows how density of meshing influences remarkably on the simulated channel characteristics in time domain, whereas in frequency domain sparser mesh is sufficient to obtain realistic results. Finally, the aim is to verify that FIT is valid in complex environments by comparing the Ultra Wideband (UWB) channel characteristics obtained by FIT-simulations and channel measurements.

Keywords—channel measurement, channel modelling, finite integration technique (FIT) based simulation

I. INTRODUCTION

Wireless body area networks (WBANs) including communication within and around the human body, has been under an intensive study recently. The standard for WBAN has been developed by the study group IEEE802.15.6 and it has been published in the February 2012 [1]. The communication links in WBAN are classified into four different categories: in-in (link between medical implants), in-on (link between medical implants and on-body sensors), on-on (link between on-body sensors) and on-off (link between on-body device and external gateway) body communication link [2].

Channel modelling for WBAN applications has been studied widely. Several channel models, both analytical and measurement based, have been proposed for WBAN, e.g., in [3]-[6]. However, these models tend to be accurate just in certain scenarios. The main challenge in this field is to find a method to generate realistic channel models for new different purposes flexibly without excessive computational efforts.

Recently, finite integration technique (FIT) [7] has shown to be promising method for the modelling of WBAN on-off body communication link [8], [9]. Comparison between the FIT-simulation results and measurement results shows good agreement in [8] and [9]. These initial experiments were performed in an anechoic chamber in order to evaluate accuracy of the FIT when only antennas and the presence of human body are included. FIT-simulators face the same problem as the other corresponding simulators: large memory and computational capacity is required in complex environments. However, these requirements can be reduced significantly especially in FIT-based simulators by a careful planning of meshing for the simulation model and by proper selection for the critical parameters. This will be discussed in Section II more in detail.

The aim of this paper is to depict and visualize how FIT-simulations should be conducted in complex scenarios taken into account meshing, accuracy of simulation results, complexity, and simulation time. The main focus is to see how density of meshing influences in time and frequency domain simulation results. The study on the impact of meshing density is conducted in the frequency band 2-5 GHz since the simulations for the whole UWB band are very time consuming due to the huge number of mesh cells. Furthermore, the aim of this paper is to verify if FIT is valid within UWB band 3-10 GHz in a complex environment, i.e., in a medium size room where the ceiling as well as the walls consist of multiple levels and varying materials. FIT-simulation results are compared with the measurement results in frequency and time domains.

The paper is organized as follows: The basic idea of FIT-based simulations, the simulation and measurement setups are presented in Section II. In Section III, the numerical results for the simulations are presented; first the impact of meshing is studied and then FIT-simulation and measurement results are compared and analysed in UWB band. Summary and conclusions are discussed in Section IV.

II. FINITE INTEGRATION TECHNIQUE BASED SIMULATIONS

A. Finite Integration Technique

Electromagnetic propagation can be modelled by solving Maxwell's equations in the given scenario with numerical approaches, such as FIT [7]. FIT provides discrete

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reformulation of Maxwell's equations in their integral form suitable for computer calculations. One of the benefits in FIT is the possibility to have two different materials within one grid cell, which prevents mesh - and thus also memory requirement - growing too large [10]. Principle of FIT with details as well as advantages of FIT in this context, are explained in [8], [10].

One of the main advantages of FIT-based simulations in channel modelling is that the channel characteristics for a specific environment can be obtained simply by drawing the environment on the software and selecting proper parameters for the simulations [9]. The frequency domain channel response resulting from the simulations can further be converted into time domain by inverse fast fourier transform (IFFT) to get a realistic channel impulse response. In this study, Computer Simulation Technology (CST) MicroWave Studio (MWS) software [11] is used for FIT-simulations.

B. Simulation and Measurement Setups

The simulation and measurement setups for the studied on-off body communication link are presented in Figs. 1a and 1b. The setups consist of a medium-size office room with floor size 3.5 m x 3.4 m and height varying from 2.8 m to 3.4 m. The materials of the walls were plasterboard (grey surfaces in Fig. 1a or concrete (white). There were windows on three walls (turquoise surfaces), the third window is on the foremost wall which is not included in the figure for the clarity of the presentation. Materials used in the simulation setup are summarized in Table I. For the simulation model, the door, windows were drawn with realistic dimensions and materials. Some simplifications were made for simulation model, e.g., the crossbars of the windows and the handles of the door were ignored. Instead, the heat radiator on the wall, ventilators, fluorescent bulbs and maintenance hatches (yellow surfaces) on the ceiling were modelled with exact dimensions and positions since they may act as a strongly reflective surface. For simplicity, the furniture was removed from the room.

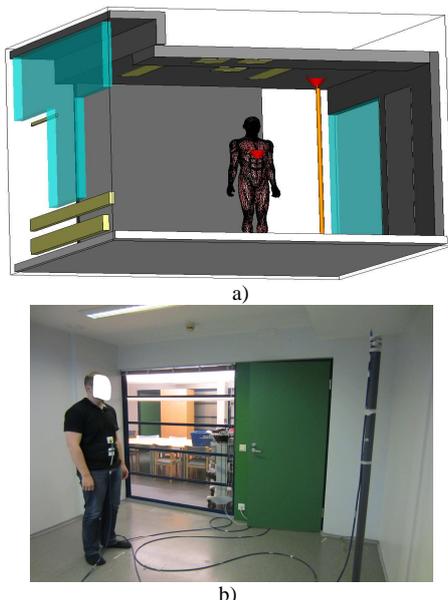


Figure 1. a) Simulation setup and b) measurement setup.

TABLE I. MATERIALS FOR SIMULATION SETUPS

Material	Element in the scenario	Color in fig.	Source for material property
Concrete	part of the walls, floor	white	CST material library
Plasterboard	part of the walls, door, ceiling	grey	[12]
Glass	Panes on three walls	turquoise	CST material library
Metal	Radiator, ventilators, fluorescent bulbs, maintenance hatches	yellow	CST material library
Plastic	Stand	orange	CST material library

The UWB antenna used in this study is a printed planar monopole antenna, designed for on-off and on-on body communication links, with $S_{11} < -10$ dB in the UWB band 3.1-10.6 GHz. The dimensions of the antenna are 33.4 mm x 36.8 mm and it is fabricated on a 1.6 mm thick FR4 substrate. More details about the properties of this antenna are found in [8].

In the simulation and measurement setups, the other antenna was placed on the plastic stand at height of 2.05 m representing the antenna for the room access point. Another antenna was attached to the human body below the chest representing the antenna of an on-body device. In the measurements, a real human acted as a test person. The test person, the height of 183 cm, was wearing a cotton T-shirt and jeans during the measurements. The measurements were carried out by using Agilent 8720ES vector network analyser (VNA) [13]. The UWB antenna prototype, produced from the model described in the previous subsection, was attached to the body by elastic bands and the antennas were fed through semi-rigid coaxial cables.

The simulations and measurements are conducted in two cases: a) the antenna is attached to 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 the body surface. In the measurements, the gap was obtained by setting a piece of Rohacell (RC31HF) [14] between the body and the antenna. Rohacell is assumed to be valid gap-material since it has corresponding material properties to air.

III. NUMERICAL RESULTS

A. Simulation parameters

The simulations were conducted using CST MWS [11], which allows several options for modifying the properties of the simulation model, e.g., in terms of meshing, material based refinement, layers, and so forth [10]. The overall density of simulation mesh in terms of number of mesh cells can significantly be reduced by using so called multilevel subgridding scheme. It allows only very dense mesh to be generated within the critical regions [10]. Hence, density of mesh can be increased locally in the essential areas, e.g., at the close proximity of the antenna. In general, lines per wavelength -parameter l adjusts the overall mesh density for the entire simulation space. The number of perfectly matched layers (PML) is the amount of absorber layers enclosing the simulation model was kept in the default value of 4. The number of frequency points over the band was 1601. Material

based refinement, which is an option to improve meshing of the object, can be taken into account or ignored depending on the requirements for accuracy. CST's homogeneous human body model is explained more with details in [15].

B. Impact of meshing

In this subsection, the impact of meshing is studied taking into account the accuracy of the simulation results, complexity and simulation time. The study is conducted with the setups presented in Figs. 1a and b. The distance between the human body and antenna stand is 1 m, so the distance between the antennas is approximately 1.5 m. The impact of meshing is studied within frequency band 2-5 GHz since the simulations for the whole UWB band are very time consuming due to the huge number of mesh cells. The simulations were conducted on the computer with Intel(R) Core(TM) i5-2400 CPU 3.10 GHz with installed memory 16.0 GB.

In this study, three different cases are evaluated: 1) human body model is meshed as the simulation space (material based refinement for the body model is not involved), 2) the whole human body model is included in the simulation scenario as an object by involving the material based refinement on the body, and 3) the human body is split in order to get different mesh properties to different parts of the body. The basic idea in the case 3 is that only the most relevant parts of the human body in terms of electromagnetic propagation (area around the antenna) are included in meshing, and hence the number of mesh cells can be reduced significantly compared with the case 2. Fig. 3 visualises different mesh configurations investigated in this paper. The left most figure depicts the situation for the case 1, the middle figure for the case 2, and the right most figure for the case 3.

First, the simplest case is evaluated, i.e., the case 1 where the material based refinement is not involved on the human body. Two mesh densities are studied: lines per wavelength values of $l = 3$ and $l = 4$. Value $l = 3$ corresponds to the sparsest possible mesh in these kinds of situations. The number of mesh cells before subgridding with $l = 3$ is 24.2 million, and $l = 4$ 41.8 million. For the comparison, the number of mesh cells in the free-space simulation model of two antennas is only 0.2 million. The simulations are conducted in the presence of the gap as well as without the

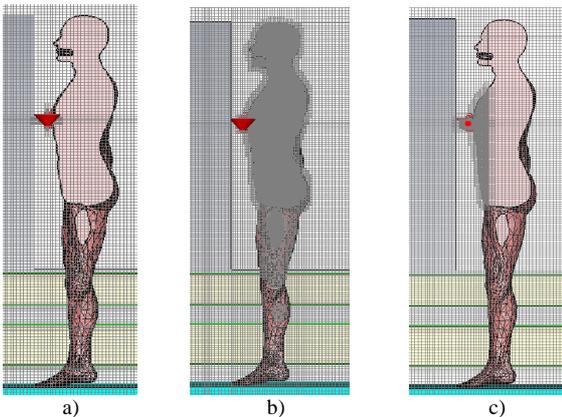


Figure 3. Mesh view after subgridding as a) body is meshed as the simulation space, b) the whole body is included as an object for meshing, and c) only essential parts of the body are included in meshing as an object.

gap between the antenna and the human body. Frequency and time domain results are shown in Figs. 4 a-d

As it can be seen in Fig. 4a, the difference between the responses obtained by $l = 3$ and $l = 4$ is relatively minor in frequency domain if there is the gap between the antenna and the body surface. Instead in time domain, the impact of mesh density is more significant, as seen in Fig. 4b. The simulation results obtained with $l = 3$ differ remarkably from the measurement results. Although the levels of the main peak in the impulse responses are somewhat at the same level, there are major differences in the following peaks. However, these differences become more notable as there is no gap between the antenna and the body surface, as seen in Fig. 4d. In this case, the timing of the main peak is slightly shifted as the mesh density is too sparse. Besides, the difference in meshing density can also be noted now in frequency domain in Fig. 4c. As the antenna is placed directly on the body surface, the impact of the body on the antenna properties is more significant as well as the impact of meshing close to the on-body antenna is more crucial.

Next, we evaluated the case 2 where the material based refinement is involved for the whole body model as well as the case 3, where the body model is included partially in meshing as an object. The complexity of the model as well as simulation time increases remarkably as the whole body is included in meshing. Table II summarizes the cases 1-3 in terms of number of mesh cells before and after subgridding and required simulation time as the $l = 3$.

The simulation results in the presence and without the gap between the human body and the antenna are presented in Figs. 5a and 5b, respectively. Due to lack of the space, only the impulse responses obtained by simulations with $l = 4$ are presented. As it can be seen, the similarity between the simulation and measurement results is clearly improved as the body is included in the meshing even partially. Actually, the difference between the cases 2 and 3 is only minor even when there is no gap between the antenna and human body. Thus, it is sufficient to use the case 2 in the simulations instead of the case 3 in order to get reliable results with reasonable simulation time. In Fig. 5, the level of the main peaks in the simulated and measured impulse responses is approximately same as well as the peaks from 8 ns onwards. Interestingly, there is a significant difference in the timing and strength of the second main peak between the simulated and measured impulse responses. The strength of the second peak in the measured impulse response is larger than in the simulated impulse response. This is presumably due to the unideal modelling of the reflective materials in the simulation models. This, and also the general shape of the impulse responses are discussed more in detail in the following subsection with results for the whole WBAN range.

TABLE II. SIMULATION REQUIREMENTS FOR CASES 1-3

Lines per wavelength = 3	Meshcells before subgridding	Meshcells after subgridding	Simulation time
Case 1	24.2 million	7.9 million	4 h
Case 2	96.8 million	12.4 million	11.5 h
Case 3	54.9 million	9.6 million	7.5 h

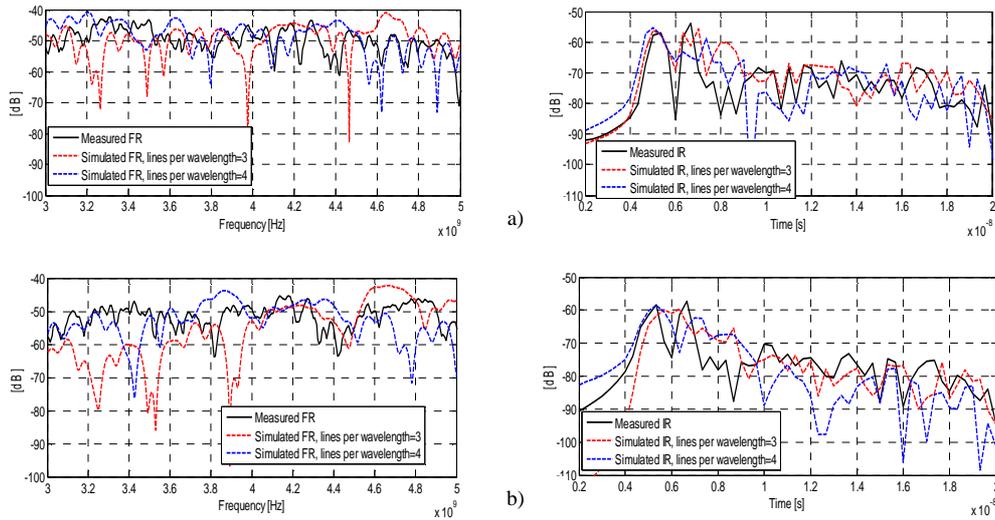


Figure 4. The impact of meshing density in the presence of the gap (a) and without the gap (b) in frequency and time domains.

C. Applicability of FIT in Complex Environment 3-10 GHz

Next, the applicability of FIT is verified within the UWB range 3-10 GHz by comparing the simulation results with the cases 1 and 3 to the measurement results. The scenarios are similar to those depicted in Figs. 1-2, with the mesh density $l = 4$. Due to a wider frequency band, the number of mesh cells for the case 1 and case 3 before subgridding is 190 million and 533 million, respectively. Thus, simulations are conducted using a computer with 2.0 GHz processor 2xIntel Xeon E5645 and 48 GB memory. Furthermore, the evaluations are performed with and without the gap between the antenna and human body.

The simulated and measured frequency and time domain responses are shown in Fig. 6. As seen in Figs. 6a and 6c, there is good visual match between the simulated and measured frequency responses both with and without the gap between the antenna and the human body. Slight level differences are noted in the results without the gap in the frequency range 6-7 GHz. However, these kinds of level differences in specific ranges are normal especially when the antenna is set directly on the human body due to unidealities in the body modelling, as explained in [8]. Furthermore, no significant differences were noted between the frequency domain simulation results with the meshing cases 1 and 3.

Also the simulated and measured impulse responses are quite similar, as seen in Figs. 6b and 6d. The only major difference is the higher level of the measured peak at the time instant 6.5 ns. This timing instant corresponds to the distance 1.95 m, which is exactly propagation distance from the on-body antenna to the room access point antenna when reflected from the maintenance hatch above. There are two explanation options for level difference: First, the material of the maintenance hatch might be more reflective in the real measurement scenario than in the model. On the other, it can be due to the unideal antenna prototyping as there might be differences in antenna patterns between simulations and measurements (i.e., pattern may be stronger towards the maintenance hatch in the measurement scenario than in the simulation scenario causing stronger reflection). A small timing difference in the main peaks of the simulated and measured impulse responses can also be noted. This is due to the unintentional misplacement of the test person in the measurement. Besides, minor timing errors between the simulated and measured responses are natural as explained in [16]. However, the shape of the main peaks is very similar when there is the gap between the antenna and the body and the body is partially included in the meshing. Without the gap, the measured main peak is slightly narrower.

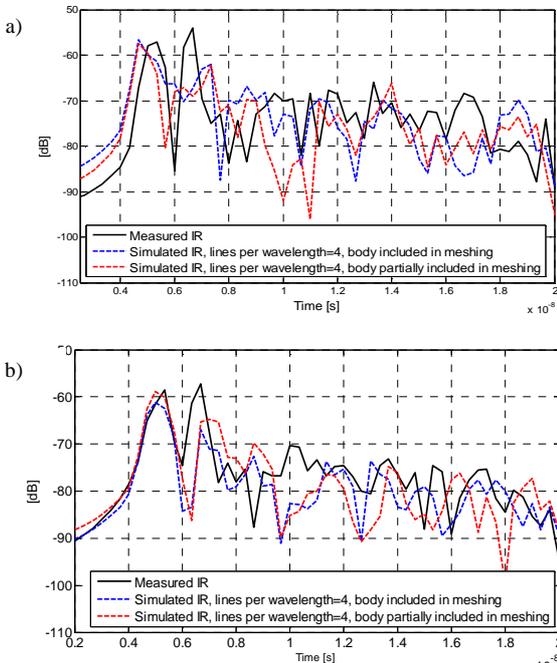


Figure 5 The comparison of measured and simulated time domain results when the body is included in meshing completely and partially a) in the presence of the gap between the antenna and human body and b) without the gap between the antenna and human body

Generally speaking, the simulation results with the meshing case 3 are more accurate than those with the case 1, especially when the antenna is placed directly on the human body. There are also some small level differences in the peaks arriving at the later time instants. Apparently, these are due to the unideal modelling of the measurement scenario in the simulation software: there are some materials which cause stronger refractions or reflections than in the simulation model. Besides, the simplifications of the simulation model explained in Section II cause some differences as well.

IV. SUMMARY AND CONCLUSIONS

This paper depicted how FIT-simulations should be conducted in complex scenarios taken into account the meshing, accuracy of simulation results, complexity, and simulation time. It was shown that the density of meshing influences remarkably on the channel characteristics in time domain, whereas in frequency domain simulation results can be realistic even with sparser mesh. Furthermore, realistic time domain results are ensured by taken account the body model in meshing as an object at least partially from the most relevant parts in terms of electromagnetic propagation. This is essential especially in the cases when the antenna is placed directly on the body surface. The study on meshing was performed in the frequency band 2-5 GHz.

The applicability of FIT was verified also within UWB band 3-10 GHz. The simulations were conducted as the material based refinement is not involved as well as when the body model is partially taken into account in meshing. The simulated and measured responses show good visual match in frequency domain and also in time domain especially when the body is included meshing partially.

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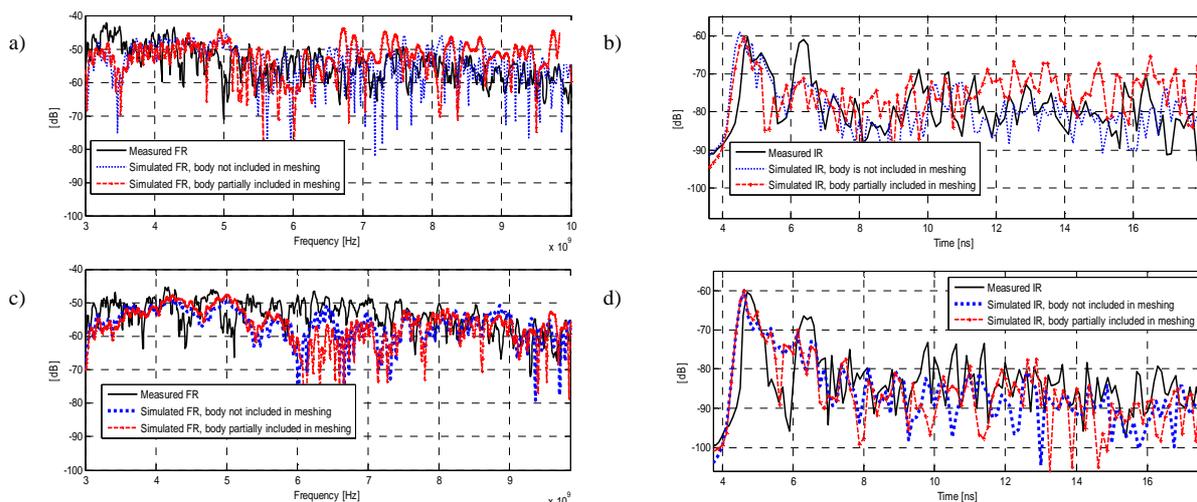


Figure 6. The comparison of the measured and simulated responses in 3-10 GHz band without and with the gap.