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An Overview of the Electromagnetic Simulation-Based Channel Modeling Techniques for Wireless Body Area Network Applications

MARIELLA SÄRESTÖNIEMI, MATTI HÄMÄLÄINEN, (Senior Member, IEEE),
AND JARI IINATTI, (Senior Member, IEEE)
Centre for Wireless Communications, University of Oulu, 90014 Oulu, Finland

Corresponding author: Mariella Särestöniemi (mariella.sarestoniemi@oulu.fi)

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ABSTRACT Electromagnetic simulation-based channel modeling is presently considered as a promising option for wireless body area network (WBAN) channel modeling. The benefits of simulation-based channel modeling are obvious: realistic channel characteristics for required environments and situations are provided flexibly and cheaply. In addition, the use of simulation-based channel modeling may overcome several challenges related to the use of measurement data, such as uncertainties and inaccuracies due to cabling, unintentional changes in the position of the test person or the antennas and so on. There are several numerical methods suitable for simulation based-channel modeling, both full-wave and an asymptotic solutions. The choice of the numerical approach depends on the nature of the communication links of the wireless body network being considered. This paper presents a general overview, including recent progress, of the electromagnetic simulation-based WBAN channel modeling techniques. Advantages, disadvantages, and the most appropriate applications are described. Furthermore, the features of the different techniques are compared.

INDEX TERMS FEM, FDTD, FIT, channel modeling, MoM, overview, ray-tracing, UTD.

I. INTRODUCTION

Wireless Body Area Network (WBAN) Systems and Applications are considered to play a key role in solving the problems and demands related to the future's healthcare. The main challenge is to develop and design systems which provide dependable, secure and fast communications while taking into account patient's safety [1]–[5].

Extensive knowledge of the radio channel is essential for the optimized system design. In the WBAN applications, the close proximity of the human body brings several challenges for channel modeling. Thus, channel modeling for the WBAN applications has been an intensively researched topic in recent years. Besides the channel models introduced by the IEEE802.15.6 standard [6], several analytical, measurement based, and electromagnetic simulation based channel models have been proposed in the literature for WBAN, reviewed in e.g. [7]–[11].

The measurement based channels are shown to be more accurate than the IEEE 802.15.6 channels, as shown e.g., in [12]. Evidently, measured data based simulations provide more realistic performance in certain environments than the analytical model based on simulations, since the analytical models approximate certain situations. However, the use of measurement data has its own challenges. First, the use of measurement data is not always possible due to the laboriousness of the measurement campaigns. Second, inaccuracies and uncertainties are always present in the use of measurement data due to cabling, coupling, unintentional changes in the positions of the test person, antennas, environment, etc., as presented in more details in [10], [13], and [14].

Electromagnetic simulation based channel modeling seems to overcome the several problems related to the use of measurement data and thus, it has gained a lot of interest in recent years. These channel modeling techniques can be categorized in full-wave and asymptotic solutions [7], [10]. In the full-wave solutions, the basic idea is to determine the channel characteristics accurately in the given scenario solving Maxwell's equations using numerical approaches.

In the WBAN context, the most commonly used full-wave numerical approaches are: Method of Moments (MoM), Finite Element Method (FEM), Finite-Difference Time-Domain (FDTD), and Finite Integration Technique (FIT). Asymptotic techniques, such as ray-tracing (RT) and Uniform Theory of Diffraction (UTD) are commonly used for larger environments or in high-frequency applications, in which full-wave solutions are too complex. The asymptotic technique can be used purely, or as a hybrid technique, i.e., in combination with a full-wave solution to obtain the optimal solution for propagation prediction in terms of accuracy, complexity and simulation time [7], [10].

The main contribution of this paper is to provide a general overview, including recent progress of the electromagnetic simulation based channel modeling techniques currently used in the WBAN channel modeling. Ray-tracing, UTD, MoM, FEM, FDTD, and FIT-based channel modeling techniques are considered and their advantages, disadvantages and the most appropriate applications are listed. Furthermore, comparative perspectives for these techniques are discussed. The aim is to aggregate information from different references to provide a comprehensive view on the topic, which could be helpful for the readers who are considering suitable channel modeling techniques for certain study cases. Detailed equations of each technique can be easily found from several references cited in the following chapters and thus, they are not repeated here. In the literature, there are only a few surveys related to simulation based channel modeling techniques, e.g. in [7] and [10]. However, our paper provides a wider review on several techniques for different WBAN communication links, including the newest references from the literature.

This paper is organized as follows: Section II describes the WBAN communication links. In Section III, simulation based channel modeling techniques are presented in the following order: *A*) Raytracing and UTD, *B*) MoM, *C*) FEM, *D*) FDTD, and *E*) FIT. In Subsection *F*, the hybrid techniques are presented. The comparison of the presented techniques is discussed in Section III. Section IV gives the summary and conclusions.

II. WBAN COMMUNICATIONS LINKS

The human body has a strong impact on the antenna performance and hence, on the channel characteristics. The shape and composition of the body, body motion, antenna placement, as well as the antenna-human body distance all strongly influence the propagation in the WBAN [7], [8], [16], [15].

WBAN communication links can be divided into three categories: on-body communications, off-body communications, and in-body communications. Figure 1 demonstrates the communication links, which are explained more in detail in the following subsections [7], [8].

A. ON-BODY COMMUNICATION

The on-body communication link covers the communication link between two nodes, both located on the surface of the body. It can be, for instance, a sensor collecting monitoring data, which is then send to the on-body device usually located on the wrist or waist [7]. In on-body communications, the impact of the human body on antenna properties is significant and hence, dominates the channel characterization. On-body channel modeling is the mostly studied communication link: there are numerous measurement, analytical or electromagnetic simulation based channel models presented in the literature, e.g., [7], [8], [17], [18].

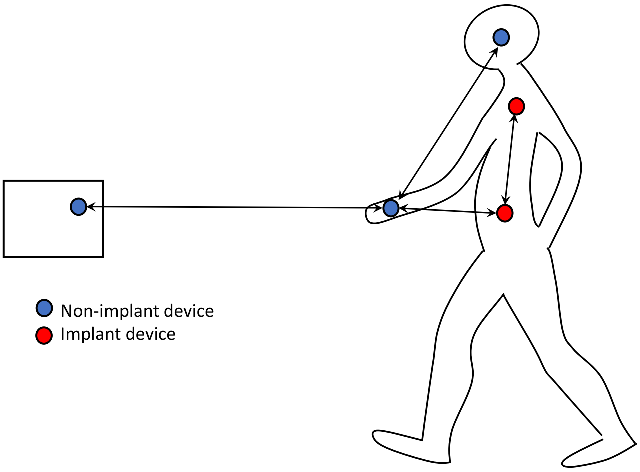

FIGURE 1. WBAN communication links.

B. OFF-BODY COMMUNICATION

The off-body communication link is related to the link between the on-body device and the external device, for instance the hospital room access point. This link is usually considered the easiest link to model since only one antenna is on the body. However, if the distance of the link is long, the computational complexity may become excessive with full-wave solutions [7], [8].

C. IN-BODY COMMUNICATION

The in-body communication link covers two links: the link between the medical implants inside the body (also referred to as in-in body communication in the literature) and the link between internal medical implants and the sensors attached to the body (in-on body communication link). Channel modeling for in-body communication has been under intensive study in recent years as the medical implant technology has increased rapidly [19]–[21].

III. SIMULATION BASED CHANNEL MODELING

A. RAY-TRACING AND UNIFORM GEOMETRICAL THEORY OF DIFFRACTION

Ray-tracing based techniques have been used to predict the channel propagation for years. These techniques are particularly applicable for site-specific prediction of radio channel characteristics and they have been widely used in both to indoor and outdoor radio propagation prediction. In these methods, propagating rays are traced while reflecting or diffracting from the objects. The reflection and diffraction coefficients depend on the geometrical and material properties of the surface [7], [22], [23]–[27].

Diffraction is the more challenging phenomenon to be predicted compared to the reflection, and thus, there is a wide variety of calculation methods for diffracted fields. Accuracy of the diffraction calculation was greatly improved with the development of geometric theory of diffraction (GTD) [28] and its improved version UTD [29], the latter being more popular in the WBAN channel modeling context [22].

Both ray-tracing and UTD have been commonly used in the propagation prediction in the environments with human bodies context for years. In [23], a model based on a dual image and ray-shooting approach considers the impact of multiple human bodies moving in an office at the 2.45 GHz frequency. In [25], a novel and efficient ray-tracing method is proposed for UWB propagation prediction. The basic idea is that UWB channel parameters can be accurately predicted by employing RT simulation carried out at different frequencies over the signal bandwidth. Since the RT algorithm is independent of frequency, calculation of the rays reaching a given location has to be conducted only once. The computational efficiency can be further improved using parallel ray approximation (PRA), introduced in [25] as well. In [30], the channel characteristics for an off-body communication link is evaluated using RT-based simulation data and measurement data, to which the Sage-Alternating Generalized Expectation-Maximization (SAGE) algorithm is applied. The measurements are conducted in a large meeting room using a phantom model wearing a body-worn antenna. The results show good agreement between the simulated and measurement data.

Nowadays, in the WBAN context, ray-tracing is commonly used as a hybrid technique, i.e., combined with other numerical methods to obtain the optimal solution for propagation prediction in terms of accuracy, complexity and simulation time. These studies are discussed in Section *F* in more detail.

As mentioned above, the UTD technique has been used widely in the propagation prediction of the WBAN communications applications during recent years. In [31], a UTD-based propagation prediction model is proposed to investigate the human body-scattering effects in the indoor channel. The human body is approximated with a perfect conducting circular cylinder and then combined with the ray-tracing technique to obtain channel characteristics of a particular indoor environment. Koutitas [32] propose a method using a modified slope UTD technique, which can be applied to accurately model scattering, radiation, coupling effects etc. The technique was investigated for the on-body propagation at 2.4 - 5 GHz and showed a good match with the measurement data [7], [33].

Recently, the UTD technique has gained strong interest when the higher frequency body-centric applications have been under an intensive scope. The human body is electrically large at millimeter-wave frequencies, and thus, the computational burden of the full-wave techniques is excessive. With UTD, the frequency does not impact on the memory resources, which makes it the most widely used technique for the propagation prediction on the V band (40 - 75 GHz) and W band (75 - 110 GHz) [10], [35].

In [35], numerical and experimental analysis of the on-body propagation around the human body is presented at 94 GHz. UTD is used as the propagation prediction method. The analysis of a body-centric environment at W band using the UTD has been investigated in [35].

There are several studies for the on- and off-body communication links on 60 GHz channels [36]–[39]. In the first studies, the human body was modeled by dielectric and perfectly conducting (PEC) cylinders, but later, human or animal body models were used in the simulations. In [36]–[38], the UTD technique is used for propagation prediction whereas in [39], channel characteristics are evaluated using ray-tracing. An extensive study on the propagation for body-centric communications at millimeter-wave frequencies is reviewed, e.g., in [10].

B. METHOD OF MOMENTS

MoM is a full-wave solution for Maxwell's equations in their integral form. The origin of the technique dates back to 1968 when Harrington proposed the ''weighted residuals'' technique [40]. MoM is the most suitable technique for modeling metallic structures, wires, etc. However, MoM is not effective with complex or inhomogeneous structures since the computational burden may grow excessive. Hence, its use in the body-centric scenarios is challenging though not impossible [7], [10].

MoM has been used for Specific Absorption Rate (SAR) evaluations for years [41], [42]. However, hybrid methods, e.g., MoM/FDTD or MoM/FEM are more commonly used techniques in the SAR studies than the purely MoM-based technique [43], [44]. Hybrid methods will be discussed in more details in Section *F*.

MoM has been used to study the body's effect on the characteristics of loop antennas, e.g., in [45]. In this study, the surface of the human body was replaced by a conducting reflector, which simplifies the computational burden significantly. In [46] and [47], the body-effect is evaluated using MoM and the coupled integral equations. Later, a Green's function approach [48], [49] and surface-based MoM approach [50] were introduced to analyze on-body antennas and radio channels. Furthermore, MoM is also used for modeling human bodies in crowds for the analysis of channel parameters in a WBAN application [51].

C. FINITE ELEMENT METHOD

The origin and the inventor of FEM is an open question since several researchers ended up with a similar approach independently. Actually, the method was develop to fill the need to solve complex elasticity and structural analysis problems in civil and aeronautical engineering in the early 1940s [52].

The basic idea of FEM is to divide the electromagnetic structures into a number of small elements, which can be either rectangular or triangular shaped. The elements are connected at points, which are common to two or more elements or boundary lines, so called nodes or nodal points. A set of algebraic equations is used to determine the nodal values of the field variables for each of the elements simultaneously [7], [52], [53].

FEM is well suited to modeling complex electromagnetic structures with curved and irregular boundaries, as well as different materials. FEM has several advantages. Since the size and form of the element can vary, FEM is remarkably flexible. It is very accurate even with geometrically complex structures. Due to the versatility of FEM, it is a commonly used method in different applications: in biomechanics, acoustics, heat transfer and, in general, in different fields of engineering, such as medical, mechanical, aerospace, and civil engineering. A major disadvantage of FEM is related to the computational complexity. The matrix solutions can be excessively time consuming and parallelization of the FEM code can be challenging in some cases [7].

FEM has been used for medical applications for years. Intensive research started in the early seventies, when FEM was introduced to the field of head biomechanics and also to implant dentistry [54], [55]. FEM is a commonly used method in medical imaging technology [56]–[59]. For instance, a virtual-training system for knee arthroscopic surgery is realized by FEM-based simulations [58].

In medical applications, FEM is mainly used at low MHz frequencies due to computer memory constraints. For instance in [60], eddy current effects on the human body were calculated using an FEM-based approach. FEM is also a commonly used method in the prediction of channel characteristics for in-body communications [61]–[63]. Furthermore, several WBAN antennas have been designed with FEM-based simulation software, e.g. ANSYS HFSS [64], as presented in [65]–[68].

D. FINITE DIFFERENCE TIME DOMAIN TECHNIQUE

FDTD is the most commonly used technique for the electromagnetic propagation prediction around the body. Similar to FEM, it requires the division of the EM structures into a set of small cells, and therefore it is suitable for modeling inhomogeneous media and complicated boundaries. FDTD is based on the iterative solution of the discretized Maxwell's equations in the time domain [7].

The FDTD technique was invented by Yee in 1966 [69]. Since then, several extensions and modifications have been proposed for FDTD for different purposes. The first body simulations date back to 1987 when the first SAR evaluations were performed using FDTD [70]. Since then, several FDTD-based SAR studies have been presented e.g in [71]–[73]. FDTD still is the most commonly used technique in SAR simulations [80]–[84]. In general, the impact of electromagnetic propagation on the human being has continuously been under intensive study and discussion [79]–[83].

The main advantage of FDTD is the simplicity of the algorithm; it is easy to implement. Mesh cells are homogenous, which means that they are easy to generate and handle. FDTD can also be parallelized, which is a major advantage in large electrical problems. FDTD is a well-known and intensively studied technique, for which exists an extensive literature with different modifications for different applications.

Like other numerical methods, FDTD also has some weaknesses. It requires the whole computational domain to be meshed into small cells, whose size should be small compared to the smallest wavelength used in the simulations. Another disadvantage is related to the use of homogeneous mesh cells: if one mesh cell can contain only one material, the number of mesh cells may become enormous in the complex models with several different materials. Thus, the computational burden may grow excessive, especially at higher frequencies.

Electromagnetic propagation around the human body was simulated for the first time using FDTD in [84]. It was shown that there is no direct transmission through the head. In that paper, the simulation results were further incorporated into a generic UWB channel model to get the channel characteristics for a certain environment. Since then, FDTD has been an intensively researched topic in body-centric channel modeling, both in static [85]–[87], later in dynamic scenarios [88]–[90]. In [13], simulation-based scenario-specific channel modeling for WBAN cooperative transmission schemes was proposed. The link properties, which are required for transmission scheme evaluation, were computed using FDTD for seven body motions. Miry *et al.* [91] proposed a bilateral dual-grid-FDTD technique, in which the overall simulation is split into three FDTD simulations, which are sequentially executed with an appropriate mesh. This technique was proved to be simple, but fast and accurate.

In large electrical problems, the number of mesh cells may grow excessively and thus, the simulation time may become unreasonably long. However, FDTD calculations can be parallelized, as proposed in [92]–[95].

In order to minimize the computational burden, several hybrid methods have been presented for FDTD. A dispersive FDTD and sub-band FDTD model for UWB channel modeling has been presented in [96]. These suboptimal methods are also compared with the ray-tracing technique. The Ray-tracing method was shown to be more efficient but less accurate. The Sub-band FDTD model has also been combined with the RT technique in [85]. In general, the combination of FDTD and ray-tracing has been shown to be efficient and useful [97], [98]. Extensive reviews of FDTD based techniques have been presented, e.g., in [7], [13], and [99].

Additionally, FDTD can also be used for in-body antenna design, as shown e.g. in [100]. It is also applicable for determining the channel characteristics for in-body communications [101]. For instance, it has been used for capsule endoscopy localization studies as described in several papers [101], [102], [102]–[104].

E. FINITE INTEGRATION TECHNIQUE

Originally, FIT was invented and published for the first time by Weiland in [105]. FIT provides a discrete reformulation of Maxwell's equations in their integral form. It enables simulation of real-world electromagnetic field problems with complex geometries, both in frequency and time domains [10].

The main advantage of FIT is the possibility to have two different materials within one grid cell, e.g. in FDTD, only one material is allowed within one grid cell. Due to this benefit, the mesh can be significantly sparser, and hence, less memory is required in FIT simulations, especially in objects with complex geometry. An extensive review for the different uses of FIT is presented in [106], which covers the research until 2000. Afterwards, no reviews have been published so far.

FIT has been a popular tool in the antenna design for years but previously it was considered to be too complex for larger models. However, with the advancements of computer resources, FIT has become a promising option for larger body-centric models as well. Nowadays, FIT is commonly used in WBAN antenna simulations for off-body communications [107], [108], on-body communications [109]–[113], and in-body communications [114]–[116].

Besides of antenna design, FIT has been used for modelling channel characteristics in different WBAN communication links for various applications. In [117], channel characteristics have been evaluated for on-body communications at 2.4 GHz and 5.8 GHz using measurements and FIT-simulations. Path loss models were determined by using measurement and simulated data.

In [118], the FIT-simulations were used to verify the validity of the first solid skin-equivalent phantom, which was developed to characterize the propagation channel for 60 GHz wireless body centric system. In [119], the impact of regular or electro textiles on the on-body propagation at 60 GHz is studied using FIT-based simulations and measurements. It was shown that regular textiles decrease path gain typically 2-5 dB, whereas the electro textiles increase the path gain by 5-15 dB. In [120], FIT has been used for modeling the impact of hair on SAR properties. It was shown that the form of the hair style has a strong impact on the SAR values. Especially spiky hair, i.e, high hair style, causes a number of additive reflections in the propagation and thus increases the overall SAR, especially at the bottom plane of the head.

Preliminary studies for the usability of FIT in the modeling of UWB WBAN on-off body communication link was presented in [14] and [121]. These studies were designed for anechoic chamber and the simulation results were compared to the measurement results. The bandwidth in the studies was 3 - 10 GHz. There was found to be an excellent match between the simulated and measured channel responses both in frequency and time domains. In [122], the usability of FIT was further enhanced for modelling WBAN communication links in complex environments by taken into account meshing, accuracy of simulation results, complexity, and simulation time.

Another option for off-body communication link evaluation is that the antenna's radiation patterns are calculated using FIT, and further, the propagation from the body to the external node is calculated using statistical model analysis [123], [124] or ray-tracing [125]. The hybrid-methods will be discussed in section F.

Applying FIT-based channel modeling to the performance evaluations of the concrete-surrounded use scenarios was presented for first time in [126]. The evaluated scenario was a system for monitoring the symptoms of Parkinson's disease presented in [127] and [128], in which the IEEE 802.15.6 based energy detector receiver is evaluated using the FIT-based channel modeling in the simulations.

Recently, FIT has gained strong interest as in-body channel modeling has become an intensively studied topic. FIT has been shown to be an efficient method for simulation-based in-body channel modeling, as shown, e.g., in [129]–[132]. FIT-based simulations are widely also used in different kinds of medical applications. For instance, in [133], the FIT-based simple simulation model was used to analyze aortic influence on the impedance cardiography signal and in [134], FIT was applied to numerical dosimetry.

F. HYBRID TECHNIQUES

The basic idea for using hybrid methods is to combine two numerical schemes with different properties and advantages to obtain the most efficient solution for the numerical problem. The most common approach for hybridization is to combine a rigorous numerical scheme (e.g., MoM, FDTD, FEM, FIT) with an asymptotic technique (e.g., ray-tracing, UTD) for structures involving both large and small objects. [97], [125], [135]–[138].

The combination of FDTD and ray-tracing has been shown to be efficient and suitable for different applications, as shown, e.g., in [97] and [98]. FEM-UTD combination is studied, e.g. in [135] and [136], to enhance calculation speed of electrically large antenna problems. The FIT-ray-tracing hybrid method has been evaluated e.g in [125] though it is seldom used in the body-centric communications.

Furthermore, hybridization techniques MoM/FDTD or MoM/FEM have been commonly used for SAR evaluations. In these cases, MoM is used for antenna evaluation and FDTD or FEM used for head impact evaluation [42], [43], [139]. Body absorption evaluations have also been conducted using the hybrid UTD/MoM technique [138], [139].

IV. COMPARISON OF THE TECHNIQUES

It is challenging to perform a fair comparison of the applicability of the different numerical methods for WBAN channel modeling due to many reasons. First, the channel characteristics are strongly influenced by the body model used in the simulations or the body shape of the volunteer in the measurements. Since different commercial simulators use different body models, the simulator whose body model happens to resemble best the person used as a volunteer in the measurements, may get better equivalence between the simulated and measured results, although the numerical method used in the simulation may not be the most accurate one.

TABLE 1. Summary of the main properties and applicability of the methods.

	In-body	On-body	Off-body	U/W band	Simulator	Main properties
Raytracing/UTD		x	x	x	REMCOM	- widely used for indoor and outdoor propagation prediction -best solution for higher frequency bands -asymptotic methods are significantly less complex than full-wave solutions
MoM		x			FEKO, CST	- best for metallic structures -design tool for several different antenna types - high computational complexity especially in inhomogeneous structures
FEM	x	x			ANSYSHFFS, CST	-flexible and versatile method for different medical applications -computational complexity excessive at higher frequencies and larger inhomogeneous structures
FDTD	x	x			REMCOM, EMPIRE	-efficient well-known technique for several applications - computational complexity may grow excessive with electrically large problems - several sub-optimal methods presented
FIT	x	x	x		CST	-most efficient in inhomogeneous structures -intensively used in WBAN studies recently
Hybrid		x	x	x	FEKO	-combine full-wave and asymptotic techniques to enhance calculation speed - less accurate than full-wave solutions

Different measurement based results are more comparable if commonly known physical body phantoms are used in the measurements instead of different test persons. The physical body phantoms are made from solid, liquid, or gel material, which are selected depending on the study case. Solid phantoms are commonly used in the SAR measurements on the body surface or in general in the study cases where the internal structure of the phantom has to be preserved. Liquid phantoms, which basically are containers filled with liquid having the same electrical characteristics as the tissues in the human body, are extensively used in the in-body SAR studies. Gel phantoms are most suitable for simulating high-water content materials, such as muscle and brain [7].

Furthermore, there are different kinds of electromagnetic body phantoms, i.e. the body models used in the simulations. Electromagnetic body models are categorized as theoretical phantoms or voxel phantoms. Theoretical phantoms are used for evaluating EM dosimetry or for confirmation of the validity of numerical simulation based results. Voxel phantoms are more detailed numerical phantoms which are composed of many voxels that describe anatomically the whole human body in detail. Voxel phantoms are needed for accurate SAR simulation, in-body simulations, etc. A comprehensive survey of the voxel models presented can be found in the literature, e.g. [7].

In the literature, different numerical methods are compared in some studies. Most of these comparisons are generic, i.e., not related only to WBAN applications. FDTD and FIT have been compared in [141], in which return loss of their proposed antenna is evaluated using both techniques. The simulation range was 0 - 10 GHz. It was shown that there is a good match between the results obtained from FDTD and FIT. The computational complexity, simulation time, etc issues were not considered in this paper.

In [142], FDTD and FIT have been evaluated for two different ground penetrating radar antennas at the frequencies 1.2 GHz and 1.5 GHz. Simulated responses were surprisingly similar and match well with the measured response.

In [143], FDTD, FEM and FIT have been used for on-body channel modeling at narrowband and UWB channels with different antennas. In this study, FDTD outperformed the other techniques when comparing the simulation results with the measurement results.

In [144], a brief review of the most commonly used computational electromagnetic interference modeling techniques is presented. The usability, capability, and limitations of each technique were outlined in principle, without simulation results. A slightly similar comparison has been done earlier in [145], which included more diverse numerical methods than in [144].

A comparison between FDTD and MoM is presented in [145]. It was shown that FDTD and MoM have the same order of accuracy, but with FDTD, the error accumulates over distance.

Comparing the computational complexity of different methods is another challenging. There exist studies of complexity analysis for FEM [149], FDTD, and MoM, [150]. The complexity order of FIT is considered to be similar to that of FEM. The complexities of UTD and raytracing are significantly less complex than the full-wave solutions [7]. However, the pure complexity order is not the only remarkable issue, since the efficiency of the calculation is also noteworthy. For instance, the calculation of the FDTD algorithm can be realized very efficiently especially with the sub-optimal solutions as discussed in Paragraph D in Chapter III. Thus, with simpler models, FDTD is more efficient than, for example, FIT. However, with the large inhomogeneous models, FIT is significantly more efficient than FDTD, since with FIT, the mesh is sparser due to the possibility of having two different materials in one mesh cell.

There are several commercial simulators providing different numerical methods for different simulation purposes. For instance CST [151], which is the most commonly used FIT-simulator in the WBAN applications, provides also MoM and FDTD methods. However, in that simulator, FDTD and MoM are targeted for different applications. Packages like FEKO [152] allow MoM, FDTD, FEM, GO, and UTD to be combined in various forms to solve problems. For instance, FEM might be used to model the head and MoM the exterior antenna problem. REMCOM [153] provides several numerical methods, from which one can choose the most suitable for the study case. EMPIRE [154] is an FDTD based simulator and HFSS AnSys [64] is a FEM-based simulator.

Table I summarizes the main properties and applications of these techniques providing the possibility to compare the techniques factually. The most commonly used commercial simulators are listed as well.

V. SUMMARY AND CONCLUSION

This paper presented a review including recent progress of the most commonly used numerical simulation based channel modeling techniques for body-centric communications. Main contributions of the ray-tracing, UTD, MoM, FEM, FDTD, and FIT-based channel modeling techniques have been considered and their advantages and disadvantages and most appropriate applications stated.

UTD has gained plenty of interest recently as the 60 GHz and 90 GHz applications have been under intensive research. It is clearly the most commonly used numerical method in the higher frequency simulation based channel modeling techniques. Ray-tracing is mostly used as a hybrid combination with some kind of full-wave solution, especially with FDTD or FEM.

The use of pure MoM has decreased as the simulation based channel modeling method in body-centric applications due to its excessive computational burden in larger models. However, it is commonly used as part of a hybrid technique. Pure MoM is still a commonly used method in the simulation of metallic structures.

FEM is a versatile method, which is used widely in the simulation based in- and on-body channel modeling. It is also suitable for off-body communication links if used as a hybrid method with ray-tracing. FEM is also commonly used in different medical imaging applications.

FDTD has been the most commonly used numerical method in WBAN context and is suitable especially for on-body and in-body communications. Additionally, it is suitable also for off-body communications if it is used as a hybrid method with, e.g., ray-tracing. Since FDTD is a well-known and long-used technique in this context, there exist several efficient solutions for FDTD calculations.

FIT has been known as an excellent method for antenna design and nowadays it has also been used for channel prediction for in-, on- and off-body communication links. FIT is appropriate especially for geometrically complex structures since one of the main characteristics of FIT is the possibility for inhomogeneous mesh cells. This feature may enable dramatic reduction in the number of mesh cells and hence in the computational complexity, compared for example to the FDTD technique.

In general it can be concluded that electromagnetic simulation based channel modeling has become a highly promising option for determining the channel characteristics needed in the optimized system design. By simulations, realistic channel characteristics can be obtained for different scenarios and environments cheaply, flexibly, and efficiently. The researcher only needs to select appropriate numerical method for the study case depending on the application and its requirements.

REFERENCES

[1] R. Cavallari, F. Martelli, R. Rosini, C. Buratti, and R. Verdone, "A survey on wireless body area networks: Technologies and design challenges," *IEEE Commun. Surveys Tuts.*, vol. 16, no. 3, pp. 1635–1657, 3rd Quart., 2014.

[2] M. Hämäläinen, J. Iinatti, and R. Kohno, "Wireless communications in healthcare—Recent and future topics," in *Proc. 4th Int. Symp. Appl. Sci. Biomed. Commun. Technol. (ISABEL)*, Oct. 2011, vol. 66, nos. 3–4, pp. 177–185.

[3] S. Ullah *et al.*, "A comprehensive survey of wireless body area networks," *J. Med. Syst.*, vol. 36, no. 3, pp. 1065–1094, 2012.

[4] B. Latre, B. Braem, I. Moerman, C. Blondia, and P. Demeester, "A survey on wireless body area networks," *J. Wireless Netw.*, vol. 17, no. 1, pp. 1–18, 2011.

[5] S. Movassaghi, M. Abolhasan, J. Lipman, D. Smith, and A. Jamalipour, "Wireless body area networks: A survey," *IEEE Commun. Surveys Tuts.*, vol. 16, no. 3, pp. 1658–1686, 3rd Quart., 2014.

[6] *IEEE Standard for Local and Metropolitan Area Networks—Part 15.6: Wireless Body Area Networks*, IEEE Standard 802.15.6-2012, IEEE Computer Society, New York, NY, USA, 2012.

[7] P. S. Hall and Y. Hao, *Antennas and Propagation for Body-Centric Wireless Communications*. Norwood, MA, USA: Artech House 2006.

[8] D. B. Smith and L. W. Hanlen, "Channel modeling for wireless body area networks," *Ultra-Low-Power Short-Range Radios*. Berlin, Germany: Springer, 2015, pp. 25–55.

[9] M. Hämäläinen, A. Taparugssanagorn, and J. Iinatti, "On the WBAN radio channel modelling for medical applications," in *Proc. Eur. Conf. Antennas Propag. (EUCAP)*, 2011, pp. 2967–2971.

[10] A. Pellegrini *et al.*, "Antennas and propagation for body-centric wireless communications at millimeter-wave frequencies: A review [wireless corner]," *IEEE Antennas Propag. Mag.*, vol. 55, no. 4, pp. 262–287, Aug. 2013.

[11] X. Lu, X. Chen, G. Sun, D. Jin, N. Ge, and L. Zeng, "UWB-based wireless body area networks channel modeling and performance evaluation," in *Proc. 7th Int. Wireless Commun. Mobile Comput. Conf. (IWCMC)*, 2011, pp. 1929–1934.

[12] H. Viittala, M. Hämäläinen, and J. Iinatti, "Different experimental WBAN channel models and IEEE802.15.6 models: Comparison and effects," in *Proc. 2nd Int. Symp. Appl. Sci. Biomed. Commun. Technol. (ISABEL)*, Nov. 2009, pp. 1–5.

[13] J.-I. Naganawa, K. Wangchuk, M. Kim, T. Aoyagi, and J.-I. Takada, "Simulation-based scenario-specific channel modeling for WBAN cooperative transmission schemes," *IEEE J. Biomed. Health Informat.*, vol. 19, no. 2, pp. 559–570, Mar. 2015.

[14] M. Särestöniemi, T. Tuovinen, M. Hämäläinen, K. Y. Yazdandoost, E. Kaivanto, and J. Iinatti, "Applicability of Finite Integration Technique for the modelling of UWB channel characterization," in *Proc. ISMICT*, San Diego, CA, USA, 2012, pp. 1–4.

[15] T. B. Welch *et al.*, "The effects of the human body on UWB signal propagation in an indoor environment," *IEEE J. Sel. Areas Commun.*, vol. 20, no. 9, pp. 1778–1782, Dec. 2002.

[16] T. Tuovinen, T. Kumpuniemi, K. Y. Yazdandoost, M. Hämäläinen, and J. Iinatti, "Effect of the antenna-human body distance on the antenna matching in UWB WBAN applications," in *Proc. 7th ISMICT*, 2013, pp. 193–197.

[17] T. Kumpuniemi, M. Hämäläinen, and J. Iinatti, "Human body shadowing effect on dynamic UWB on-body radio channels," *IEEE Antennas Wireless Propag. Lett.*, to be published, doi: 10.1109/LAWP.2017.2656246.

[18] T. Kumpuniemi, M. Hämäläinen, K. Yekeh Yazdandoost, and J. Iinatti, "Categorized UWB on-body radio channel modeling for WBANs," *Progr. Electromagn. Res. B*, vol. 67, pp. 1–16, 2016.

[19] M. Seyedi, B. Kibret, D. T. H. Lai, and M. Faulkner, "A survey on intrabody communications for body area network applications," *IEEE Trans. Biomed. Eng.*, vol. 60, no. 8, pp. 2067–2079, Aug. 2013.

[20] R. Chávez-Santiago *et al.*, "Propagation models for IEEE 802.15.6 standardization of implant communication in body area networks," *IEEE Commun. Mag.*, vol. 51, no. 8, pp. 80–87, Aug. 2013.

[21] R. M. Shubair and H. Elayan, "*In vivo* wireless body communications: State-of-the-art and future directions," in *Proc. Antennas Propag. Conf. (LAPC)*, Nov. 2015, pp. 1–5.

[22] Z. Yun and M. F. Iskander, "Ray tracing for radio propagation modeling: Principles and applications," *IEEE Access*, vol. 3, pp. 1089–1100, Jun. 2015.

[23] F. Villanese, W. G. Scanlon, N. E. Evans, and E. Gambi, "Hybrid image/ray-shooting UHF radio propagation predictor for populated indoor environments," *Electron. Lett.*, vol. 35, no. 21, pp. 1804–1805, Oct. 1999.

[24] D. N. Schettino, F. J. S. Moreira, and C. G. Rego, "Efficient ray tracing for radio channel characterization of urban scenarios," *IEEE Trans. Magn.*, vol. 43, no. 4, pp. 1305–1308, Apr. 2007.

[25] G. Tiberi, S. Bertini, W. Q. Malik, A. Monorchio, D. J. Edwards, and G. Manara, "Analysis of realistic ultrawideband indoor communication channels by using an efficient ray-tracing based method," *IEEE Trans. Antennas Propag.*, vol. 57, no. 3, pp. 777–785, Mar. 2009.

[26] Y. Zhang and A. K. Brown, "Ultra-wide bandwidth communication channel analysis using 3-D ray tracing," in *Proc. Int Symp. Wireless Commun. Syst.*, Sep. 2004, pp. 443–447.

[27] A. Corucci *et al.*, "A remotely distributed ray tracing for the analysis of electromagnetic propagation in complex indoor and outdoor environments," in *Proc. IEEE Int. Symp. APSURSI*, Jun. 2009, pp. 1–4.

[28] J. B. Keller, "Geometrical theory of diffraction," *J. Opt. Soc. Amer.*, vol. 52, no. 3, pp. 116–130, Feb. 1952.

[29] R. G. Kouyoumjian and P. H. Pathak, "A uniform geometrical theory of diffraction for an edge in a perfectly conducting surface," *Proc. IEEE*, vol. 62, no. 11, pp. 1448–1461, Nov. 1974.

[30] N. Amiot, M. Mhedhbi, B. Uguen, and R. Derrico, "WBAN off-body channel angular structure comparison between SAGE estimation and ray tracing simulation," in *Proc. 9th Eur. Conf. Antennas Propag. (EUCAP)*, 2015, pp. 1–5.

[31] M. Ghaddar, L. Talbi, and T. A. Denidni, "Human body modelling for prediction of effect of people on indoor propagation channel," *Electron. Lett.*, vol. 40, no. 25, pp. 1592–1594, Dec. 2004.

[32] G. Koutitas, "Multiple human effects in body area networks," *IEEE Antennas Wireless Propag. Lett.*, vol. 9, pp. 938–941, 2010.

[33] E. Plouhinec, B. Uguen, M. Mhedhbi, and S. Avrillon, "3D UTD modeling of a measured antenna disturbed by a dielectric circular cylinder in WBAN context," in *Proc. IEEE 79th Veh. Technol. Conf. (VTC Spring)*, May 2014, pp. 1–5.

[34] A. Pellegrini, A. Brizzi, L. Zhang, and Y. Hao, "Numerical and experimental analysis of the on-body propagation channel at W band," in *Proc. 6th Eur. Conf. Antennas Propag. (EUCAP)*, 2011, pp. 750–754.

[35] A. Pellegrini, A. Brizzi, L. Zhang, and Y. Hao, "Body-centric wireless communications at 94 GHz," in *Proc. Int. Symp. Antennas Propag.*, 2012, pp. 219–222.

[36] C. Constantinou, Y. Nechayev, X. Wu, and P. Hall, "Body-area propagation at 60 GHz," in *Proc. Loughborough Antennas Propag. Conf. (LAPC)*, 2012, pp. 1–4.

[37] S. Alipour, F. Parvaresh, H. Gajari, and F. K. Donald, "Propagation characteristics for a 60 GHz wireless body area network (WBAN)," in *Proc. Military Commun. Conf.*, 2010, pp. 719–723.

[38] T. Mavridis, L. Petrillo, J. Sarrazin, D. Lautru, A. Benlarbi-Delaï, and P. de Doncker, "Theoretical and experimental investigation of a 60-GHz off-body propagation model," *IEEE Trans. Antennas Propag.*, vol. 62, no. 1, pp. 393–402, Jan. 2014.

[39] P. Usai, A. Monorchio, A. Brizzi, A. Pellegrini, L. Zhang, and Y. Hao, "Analysis of on-body propagation at W band using ray tracing model and measurements," in *Proc. IEEE Int. Symp. Antennas Propag.*, Aug. 2012, pp. 1–2.

[40] R. F. Harrington, *Field Computation by Moment Methods*. New York, NY, USA: Macmillan, 1968.

[41] R. J. Spiegel, "A review of numerical models for predicting the energy deposition and resultant thermal response of humans exposed to electromagnetic fields," *IEEE Trans. Microw. Theory Techn.*, vol. MTT-32, no. 8, pp. 730–746, Aug. 1984.

[42] S. J. Priyadarshihi, "Impact of inverted F antenna on human head model," in *Proc. Int. Conf. Emerg. Trends Sci., Eng. Technol. (INCOSET)*, 2012, pp. 350–353.

[43] O. Kivekis, J. Ollikainen, T. Lehtiniemi, and P. Vainikainen, "Connection between the chassis length, bandwidth, efficiency, and SAR of internal handset antennas," in *Proc. IEEE Conf. Antennas Propag.*, Mar./Apr. 2003, pp. 735–738.

[44] J. Chakarothai, K. Wake, and S. Watanabe, "SAR assessment of a human body exposed to electromagnetic fields from a wireless power transfer system in 10 MHz band," in *Proc. 31st URSI General Assembly Sci. Symp.*, Aug. 2014, pp. 1–4.

[45] K. Ito, I. Ida, and M.-S. Wu, "Body effect on characteristics of small loop antenna in pager systems," in *Proc. IEEE Antennas Propag. Soc. Int. Symp.*, 1992, pp. 1081–1084.

[46] H.-R. Chuang and W.-T. Chen, "Computer simulation of the human-body effects on a circular-loop-wire antenna for radio-pager communications at 152, 280, and 400 MHz," *IEEE Trans. Veh. Technol.* vol. 46, no. 3, pp. 544–559, Aug. 1997.

[47] W.-T. Chen and H.-R. Chuang, "Numerical computation of the EM coupling between a circular loop antenna and a full-scale human-body model," *IEEE Trans. Microw. Theory Techn.*, vol. 46, no. 10, pp. 1516–1520, Oct. 1998.

[48] D. P. Chrissoulidis and J.-M. Laheurte, "Dyadic Green's function of a nonspherical model of the human torso," *IEEE Trans. Microw. Theory Techn.*, vol. 62, no. 6, pp. 1265–1274, Jun. 2014.

[49] F. Keshmiri and C. Craeye, "Moment-method analysis of normal-to-body antennas using a green's function approach," *IEEE Trans. Antennas Propag.*, vol. 60, no. 9, pp. 4259–4270, Sep. 2012.

[50] A. M. Eid and J. W. Wallace, "Accurate modeling of body area network channels using surface-based method of moments," *IEEE Trans. Antennas Propag.*, vol. 59, no. 8, pp. 3022–3030, Aug. 2011.

[51] D. I. Olcan, A. J. Krneta, and B. M. Kolundzija, "Modeling of human bodies for analysis of wireless body area networks in crowds," in *Proc. Int. Symp. Antennas Propag. Soc.*, 2014, pp. 406–407.

[52] *Introduction to Finite Element Analysis*, accessed on Jan. 2017. [Online]. Available: http://www.engr.uvic.ca/~mech410/lectures/FEA_Theory.pdf

[53] O. de Wick and I. Y. Kim. *Finite Element Method*, accessed on Jan. 2017. [Online]. Available: http://web.mit.edu/16.810/www/16.810_L4_CAE.pdf

[54] R. Ishikawa, K. Kato, M. Kubo, T. Uzuka, and H. Takahashi, "Finite element analysis and experimental study on mechanism of brain injury using brain model," in *Proc. IEEE EMB*, 2006, pp. 1327–1330.

[55] P. Konda and S. A. Tarannum, "Basic principles of finite element method and its applications in orthodontics," *J. Pharmaceutical Biomed. Sci.*, vol. 16, no. 16, pp. 1–8, 2012.

[56] A. Sitek, G. T. Gullberg, D. N. Ghosh, and E. V. R. DiBella, "Use of imaging data for modeling heart deformation by finite element methods," in *Proc. IEEE Nucl. Sci. Symp. Med. Imag. Conf. Rec.*, Oct. 1999, pp. 1566–1568.

[57] Y. Yang, P. Rahmanivahid, W. Xu, and A. D. Crocombe, "A finite element analysis and experimental study of human edentulous mandible," in *Proc. Biomed. Sci. Eng. Conf.*, 2011, pp. 1–3.

[58] P.-A. Heng *et al.*, "A virtual-reality training system for knee arthroscopic surgery," *IEEE Trans. Inf. Technol. Biomed.*, vol. 8, no. 2, pp. 217–227, Jun. 2004.

[59] J. Sotelo *et al.*, "3D quantification of wall shear stress and oscillatory shear index using a finite-element method in 3D CINE PC-MRI data of the thoracic aorta," *IEEE Trans. Med. Imag.*, vol. 35, no. 6, pp. 1475–1487, Jun. 2016.

[60] W. Renhart, C. A. Magele, and R. Stollberger, "Modelling and calculation of influences of RF-fields on the human body using the finite element method," *IEEE Trans. Magn.*, vol. 30, no. 5, pp. 3092–3095, Sep. 1994.

[61] R. Xu, H. Zhu, and J. Yuan, "Electric-field intrabody communication channel modeling with finite element method," *IEEE Trans. Biomed. Eng.*, vol. 58, no. 3, pp. 705–712, Mar. 2011.

[62] M. Amparo Callejon, J. Reina-Tosina, D. Naranjo-Hernandez, and L. M. Roa, "Galvanic coupling transmission in intrabody communication: A finite element approach," *IEEE Trans. Biomed. Eng.*, vol. 61, no. 3, pp. 775–783, Mar. 2014.

[63] Y. Song, K. Zhang, Q. Hao, L. Hu, J. Wang, and F. Shang, "A finite-element simulation of galvanic coupling intra-body communication based on the whole human body," *Sensors*, vol. 12, no. 10, pp. 13567–13582, Oct. 2012.

[64] *ANSYS HFFS: High Frequency Electromagnetic Field Simulation*, accessed on Jan. 2017. [Online]. Available: www.ansys.com/products/electronics/ansys-hfss

[65] K. Y. Yazdandoost and R. Miura, "Compact printed multiband antenna for M2M applications," in *Proc. 8th Eur. Conf. Antennas Propag. (EuCAP)*, Apr. 2014, pp. 2521–2524.

[66] K. Y. Yazdandoost and R. Miura, "Antenna polarization mismatch in BAN communications," in *Proc. IEEE MTT-S Int. Microw. Workshop Ser. RF Wireless Technol. Biomed. Healthcare Appl. (IMWS-BIO)*, Dec. 2013, pp. 1–3.

[67] H. Li, Y. Zhou, P. Han, L. Wang, X. Wen, and S. Zhang, "A CPW-fed 5.8 GHz wideband antenna applied on the human body," in *Proc. 4th Int. Conf. Intell. Syst., Modelling Simulation*, 2013, pp. 157–159.

[68] J. Tak, K. Kwon, S. Kim, and J. Choi, "Dual-band on-body repeater antenna for In-on-On WBAN applications," *Int. J. Antennas Propag.*, vol. 2013, Oct. 2013, Art. no. 107251.

[69] S. Yee, "Numerical solution of initial boundary value problems involving Maxwell's equations in isotropic media," *IEEE Trans. Antennas Propag.*, vol. 14, no. 3, pp. 302–307, May 1966.

[70] D. M. Sullivan, D. T. Borup, and O. P. Gandhi, "Use of the finite-difference time-domain method in calculating EM absorption in human tissues," *IEEE Trans. Biomed. Eng.*, vol. BME-34, no. 2, pp. 148–157, Feb. 1987.

[71] D. M. Sullivan, "Frequency-dependent FDTD methods using Z transforms," *IEEE Trans. Antennas Propag.*, vol. 40, no. 10, pp. 1223–1230, Oct. 1992.

[72] P. J. Dimbylow, "Finite-difference time-domain calculations of absorbed power in the ankle for 10–100 MHz plane wave exposure," *IEEE Trans. Biomed. Eng.*, vol. 38, no. 5, pp. 423–428, May 1991.

[73] K. Masumnia-Bisheh, M. Ghaffari-Miab, and B. Zakeri, "Evaluation of different approximations for correlation coefficients in stochastic FDTD to estimate SAR variance in a human head model," *IEEE Trans. Electromagn. Compat.*, vol. 59, no. 2, pp. 509–517, Apr. 2017.

[74] R. Takei, T. Nagaoka, K. Saito, S. Watanabe, and M. Takahashi, "SAR variation due to exposure from a smartphone held at various positions near the torso," *IEEE Trans. Electromagn.*, vol. 59, no. 2, pp. 747–753, Apr. 2017.

[75] J. Borges Ferreira, A. A. Almeida de Salles, and C. E. Fernández-Rodriguez, "SAR simulations of EMF exposure due to tablet operation close to the user's body," in *Proc. SMBO/IEEE MTT-S Int. Microw. Optoelectron. Conf.*, Nov. 2015, pp. 1–5.

[76] C. E. Fernández-Rodríguez, A. A. A. de Salles, and D. L. Davis, "Dosimetric simulations of brain absorption of mobile phone radiation—The relationship between psSAR and age," *IEEE Access*, vol. 3, pp. 2425–2430, 2015.

[77] B. B. Beard *et al.*, "Comparisons of computed mobile phone induced SAR in the SAM phantom to that in anatomically correct models of the human head," *IEEE Trans. Electromagn. Compat.*, vol. 48, no. 2, pp. 397–407, May 2006.

[78] A. Hadjem, E. Conil, A. Gati, M.-F. Wong, and J. Wiart, "Analysis of power absorbed by children's head as a result of new usages of mobile phone," *IEEE Trans. Electromagn. Compat.*, vol. 52, no. 4, pp. 812–819, Nov. 2010.

[79] B. Panchenko, E. Glotov, and M. Gizatullin, "Scattering and absorption of electromagnetic waves in inhomogeneous bodies," in *Proc. 1st Eur. Conf. Antennas Propag.*, 2006, pp. 1–5.

[80] J. Wnag, O. Fujiwara, S. Watanabe, and Y. Yamanaka, "Computation with a parallel FDTD system of human-body effect on electromagnetic absorption for portable telephones," *IEEE Trans. Microw. Theory Techn.*, vol. 52, no. 1, pp. 53–58, Jan. 2004.

[81] R. D. Morris, L. L. morgan, and D. Davis, "Children absorb higher doses of radio frequency electromagnetic radiation from mobile phones than adults," *IEEE Access*, vol. 3, pp. 2379–2387, 2015.

[82] O. P. Gandhi, "Yes the children are more exposed to radiofrequency energy from mobile telephones than adults," *IEEE Access*, vol. 3, pp. 985–988, 2015.

[83] K. R. Foster and C.-K. Chou, "Response to 'Children absorb higher doses of radio frequency electromagnetic radiation from mobile phones than adults' and 'yes the children are more exposed to radiofrequency energy from mobile telephones than adults,"' *IEEE Access*, vol. 4, pp. 5322–5326, 2016.

[84] A. Fort, C. Desset, J. Ryckaert, P. De Doncker, L. V. Biesen, and S. Donnay, "Ultra wide-band body area channel model," in *Proc. IEEE Int. Conf. Commun. (ICC)*, May 2005, vol. 4, pp. 2840–2844.

[85] Y. Zhao, Y. Hao, A. Alomainy, and C. Parini, "UWB on-body radio channel modeling using ray theory and subband FDTD method," *IEEE Trans. Microw. Theory Techn.*, vol. 54, no. 4, pp. 1827–1835, Jun. 2006.

[86] S. Dumanli and C. J. Railton, "On-body transmission at 5.2 GHz: Simulations using FDTD with a time domain huygens' technique," *IEEE Trans. Antennas Propag.*, vol. 59, no. 10, pp. 3910–3917, Oct. 2011.

[87] Q. Wang, T. Tayamachi, I. Kimura, and J. Wang, "An on-body channel model for UWB body area communications for various postures," *IEEE Trans. Antennas Propag.*, vol. 57, no. 4, pp. 991–998, Apr. 2009.

[88] T. Aoyagi, M. Kim, J. Takada, K. Hamaguchi, and R. Kohno, "Numerical simulations for wearable BAN propagation channel during various human movements," *IEICE Trans. Commun.*, vol. E94.B, no. 9, pp. 2496–2500, Sep. 2011.

[89] M. Gallo, P. S. Hall, Q. Bai, Y. I. Nechayev, C. C. Constantinou, and M. Bozzetti, "Simulation and measurement of dynamic on-body communication channels," *IEEE Trans. Antennas Propag.*, vol. 59, no. 2, pp. 623–630, Feb. 2011.

[90] T. Uusitupa and T. Aoyagi, "Analysis of dynamic on-body communication channels for various movements and polarization schemes at 2.45 GHz," *IEEE Trans. Antennas Propag.*, vol. 61, no. 12, pp. 6168–6179, Dec. 2013.

[91] C. Miry, R. Loison, and R. Gillard, "An efficient bilateral dual-grid-FDTD approach applied to on-body transmission analysis and specific absorption rate computation," *IEEE Trans. Microw. Theory Techn.*, vol. 58, no. 9, pp. 2418–2428, Sep. 2010.

[92] T. Uusitupa, "Parallel FDTD simulations for WBAN channel characterization using different body models," in *Proc. 6th Eur. Conf. Antennas Propag. (EUCAP)*, Mar. 2012, pp. 520–524.

[93] H. Hoteit, R. Sauleau, B. Philippe, P. Coquet, and J.-P. Daniel, "Vector and parallel implementations for the FDTD analysis of millimeter wave planar antennas," *Int. J. High Speed Comput.*, vol. 10, no. 2, pp. 209–234, 1999.

[94] A. Sani, Y. Hao, Y. Zhao, A. Alomainy, and C. Parini, "An efficient FDTD an efficient FDTD algorithm based on the equivalence principle for analyzing onbody antenna performance," *IEEE Trans. Antennas Propag.*, vol. 57, no. 4, pp. 1006–1014, Apr. 2009.

[95] Q. H. Abbasi, A. Sani, A. Alomainy, and Y. Hao, "On-body radio channel characterization and system-level modeling for multiband OFDM ultra-wideband body-centric wireless network," *IEEE Trans. Microw. Theory Techn.*, vol. 58, no. 12, pp. 3485–3492, Dec. 2010.

[96] Y. Zhao, Y. Hao, and C. Parini, "Two novel FDTD based UWB indoor propagation models," in *Proc. IEEE Int. Conf. Ultra-Wideband (ICU)*, Zurich, Switzerland, Sep. 2005, pp. 124–129.

[97] M. Porebrska, T. Kayser, and W. Wiesbeck, "Verification of a hybrid ray-tracing/FDTD model for indoor ultra-wideband channels," in *Proc. Eur. Conf. Wireless Technol.*, Nov. 2007, pp. 169–172.

[98] Y. Wang, S. Safavi-Naeini, and S. K. Chaudhuri, "A hybrid technique based on combining ray tracing and FDTD methods for site-specific modeling of indoor radio wave propagation," *IEEE Trans. Antennas Propag.*, vol. 48, no. 5, pp. 743–754, May 2000.

[99] J. B. Schenider and K. L. Shlager, "FDTD simulations of TEM horns and the implications for staircased representations," *IEEE Trans. Antennas Propag.*, vol. 45, no. 12, pp. 1830–1838, Dec. 1997.

[100] W. G. Scanlon, "Analysis of tissue-coupled antennas for UHF intra-body communications," in *Proc. 12th Int. Conf. Antennas Propag.*, vol. 2. Mar./Apr. 2003, pp. 747–750.

[101] V. De Santis and M. Feliziani, "Intra-body channel characterization of medical implant devices," in *Proc. 10th Int. Symp. Electromagn. Compat. (EMC Europe)*, York, U.K., Sep. 2011, pp. 816–819.

[102] P. Swar, K. Pahlavan, and U. Khan, "Accuracy of localization system inside human body using a fast FDTD simulation technique," in *Proc. 6th Int. Symp. Med. Inf. Commun. Technol. (ISMICT)*, 2012, pp. 1–6.

[103] U. I. Khan, K. Pahlavan, and S. Makarov, "Comparison of TOA and RSS based techniques for RF localization inside human tissue," in *Proc. Annu. Int. Conf. IEEE Eng. Med. Biol. Soc. (EMBC)*, Aug./Sep. 2011, pp. 5602–5607.

[104] S. Mohan, A. Boddupulli, D. Hossain, F. Gozasht, and S. S. H. Ling, "Techniques for RF localization of wireless capsule endoscopy," in *Proc. Int. Conf. Electromagn. Adv. Appl. (ICEAA)*, 2016, pp. 856–859.

[105] T. Weiland, "A discretization model for the solution of Maxwell's equations for six-component fields," *Arch. Elektronik Uebertragungstechnik*, vol. 31, pp. 116–120, Mar. 1977.

[106] R. Marklein, "The finite integration technique as a general tool to compute acoustic, electromagnetic, elastodynamic, and coupled wave fields," *Rev. Radio Sci.*, pp. 201–204, 2002.

[107] P. B. Samal, P. J. Soh, and G. A. E. Vandenbosch, "UWB all-textile antenna with full ground plane for off-body WBAN communications," *IEEE Trans. Antennas Propag.*, vol. 62, no. 1, pp. 102–108, Jan. 2014.

[108] L. A. Y. Poffelie, P. J. Soh, S. Yan, and G. A. E. Vandenbosch, "A high-fidelity all-textile UWB antenna with low back radiation for off-body WBAN applications," *IEEE Trans. Antennas Propag.*, vol. 64, no. 2, pp. 757–760, Feb. 2016.

[109] N. Chahat, M. Zhadobov, R. Sauleau, and K. Ito, "A compact UWB antenna for on-body applications," *IEEE Trans. Antennas Propag.*, vol. 59, no. 4, pp. 1123–1131, Apr. 2011.

[110] T. S. P. See, T. M. Chiam, M. C. K. Ho, and M. R. Yuce, "Experimental study on the dependence of antenna type and polarization on the link reliability in on-body UWB systems," *IEEE Trans. Antennas Propag.*, vol. 60, no. 11, pp. 5373–5380, Nov. 2012.

[111] T. Tuovinen, M. Berg, K. Y. Yazdandoost, and J. Iinatti, "Ultra wideband loop antenna on contact with human body tissues," *IET Microw., Antennas Propag.*, vol. 7, no. 7, pp. 588–596, May 2015.

[112] T. Tuovinen, M. Berg, E. Salonen, M. Hämäläinen, and J. Iinatti, "Conductive layer under a wearable UWB antenna: Trade-off between absorption and mismatch losses," in *Proc. 8th Int. Symp. Med. Inf. Commun. Technol.*, Florence, Italy, Apr. 2014, pp. 1–5.

[113] X. Y. Wu, L. Akhoondzadeh-Asl, Z. P. Wang, and P. S. Hall, "Novel Yagi-Uda antennas for on-body communication at 60 GHz," in *Proc. Loughborough Antennas Propag. Conf.*, 2010, pp. 153–156.

[114] R. Alrawashdeh, Y. Huang, A. A. B. Sajak, L. Xing, and M. Kod, "Orientation effect of flexible implantable antennas on performance," in *Proc. Int. Symp. Antennas Propag. (APSURSI)*, 2014, pp. 973–974.

[115] M. A. S. Tajin, M. Ahmed, and P. K. Saha, "Performance analysis of an ultra wideband antenna for wireless capsule endoscopy," in *Proc. Int. Conf. Med. Eng., Health Inform. Technol. (MediTec)*, 2016, pp. 1–4.

[116] J. Faerber and M. P. Y. Desmulliez, "Conformal meander shaped antenna for biotelemetry in endoscopic capsules," in *Proc. LAPC*, 2015, pp. 1–4.

[117] A. R. Guraliuc, A. A. Serra, P. Nepa, and G. Manara, "Channel model for on body communication along and around the human torso at 2.4 GHz and 5.8 GHz," in *Proc. Int. Workshop Antenna Technol. (iWAT)*, Mar. 2010, pp. 1–4.

[118] A. R. Guraliuc, M. Zhadobov, O. De Sagazan, and R. Sauleau, "Solid phantom for body-centric propagation measurements at 60 GHz," *IEEE Trans. Microw. Theory Techn.*, vol. 62, no. 6, pp. 1373–1380, Jun. 2004.

[119] A. R. Guraliuc, M. Zhadobov, G. Valerio, R. Sauleau, and N. Chahat, "On-body propagation at 60 GHz: Impact of a textile presence," in *Proc. Int. Symp. IEEE Antennas Propag. Soc. (APSURSI)*, Jul. 2014, pp. 715–716.

[120] A. Harmouch, N. Ghazi, R. Barake, M. Kenaan, and M. Ziade, "Impact of human hair configuration on the human head absorption rate," in *Proc. Int. Conf. Adv. Biomed. Eng. (ICABME)*, Sep. 2015, pp. 201–204.

[121] M. Särestöniemi, T. Tuovinen, M. Hämäläinen, K. Y. Yazdandoost, and J. Iinatti, "Channel modeling for UWB WBAN on-off body communication link with finite integration technique," in *Proc. 7th Int. Conf. Body Area Netw. (BodyNets)*, Oslo, Norway, 2012, pp. 235–241.

[122] M. Särestöniemi, T. Tuovinen, M. Hämäläinen, and J. Iinatti, "Finite integration technique for modelling of WBAN communication links in complex environments," in *Proc. 7th ISMICT*, Tokyo, Japan, 2013, pp. 154–158.

[123] M. Mackowiak and L. M. Correia, "Towards a radio channel model for off-body communications in a multipath environment," in *Proc. 18th Eur. Wireless Conf. (EW)*, Poznań, Poland, Apr. 2012, pp. 1–7.

[124] S. J. Ambroziak *et al.*, "An off-body channel model for body area networks in indoor environments," *IEEE Trans. Antennas Propag.*, vol. 64, no. 9, pp. 4022–4035, Sep. 2016.

[125] A. Skarlatos, R. Schuhmann, and T. Weiland, "Coupling of finite integration technique and ray tracing," in *Proc. IEEE Antennas Propag. Soc. Int. Symp.*, vol. 4. Jul. 2001, pp. 318–321.

[126] M. Särestöniemi, T. Tuovinen, V. Niemelä, M. Hämäläinen, and J. Iinatti, "Finite integration technique based channel modeling on the WBAN receiver performance evaluation," in *Proc. 11th ISMICT*, Lisbon, Portugal, Feb. 2017, pp. 39–43.

[127] N. Keränen *et al.*, "IEEE802.15.6-based multi-accelerometer WBAN system for monitoring Parkinson's disease," in *Proc. 35th Annu. Int. Conf. IEEE Eng. Med. Biol. Soc. (EMBC)*, Osaka, Japan, Jul. 2013, pp. 1656–1659.

[128] M. Särestöniemi *et al.*, "Receiver performance evaluation on IEEE 802.15.6 based WBAN for monitoring Parkinson's disease," in *Proc. 8th ISMICT*, Florence, Italy, 2014, pp. 1–5.

[129] S. Gutschling and T. Weiland, "Simulation of electromagnetic fields inside the human body using the finite integration technique," in *Proc. Symp. Antenna Technol. Appl. Electromagn.*, 1996, pp. 451–454.

[130] A. Khaleghi, R. Chávez-Santiago, X. Liang, I. Balasingham, V. C. M. Leung, and T. A. Ramstad, "On ultra wideband channel modeling for in-body communications," in *Proc. 5th IEEE Int. Symp. Wireless Pervas. Comput. (ISWPC)*, May 2010, pp. 140–145.

[131] S. Støa, R. Chávez-Santiago, and I. Balasingham, "An ultra wideband communication channel model for capsule endoscopy," in *Proc. Int. Symp. Appl. Sciences Biomed. Commun. Technol. (ISABEL)*, Rome, Italy, 2010, pp. 1–5.

[132] K. M. S. Thotahewa, J.-M. Redoutè, and M. R. Yuce, "Propagation, power absorption, and temperature analysis of UWB wireless capsule endoscopy devices operating in the human body," *IEEE Trans. Microw. Theory Techn.*, vol. 63, no. 11, pp. 3823–3833, Nov. 2015.

[133] M. Ulbrich, A. Schauermann, and S. Leonhardt, "Analysis of the aortic influence on the impedance cardiography signal by a simple model using finite integration technique," *SNE Simul. Notes Eur. SNE*, vol. 20, no. 2, pp. 51–54, 2010, doi: 10.11128/sne.20.sn.0997.

[134] A. Laisne and J. Drouet, "Comparison of finite integration technique (FIT) and transmission line matrix (TLM) for numerical dosimetry in HF/VHF band," in *Proc. Int. Symp. Electromagn. Compat.*, 2013, pp. 659–664.

[135] R. Fernández-Recio, L. E. García-Castillo, I. Gómez-Revuelto, and M. Salazar-Palma, "Fully coupled hybrid FEM-UTD method using NURBS for the analysis of radiation problems," *IEEE Trans. Antennas Propag.*, vol. 56, no. 3, pp. 774–783, Mar. 2008.

[136] D.-H. Han, A. C. Polycarpou, and C. A. Balanis, "FEM-based hybrid methods for the analysis of antennas on electrically large structures," in *Proc. IEEE Radio Wireless Conf.*, Sep. 2000, pp. 59–61.

[137] P. Bernardi, M. Cavagnaro, R. Cicchetti, S. Pisa, E. Piuzzi, and O. Testa, "A UTD/FDTD investigation on procedures to assess compliance of cellular base-station antennas with human-exposure limits in a realistic urban environment," *IEEE Trans. Microw. Theory Techn.*, vol. 51, no. 12, pp. 2409–2417, Dec. 2003.

[138] O. Aydin CiVi, P. H. Pathak, and H.-T. Chou, "An efficient hybrid UTD-MoM analysis of radiation/scattering from large truncated periodic arrays," in *Proc. IEEE Antennas Propag. Soc. Int. Symp.*, vol. 2. Jun. 1998, pp. 748–751.

[139] C. Ullrich, K. F. Warnick, and P. Russer, "Radiation from a monopole antenna in an aperture backed by an absorbing body using a hybrid MoM/UTD approach," in *Proc. IEEE Antennas Propag. Soc. Int. Symp.*, Jul. 2008, pp. 1–4.

[140] F. J. C. Meyer, D. B. Davidson, U. Jakobus, and M. A. Stuchly, "Human exposure assessment in the near field of GSM base-station antennas using a hybrid finite element/method of moments technique," *IEEE Trans. Biomed. Eng.*, vol. 50, no. 2, pp. 224–233, Feb. 2003.

[141] V. Dhoot and S. Gupta, "Return loss validation of a novel cantor based antenna using FIT and FDTD," in *Proc. Int. Conf. Commun. Signal Process.*, 2011, pp. 374–378.

[142] C. Warren, L. Pajewski, A. Ventura, and A. Giannopoulos, "An evaluation of finite-difference and finite-integration time-domain modelling tools for ground penetrating radar antennas," in *Proc. EUCAP*, 2016, pp. 1–5.

[143] Y. Hao, A. Alomainy, P. S. Hall, Y. I. Nechayec, C. G. Parini, and C. C. Constantinou, "Antennas and propagation for body centric wireless communications," in *Proc. Int. Conf. Wireless Commun. Appl. Comput. Electromagn.*, Apr. 2005, pp. 586–589.

[144] V. Jithesh and D. C. Pande, "A review on computational EMI modelling techniques," in *Proc. 8th Int. Conf. Electromagn. Interference Compat.*, 2003, pp. 159–166.

[145] P. R. Foster, "Computer modelling of antennas: A comparison of available techniques," in *Proc. 8th Int. Conf. Antennas Propag.*, 1993, pp. 755–760.

[146] K. F. Warnick, "An intuitive error analysis for FDTD and comparison to MoM," *IEEE Antennas Propag. Mag.*, vol. 47, no. 6, pp. 111–115, Dec. 2005.

[147] G. Noetscher, S. N. Makarov, and N. Clow, "Modeling accuracy and features of body-area networks with out-of-body antennas at 402 MHz," *IEEE Antennas Propag. Mag.*, vol. 53, no. 4, pp. 118–143, Aug. 2011.

[148] P. N. Zakharov, E. V. Mikhailov, A. A. Potapov, A. F. Korolev, and A. P. Sukhorukov, "Comparative Analysis of Ray tracing, finite integration technique and empirical models using ultra-detailed indoor environment model and measurements," in *Proc. 3rd IEEE Int. Symp. Microw. Antenna Propag. EMC Technol. Wireless Commun.*, Oct. 2009, pp. 169–176.

[149] I. Farmaga, P. Shmigelskyi, P. Spiewak, and L. Ciupinski, "Evaluation of computational complexity of finite element analysis," in *Proc. 11th Int. Conf. Exper. Designing Appl. CAD Syst. Microelectron. (CADSM)*, 2011, pp. 213–214.

[150] I. Rasheed *et al.*, "Fast numerical techniques based analysis of electromagnetic problems using MATLAB," in *Proc. 12th Int. Conf. Frontiers Inf. Technol.*, 2014, pp. 115–120.

[151] *CST Microwave Studio*, accessed on Sep. 2017. [Online]. Available: http://www.cst.com

[152] *FEKO—EM Simulation Software*, accessed on Jan. 2017. [Online]. [Online]. Available: www.feko.info.

[153] *REMCOM Electromagnetic Simulation Software & EM Modeling*, accessed on Sep. 2017. [Online]. Available: www.remcom.com

[154] *EMPIRE XPU, FDTD Simulation Software*, accessed on Sep. 2017. [Online]. Available: www.empire.de

MARIELLA SÄRESTÖNIEMI received the M.Sc. and Lic.Tech degrees from the University of Oulu, Oulu, Finland, in 2003 and 2005, respectively, where she is currently pursuing the Ph.D. degree with the Center for Wireless Communications. Her research interests include medical ICT, wireless body-area networks, and simulation-based channel modeling and measurements.

MATTI HÄMÄLÄINEN (SM'09) received the M.Sc., Lic.Tech., and Dr.Sc. degrees from the University of Oulu, Oulu, Finland, in 1994, 2002, and 2006, respectively. He is currently an Adjunct Professor and a University Researcher with the Center for Wireless Communications, University of Oulu, and an IAS Visiting Professor with Yokohama National University, Japan. He has published over 150 scientific publications. He is a co-editor of one book and a co-author of one book and two book chapters. His research interests include ultrawideband systems, radio channel modeling, wireless body-area networks, and medical ICT. He is a member of the European Telecommunications Standard Institute Smart Body Area Network Group. He served as a Reviewer for IEEE and IET journals and as Technical Program Committee Member for numerous IEEE conferences.

JARI IINATTI (SM'05) received the M.Sc., Lic.Tech., and Dr.Tech. degrees in electrical engineering from the University of Oulu, Oulu, Finland, in 1989, 1993, and 1997, respectively. From 1989 to 1997, he was a Research Scientist with the Telecommunication Laboratory, University of Oulu. From 1997 to 2002, he was an acting Professor of Digital Transmission Techniques, and a Senior Research Scientist, the Project Manager, and the Research Director with the Center for Wireless Communications, University of Oulu, where, since 2002, he has been a Professor of Telecommunication Theory. He is currently the Head of the Center for Wireless Communcations-Networks and Systems. He has supervised 13 doctoral theses and over 60 master's theses. He has authored over 200 international journal and conference papers, holds six patents, and is a co-editor of the book *UWB: Theory and Applications* (Chichester, U.K.: Wiley & Sons, Ltd., 2004). His research interests include future wireless communications systems, transceiver algorithms, wireless body area networks, and medical ICT. He has been a Technical Program Committee Member in about 25 conferences. He was a TPC Co-Chair of the IEEE PIMRC2006, BodyNets2012, and PIMRC2014, a TPC Chair of the ISMICT2007, a General Co-Chair of the ISMICT2011, ISMICT2014, and ISMICT2015, and a TPC Program Track Co-Chair of the BodyNets 2012. He was also an Organizer of the FEELIT 2008, the FEELIT2011, the UWBAN2012, and the UWBAN2013. He is Steering Committee Co-Chair of the ISMICT series.

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