# Analysis of Measurement Techniques Used in Channel Characterization of UWB Wireless Body Area Networks

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Keywords: Wireless Body Area Networks, Channel Modelling, Internet of Things, Ultra-Wide Band, Propagation, Antennas.

Abstract: The Wireless Body Area Networks (WBAN) has evolved over the past two decades, making a significant impact on the communication sector, specifically the Internet of Things (IoT) domain, giving new directions to health monitoring, wellness and assisted living, entertainment, and many more. WBANs are networks of interconnected devices which are worn, implanted, swallowed, or embedded i.e., in, on and around human body. As a propagation medium, the human body is complex to study because of its partially conductive nature and heterogeneous dielectric properties, which makes it a major challenge to characterize its behavior as a communication channel in the WBAN environment. Further body movements, curvatures and characteristics of the surrounding environment add further to its complexity. In the last two decades, different properties of communication channels for radio links used in WBAN have been studied by researchers. The major challenge for the WBAN is modelling the propagation channels of the radio links for the development of more accurate and efficient systems. In this research, measurement is a key issue as it helps to quantify the physical properties of available human body communication channels. Authors have used different methods like experimentation, numerical techniques and statistical methods for characterizing and evaluation of on and off-human body radio channels. In this paper, various measurement techniques used by the authors over the last two decades for characterizing Human Body Channels have been analyzed and discussed their evolution along with the issues, challenges and future research trends.

## 1 INTRODUCTION

A wireless network of sensor devices that are either wearable, implanted, or carried over the human body at different locations is referred to as a wireless body area network (WBAN). WBAN development began around the mid 90s due to its potential use in the area of wireless personal area network (WPAN) technologies. The main driving force behind WBAN development is mainly due to the growing demand for remote, efficient healthcare systems that are focused on prevention and early risk detection of fatal diseases which are normally diagnosed after people start experiencing the symptoms (Zasowski, Althaus, et al. , 2003). Moreover, the increasing demand for low-cost assisted living solutions for the increasing population of elderly people remains another driver. WBANs are basically developing as a more advanced and separate addition to wireless communication in general. As a wireless communication system, its basic operating characteristics remain the same as any other wireless system, but it has many additional features and specific problems that need to be addressed separately from other wireless communication systems. Significant variations observed in the WBAN radio channels are due to scattering and dispersive effects along with changes in the geometry of the human body. Moreover, the human body is also subjected to many types of movements, right from breathing to larger movements during vigorous activity like sports. This results in significant degradation of WBAN radio channel behavior. Thus, accurate characterization and modelling of the communication channels, both in static and dynamic conditions, is the key issue in the WBANs, as it not only affects system performance but also the reliability of the system. Apart from this, WBAN radio channel link quality also gets affected due to changed radiation characteristics of the antenna when located in proximity to the human body. Hence, these issues have to be well understood and explored while designing wireless



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communication systems for WBAN, allowing reliability, maximum channel throughput, and energy efficiency. Over the last two decades, different authors have used different methods for measurement, data processing, and parameter extraction for evaluation and characterizing on- and off-body Ultra-Wide Band (UWB) communication channel models.

# 2 MEASUREMENT TECHNIQUES

Presently most of the engineering research is dedicated to the development of various applications in IoT domains. Advances in microelectronics fabrication technologies moving from micro to nanoscale, along with inexpensive signal processing systems, cloud computing are already aiding it. Because of the advances in IoT, further research is dedicated to the development of personalised healthcare services for individuals and patients. In healthcare research, the factors like accuracy, sensing unreliability, and standardisations are of utmost importance due to underlying reasons. Wrong results due to erroneous measurements can affect the efficiency and reliability of the system under development. Many factors, like sensors, measurement equipment, and data processing techniques used, contribute to actual research in the development of these systems. The key area of research in the development of personal healthcare monitoring and assisted living is the development of more accurate WBAN channel models. Measurement is basically a quantitative comparison between the known and unknown quantity. It helps to quantify the physical properties of the available WBAN communication channels. The data obtained with this can be further processed with different statistical and numerical techniques for more accurate modelling of WBAN channels. The following diagram gives the information about different measurement techniques used by researchers for characterisation of WBAN channels.

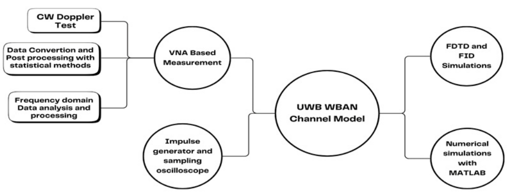


Figure1: Various methods used for development of UWB-WBAN channel Models.

The Methods used by the researchers in development of Channel Models for UWB WBAN networks can be mainly categorized as:

1) Measurements using Vector Network Analyzer and post-processing.
2) Measurements using Impulse generator and Sampling oscilloscope.
3) Simulation study:
   a) Finite integration technique (FIT) and Finite Difference Time Domain (FDTD) techniques with
      i) Heterogeneous voxel-based phantoms.
      ii) Homogeneous Layered phantoms.
   b) Numerical Simulations with MATLAB.

These methods are discussed in detail in the following sections.

## 2.1 Vector Network Analyser Measurements

Vector Network Analyzer, more popularly known as VNA, is a very important test and measurement instrument used in the design and development of RF and high-frequency systems. VNAs are mainly used in processes for accurate measurements at high frequencies and validation of simulation results. It basically measures network parameters of electrical networks and is hence named a Vector Network Analyzer (VNA). Key specifications of it include frequency range, dynamic range, measurement speed, and trace noise. It measures scattering parameters, giving information about transmission and reflection coefficients of devices under test (DUT). i.e. $S_{11}$ and $S_{21}$ parameters, and after reversing the DUT, one can measure $S_{22}$ and $S_{12}$ also. There are several calibration standards that can be used in user calibration, which are short, open, load, and SOLT. It has a built-in source and receiver also.

This method is a very popular method among the researchers working on the development of channel models for UWB WBAN channel characterization, and most of the literature published uses this method. After an extensive survey of the published literature, it is found that there are different techniques that are used by the authors for the characterization of channel models. The mostly used technique is after obtaining the $S_{21}$ data from the measurement campaigns, which is in the frequency domain, converting it into the time domain using the inverse Fourier transform (IFT).

(Zasowski, Althaus, et al. , 2003), Thomas Zosovoski et al. obtained an impulse response using inverse Fourier transform for the frequency range of 3-6 GHz, and then from this impulse response, parameters like mean delay spread and path loss are extracted. The similar approach is used for the different scenarios for channel characterization in both line of sight (LOS) and non line of sight (NLOS) environments. In (Yamamoto and Kobayashi, 2009), authors examined the effect of the size of rooms on the channel properties using parameters like cumulative distribution function (CDF), root mean square delay, and spatial distributions. In (Chen, Lu, et al. , 2011), authors used a Hamming window for sideband reduction, and a complex baseband inverse Fourier transform is used for obtaining the impulse response. Parameters like path loss and power delay profile are used, and a study was carried out in an anechoic chamber for different body types and 10 sitting positions. Here, 1001 frequency points are used with full 2-port calibration. In (Särestüniemi, Tuovinen, et al. , 2013), (Säreströniemi, Tuovinen, et al. , 2012), authors did analysis in both time and frequency domains. $S_{21}$ data obtained from VNA is transformed into impulse response using inverse fast Fourier transform (IFFT) and compared with simulated results obtained using the FIT technique. The results obtained were in good agreement, validating the applicability of FIT in analysis, which is similar to the FDTD method but uses the integral form of Maxwell's equations to solve them in a given scenario. In (Chen, Ye, et al. , 2012), authors have used the inverse chirp Z-transform for converting to the time domain, and the parameters used are time of arrival, distance measurement error, received signal strength, and total path loss. Total frequency points are 1601; over 3-10 GHz, transmitter power used is 0 dBm. study focused on angle-based channel models. In (Kumpuniemi, Tuovinen, et al. , 2013), authors used IFFT to transform $S_{21}$ to time domain frequency 2-8 GHz, using 4 test ports, 1601 test points, and 100 sweeps, with an IF bandwidth of 100 MHz and transmitter power of +10 dBm. Main emphasis on the effect of different types of antennas, distance error for large-scale path loss parameters, and detection of all arriving signals instead of the first arriving path study carried out in anechoic chambers on one subject for static positions. In (Gao, Peng, et al. , 2012), the author tried to evaluate the performance in the presence of Wi-Fi and WiMAX; here too, initial $S_{21}$ measurements taken with VNA are then transformed into Channel Transfer Function (CTF) using IFFT, and then two performance metrics are studied with the obtained AP model. number of frequency points: 1001 measurements taken for 3.1 to 5.1 GHz. Here Full two-port calibration is used in VNA. In (Xu, Gao, et al. , 2013), the same technique is used by the author with a focus on developing a combined channel model with realistic combined effects in the presence of WiMAX. Only standing posture with fixed transmission distance is considered by the author in this paper. In (Kumpuniemi, Hämäläinen, et al. , 2014), on body measurements for 2-8 GHz, total frequency points taken are 1601 per sweep for dipole and loop antennas. VNA-based Measurements were done for Walking sequence with five static postures and obtained results are transformed to the time domain with IFFT using MATLAB. A two-phase study approach is proposed by the author to develop three different channel models for 2 antennas. In (Yang, et al. , 2014), authors used VNA measurements taken for 3-10 GHz with a sampling time of 50 ps. Channel impulse response was obtained from $S_{21}$ with the inverse discrete Fourier transform. Main emphasis on development of nonparametric probability model for NLOS link. In (Hirose, Kobayashi, et al. , 2014), authors used this method for a frequency range of 3-10.6 GHz with 751 frequency points. Transmitter power is 0 dBm, and IF bandwidth is 100 Hz. $S_{21}$ data transformed to time domain with inverse Fourier transform. Main emphasis on the effect of room volume on channel model. In (Serna, Pardo , et al. , 2015), Ruben Gregorio used this method to study off-body channel model characterization (3-8 GHz) with two types of measurement campaigns. One with on body for different genders for standing posture and the other without a body. Measured data is converted to the time domain using inverse Fourier transform. Path loss and RMS delay spread extracted from channel impulse response. In (Goswami, Sarma, et al. , 2015), D. Goswami used the same method for studying the effect of different size subjects with a different approach. He averaged measured VNA data for 10 sweeps. Path loss is calculated from attenuation and IFFT used for obtaining impulse response. Total 1601 sampling points were considered by the authors. Timo Kumpunemi did the experimentation with VNA (Kumpuniemi, Hämäläinen, et al. , 2015) and obtained Channel Impulse Response (CIR) using IFFT without windowing. Absolute values used for results. Path loss and standard deviation measured link by link. First arriving paths data considered. Christopher Robin used the same approach to estimate the effect of the surrounding environment on channel characteristics with a focus on the dense multi-path component. He extracted reverberation time from Average PDPs (Roblin, Yunfei, et al. , 2015). In (Sangodoyin and Molisch, 2017), (Sangodoyin and Molisch, 2017), authors carried out VNA measurement campaigns for subjects of different Body Mass Index (BMI) for investigating the effect of BMI on channel characteristics and channel capacity with a MIMO sounder and time domain conversions carried out with IFT with a Hamming window to reduce side lobes. Parameters like path loss, frequency-dependent decay factor, and shadowing gain were considered for results. In (Kumpuniemi, Mäkelä, et al. , 2017), Timo Kumpuniemi carried out a study on shadowing effects on dynamic off-body channels using two dissimilar antennas with VNA measurements. Channel impulse response was obtained without using windowing by the author with IFFT. Authors cited reasons for not using windowing as loss of resolution and signal power.

Authors have also used statistical methods for model characterizations, which are discussed here. For evaluating the diffraction effects after time domain conversion with IFFT, curve fitting is done with correlated lognormal variables, which gives the effect of reflection and diffraction effects both (Fort, Desset, et al. , 2006). In (Hao, Alomainy, et al. , 2006), authors have focused mainly on the generalization of the model for LOS and NLOS using the sub-band FDTD technique. A BMI-specific study was carried out by authors in (Takizawa, et al. , 2008), where impulse responses obtained with windowing were then normalized using MATLAB. Based on actual VNA measurements, two different stochastic channel models were proposed by authors for average path loss and PDP. (Takizawa, Aoyagi, et al. , 2009). Statistical model based on actual measurements proposed by authors where CTF is obtained from $S_{21}$, later BER and PER examined for different modulation schemes (Takizawa, Aoyagi, et al. , 2009). A combinatory approach is used by authors for qualitative study based on CTF obtained from sampled $S_{21}$ data from actual VNA measurements (Roblin, 2010). Statistical parameter estimation was done by authors based on Poisson's process after converting measured $S_{21}$ data with real passband IFFT with a Hamming window (Lu, Chen, et al. , 2011). Authors used a modified Friis transmission formula for channel modeling. Calibration was done at the connectors of the cables for more accurate results (Ruckveratham, Teawehim, et al. , 2011). Effect of room volume evaluated by authors in terms of delay profile and path loss; $S_{21}$ data converted to time domain with inverse Fourier transform with rectangular window (Koiwai, Yamamoto, et al. , 2012). The applicability of the FIT technique is validated by authors through CST simulations and actual measurements through comparisons of Frequency and Impulse Response (Särestüniemi, 2013). Koiwai et al. investigated the effect of variation due to subjects positions in the room and ceiling height with spatial distributions and power delay profiles for both LOS and NLOS using VNA measurements and post-processing processing (Koiwai and Kobayashi, 2011).

Along with experimental measurements, authors have carried out investigations in the frequency domain. In (Kovacs, Pedersen, et al. , 2004), Estvan Covas et al. investigated the impact of the human body on the impedance and radiation characteristics of the antenna using the FDTD technique. The investigation of the effect of different sizes of human arms with the effect of skin layers was done with measurements and simulation using the FDTD technique (Lim, Baumann, et al. , 2011). Another approach used by Ruijun Fu et al. to investigate the effect of three continuous body motions on characteristics of dynamic on-body channels. For VNA measurements, a single-tone waveform is used for different frequency bands, including UWB, and later investigated for Doppler shift using Doppler spread and RMS Doppler bandwidth. This gives good insight into the effects of motions on propagation model characteristics (Ruijun, Yunxing, et al. , 2011). Four on body channels were investigated for body shadowing effects in real time for multiple time intervals (Mallat, Zia, et al. , 2018). Here the experimental model is built with 2X2 MIMO antennas with Inverted F antenna elements and measurements were carried out using VNA. Shadowing effects introduced by body movements were effectively countered in UWB by MIMO antennas which were validated with numerical simulations in terms of improved capacity and throughput in low SNR scenarios. In (Suwan and Promwong, 2022) shadowing effects were investigated using a measurement based model of impulse radio transmission in an indoor environment. Here study was based on extracted multi-path impulse parameters like log normal deviation, decay factor and cluster and ray arrival rates. Influence of human breathing on high bandwidth radio channels was investigated for in, on and off body channels (Serna, Pardo, et al. , 2020). Effect of relative movement between the nodes due to breathing was addressed in terms of Doppler frequency shift effects. Experimentation was carried out in liquid Phantom.

## 2.2 Impulse Generator and Sampling Oscilloscope

Jianqui Teo et al. and Yifun Chen et al. proposed a new approach for modelling UWB radio channels in their work (Teo, Chan, et al. , 2007), (Chen, et al. , 2009). Instead of using the popular method of VNA measurements ($S_{21}$) and later converting to the time domain with post-processing, they used a UWB pulse generator along with a sampling oscilloscope for directly making measurements in the time domain. The reasons cited by authors are that careful calibration is required for accurate measurements, and frequency-to-time domain conversion with the inverse discrete Fourier transform gives a band-limited version, whereas full bandwidth study is possible for available paths with the proposed approach. Mainly focused on the effect of static postures (Teo, Chan, et al. , 2007) and later extended to additional postures with an extension to cooperative schemes. Results obtained are in good agreement.

## 2.3 Simulation Study

Angelos Goulians et al did the simulation study for evaluating multi-path combining effects using first order non homogeneous Markov model. Numerical simulation is carried out by the author after doing measurements of inter-arrival times using spread spectrum sliding correlator sounder. This is mostly a qualitative study for limited bandwidth in UWB range with new parameters like path occurrence probabilities and clustering coefficients (Goulianos and Stavrou, 2007). Takeyosh tayamachi et al did the numerical simulation study for the entire UWB band using frequency dependent finite difference time domain method and statistical curve fitting with MATLAB. This is done using high precision Human body models for on body LOS channels. Computational complexity is higher for FDTD methods (Tayamachi, Wang, et al. , 2007). Qiong Wang et al carried out a numerical simulation approach with limited experimentation for validation in their work which investigated body links on a human body model derived from average statistical values of body parameters. Different Body postures statistical characteristics were considered by authors in their study (Wang, Tayamachi, et al. , 2009). A Khaleghi et al used a new approach in numerical simulation with Finite Integration technique (FIT). Voxel Human body model with 4mm resolution used by the authors to study various LOS and NLOS links where the antennas were located to obtain different wave polarisations. Channel characteristics for different polarisation were evaluated in this qualitative study (Khaleghi and Balasingham, 2009). Angelos Goulianos et al proposed statistical off-body channel with the numerical simulation for indoor environment in a limited frequency band of 3.5-6.5 GHz. Authors modelled signal power gain with a log-linear dual breakpoint model. Parameters like ray and cluster arrival times, inter and intra cluster decay rates extracted for particular antennas are used for model development (Goulianos, Brown, et al. , 2009). Masafumii Fujii et al investigated channel models for static positions with numerical simulations with FDTD technique based on 2 pole Debye dispersion model. Human body model for 50 tissues obtained from Gabriels Cole ole data. Authors used least square fitting technique over the limited frequency range with the emphasis on computational efficiency (Fujii, Yotsuki, et al. , 2010). Tommi Tuovinen et al did the simulation study on the effect of human body tissues in terms of impedance and reflection coefficient with Debye's dispersion model. This was later extended to other near field parameters like antenna efficiency radiation pattern in the near field reactive region by the authors (Tuovinen, Berg, et al. , 2012), (Tuovinen, Berg, et al. , 2012). Heterogeneous Voxel based FDTD simulations were used by authors to investigate dynamic WBAN channel model characteristics while walking for on, off and body to body communication in an empty environment (Mohamed, Joseph, et al. , 2019). Channel characteristics were studied with reference to Fade variations and correlated amplitude distributions. Fade variations for on body channels were found periodic whereas for off body channels show constructive and destructive interference with distance variations. In (Intissar, Sofiane, et al. , 2023) based on incident Electromagnetic (EM) wave authors investigated channel characteristics in simple layered tissue models. Field distributions were calculated for MOM method and results were obtained for Path loss and Power density function. Further validation was done using FEM computations. In another paper authors have investigated parametric statistical path loss model for WBAN for indoor environments (Youssef, Roblin, et al. , 2024). Simplified Ray tracing code in MATLAB was used for calculating input parameters for the environment which was used in CST simulations with Voxel models. Overall combined approach was used by authors i.e., EM simulations with RT simulations which can be helpful in building local models which can further expanded by adding scattering objects in an indoor environment.

# 3 ANALYSIS AND DISCUSSION

After referring to the literature published in the last two decades on the characterization of channel models for UWB WBAN systems, using VNA for frequency domain measurements remains the most popular method among researchers. VNA is highly sensitive equipment that is widely used in RF and microwave experimentation, but its calibration and synchronization are very important before any measurement campaign for more accurate channel model development. Time domain conversion of frequency domain data is done with different inverse Fourier transform techniques like IFT, IFFT, and chirp Z transform with and without windowing. Windowing suppresses side lobes but also drops signal power and gives band-limited information. Several statistical methods are used for extracting different parameters like large-scale path loss and path gain, which give information about the attenuation, but their accuracy depends on the accuracy of the measurement of distance or separation between the two antennas. Other effects, like reflection and multi-path effects, are studied in terms of delay spread, power delay profile, and amplitude distortion, which are obtained from channel impulse response. The Doppler technique with VNA is used by one author where Doppler shift is measured for phase changes, giving more accurate results. This approach is new and needs to be explored more.

Another approach used by authors is measurements using a UWB pulse generator and time domain sampling oscilloscope. This method facilitates direct measurements in the time domain, which can be later processed to get a CDF based on power distribution measurements. A parametric study can be done using it for channel characterization. This method gives a full-bandwidth view, which is not possible with the VNA measurement method.

Table1: Measurement techniques used for UWB channel characterization.

| Sr. No | Measurement Technique used | References | Remarks |
|---|---|---|---|
| 1 | VNA Measurements | (Zasowski, Althaus, et al. , 2003), (Yamamoto and Kobayashi, 2009), (Chen, Lu, et al. , 2011), (Särestüniemi, Tuovinen, et al. , 2013), (Säreströniemi, Tuovinen, et al. , 2012), (Chen, Ye, et al. , 2012), (Kumpuniemi, Tuovinen, et al. , 2013), (Gao, Peng, et al. , 2012), (Xu, Gao, et al. , 2013). (Kumpuniemi, Hämäläinen, et al. , 2014), (Yang, et al. , 2014), (Hirose, Kobayashi, et al. , 2014), (Serna, Pardo , et al. , 2015), (Goswami, Sarma, et al. , 2015), (Kumpuniemi, Hämäläinen, et al. , 2015), (Roblin, Yunfei, et al. , 2015), (Sangodoyin and Molisch, 2017), (Sangodoyin and Molisch, 2017), (Kumpuniemi, Mäkelä, et al. , 2017), (Fort, Desset, et al. , 2006), (Hao, Alomainy, et al. , 2006), (Takizawa, et al. , 2008), (Takizawa, Aoyagi, et al. , 2009), (Takizawa, Aoyagi, et al. , 2009), (Roblin, 2010), (Lu, Chen, et al. , 2011), (Ruckveratham, Teawehim, et al. , 2011), (Koiwai, Yamamoto, et al. , 2012), (Koiwai and Kobayashi, 2011), (Kovacs, Pedersen, et al. , 2004), (Lim, Baumann, et al. , 2011), (Ruijun, Yunxing, et al. , 2011), (Mallat, Zia, et al. , 2018), (Suwan and Promwong, 2022), (Serna, Pardo, et al. , 2020) | Most popular and widely used method. VNA has higher sensitivity but careful calibration and synchr-onization is required. Frequency domain data obtained has to be converted to time domain data with different IFT methods. With Post processing parameters like Path loss, Path gain, Delay spread, Power gain, PDP extracted. |
| 2 | Impulse Generator and Sampling Oscilloscope | (Teo, Chan, et al. , 2007), (Chen, et al. , 2009) | Time domain data directly measured which provides full bandwidth information. Using cross correlation path loss, PDP, power variation can be obtained |
| 3 | Numerical Simulations | | More flexible for dynamic models as different postures |

| Sr. No | Measurement Technique used | References | Remarks |
|---|---|---|---|
| | | (Goulianos and Stavrou, 2007), (Tadamichi, Wang, et al. , 2007), (Wang, Tayamachi, et al. , 2009), (Khaleghi and Balasingham, 2009), (Goulianos, Brown, et al. , 2009), (Fujii, Yotsuki, et al. , 2010), (Tuovinen, Berg, et al. , 2012), (Tuovinen, Berg, et al. , 2012), (Mohamed, Joseph, et al. , 2019), (Intissar, Sofiane, et al. , 2023), (Youssef, Roblin, et al. , 2024) | can be easily simulated. No need for human subjects. High resolution multipath results can be obtained FIT, FDTD or MATLAB codes are used. Time required for simulation is more. Surrounding effects cannot be included. |

Several authors have used numerical simulation techniques with MATLAB curve fitting tools whereas another approach used is simulation using either FDTD or FID techniques based on heterogeneous Voxel based Phantoms or homogeneous layered Phantoms. Simulation techniques provide greater flexibility as different body postures can be easily simulated and investigated using Voxel based models. Using statistical average human models works better in development of generalised channel models without taking measurements over the number of human subjects. It is also possible to obtain higher resolution multi-path results with simulation techniques. Computational complexity of simulation remains high and requires more processing time and high end processing machines. Other drawbacks are assumption of ideal point sources as radiators and limitation of considering surrounding effects in simulations.

## 4 CONCLUSIONS

Over the last two decades, researchers have used different methods for evaluation and characterization of UWB WBAN channel models, like actual measurements in frequency and time domains, Doppler shift measurements, and numerical simulations with MATLAB and other commercially available simulators. More emphasis was placed on developing static and pseudo-dynamic channel models with more accuracy. Different parameters like path loss/gain, shadowing, multipath fading, delay spread, power delay profile, average fade duration, level crossing rate, Doppler frequency shift, etc., are used by authors for analyzing associated large- and small-scale effects. In view of developments happening in the Internet of Things domain, developing generalized dynamic WBAN radio channel models still remains the challenge for researchers and needs to be explored and studied further for enabling a variety of services and applications in wellness, medicine, safety, security, and many more. More realistic study is possible with experimentation and hence will remain the popular choice among the researchers for the characterization of UWB WBAN on- and off-body channels.

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