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Mathematical Modeling of Ultra Wideband *in Vivo* Radio Channel

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ABSTRACT This paper proposes a novel mathematical model for an *in vivo* radio channel at ultra-wideband frequencies (3.1–10.6 GHz), which can be used as a reference model for *in vivo* channel response without performing intensive experiments or simulations. The statistics of error prediction between experimental and proposed model is RMSE = 5.29, which show the high accuracy of the proposed model. Also, the proposed model was applied to the blind data, and the statistics of error prediction is RMSE = 7.76, which also shows a reasonable accuracy of the model. This model will save the time and cost on simulations and experiments, and will help in designing an accurate link budget calculation for a future enhanced system for ultra-wideband body-centric wireless systems.

INDEX TERMS Channel characterization, implants/wearable devices, *in vivo* channel, mathematical modeling, wireless body area networks.

I. INTRODUCTION

Wireless body area networks (WBAN's) have been under research for a few years now [1]–[5]. Constant assessment of physiological parameters, particularly in chronic diseases including cardiac failure, asthma, bipolar mood disorder and diabetes, can provide insight into disease progression over time and assist healthcare providers in making the best therapeutic decisions. Personal heath monitoring systems are developed to continuously monitor human health by placing sensors on them and getting a real-time reading from the patients [6]. Previous studies have been performed on heterogeneous sensor networks, which combine wireless sensor networks (WSN's) and personal area networks (PAN's) using a transmission control protocol/internet protocol (TCP/IP) [7]. Due to the low power requirements of WBAN's low power control protocols are needed for the communication [9]. Physical layer for WBAN has also been studied using a complementary metal oxide semiconductor (CMOS) in which the human body was used as a communication channel to transfer data [8]. In some cases, due to strategic placement, the sensors on the body are required to send large amount of data quickly. This requires Ultra-wide band (UWB) communication [9] but due to UWB, inter-symbol interference (ISI) can be observed especially with Band width (BW) of more than 500 megahertz (MHz). Multipath fading [11] is a major problem in indoor environments and short distance communication especially in the presence of other objects like desk, chairs, walls and electronic equipment. This results in reflection, refraction, dispersion and diffraction of the signal and results in multipath small and long scale fading. Signaling fading can also occur to varying degrees depending on antenna propagation [12], the way a signal propagates. For instance, the multipath fading effect is less significant with directional antennas, when compared to an Omni directional antenna. Researchers are trying their best to come up with different types of channel characteristics and path loss models [14] to improve the communication and make it more secure and risk free.

Many studies utilize the use of live animals to better understand the use of implantable devices and *in vivo* communication for collecting physiologically relevant recordings and data. Anzai *et al.* [13] conducted experiments on animals using UWB impulse radio, which resulted in a path of 80dB and a bit error rate (BER) of 10^{-2} within the distance of 120mm, with a high data rate of 1Mb/s. In [15], Propagation model was proposed for UWB body-centric wireless communication. BER performance was also measured using multi-band orthogonal frequency division multiplexing (OFDM). *In vivo* channel model in body-centric wireless communication is also presented and explained in [16]. Path loss models [17] are explained and presented using different frequencies by simulations and real experiments using animals and human bodies by placing the sensors on top of the body. Wireless capsules are used to get the human data from inside the body by studying variations of path losses [18].

Different types of implantable and wearable devices [19]–[21] have been the focus of many research articles in recent years. Few of the latest research is expanding the implantable technology to the Nanoscale for which the frequencies they are selecting and considering the best are in the terahertz range. In [25], terahertz channel characteristics under the human skin are presented using measurement data, and modelled data is shown. Analytical characteristics of terahertz in Nano communications are also studied by Zhang *et al.* [26].

Although some studies are showing the characteristics and analysis of *in vivo* channels, most of them are limited to simulations and models based on assumptions or by using experiments only. To the best of author's knowledge, there is no explicit investigation performed to present a generic mathematical model and applying it to the experimental measurements with high accuracy. In this paper, we presented a novel mathematical model for *in vivo* radio channel at UWB with the highest accuracy of RMSE = 5.297, while applied on the channel response extracted from experimental data. Additionally, blind testing is performed on the proposed model for validating the analytical results with the simulated data. This novel mathematical model will save the cost and time on simulation and measurements for UWB *in vivo* radio channel.

The rest of this paper is organized as follows. Section II presents the experimental setup and simulation of the measurement data. Section III focuses on the proposed mathematical model along with the simulated measurement data results. Finally, future developments are discussed in conclusion in section IV.

II. MEASUREMENT SETTINGS

The experiments were performed using a human cadaver as presented in [22]. Only the torso part of the cadaver was taken into consideration and simulated in ANSYS-HFSS [24]. Two antennas were used in this experiment the first one is an *ex vivo* dipole antenna and the second one is a coplanar waveguide (CPW)-fed *in vivo* antenna. Compatible polyethylene protective layer [27] was used to wrap the antennas and part of the cable to avoid any physical connection with cadaver, organs, or tissues.

In vivo antennas were placed in six different parts inside the human torso, including on top and beneath the heart, stomach, and intestines, whereas *ex vivo* antennas were placed outside the human torso, including near the head, beside the torso and near the foot to get different readings [22]. It was found that electromagnetic wave propagation was highly dependent on the location of the *in vivo* antenna, particularly if the antenna was placed deep inside the torso or within a dense region, like near the intestines. Furthermore, significant multipath and small-scale fading occurred during testing [22]. Antenna depth and path loss model for the experimental data compared to the simulated environment is presented in [14].

These experiments allow us to further our understanding of *in vivo* communication and channel characteristics, which could potentially help doctors and engineers better understand how waves are propagating and the effect of fading while communicating wirelessly under real scenarios. The primary aim of this study is to provide a new tool for healthcare providers that allows constant monitoring of patients. The doctors will be able to follow his patient using wireless technology with the help of a device implanted in the human body, which actively collects and reports physiologically relevant data regarding the patient. The measurements will be automatically sent to the doctors through Wi-Fi, Bluetooth or GSM as shown in Fig. 1. this information will allow patients and doctors to follow disease progression more accurately and thereby provide an opportunity for more effective and efficient care.

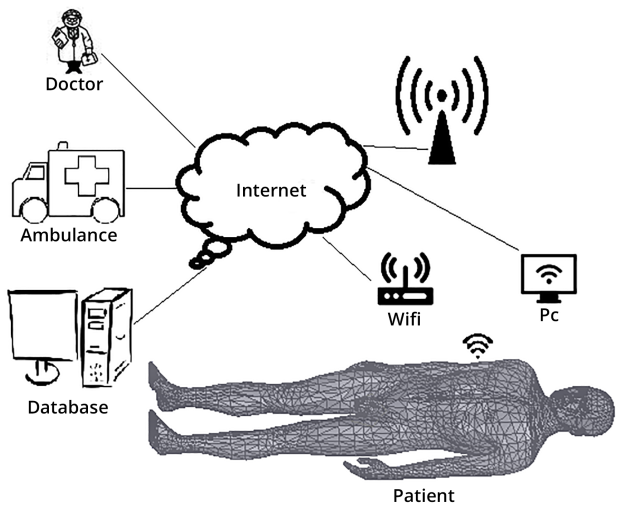

FIGURE 1. Envisaged patient system model with *in vivo* implant communicating through different conventional communication devices.

III. SIMULATION AND MATHEMATICAL MODELING

To correctly understand the multipath propagation and waveform design the amount of delay spread must be evaluated since this information is essential in designing a better *in vivo* communication system. It is shown in [14] that the tissues of the human body cannot absorb the EM waves completely, which contribute to small-scale fading over short distances.

A. POWER DELAY PROFILE

The power delay profile (PDP) is generated from measurement data as presented in [14]. It gives the distribution of signal power received over a multipath channel as a function of propagation delays. It is obtained as [23]. Mean excess delay ($\bar{\tau}$) and RMS delay spread (σ_τ) are the two most commonly used parameters for the time dispersive properties of wide band multipath channels [23]. Mean excess delay is define as

$$\bar{\tau} = \frac{\sum_k p(\tau_k)\tau_k}{\sum_k p(\tau_k)} \tag{1}$$

The RMS delay spread is defined as

$$\sigma_\tau = \sqrt{\bar{\tau^2} - (\bar{\tau})^2} \tag{2}$$

Where

$$\bar{\tau^2} = \frac{\sum_k p(\tau_k)\tau_k^2}{\sum_k p(\tau_k)} \tag{3}$$

TABLE 1. Simulation parameters in matlab.

Parameters	Values/units
Bandwidth	50MHz
Central Frequency	6.75GHz
S-parameters	S_{21}
Time	μsec
Channel Response	dB

The channel response was extracted from the measurement data. The channel impulse response, *h(t)*, is derived by taking the inverse discrete Fourier transform (IDFT) of the channel frequency response, S_{21} in MATLAB. The parameter of the simulation is shown in Table 1. Fig. 2 shows the channel response for BW = 50 MHz, Theoretically it can be stated that ISI is not a big issue for low BW's, however, it can cause problems for higher BW's, which require a complex equalizer to deal with the ISI.

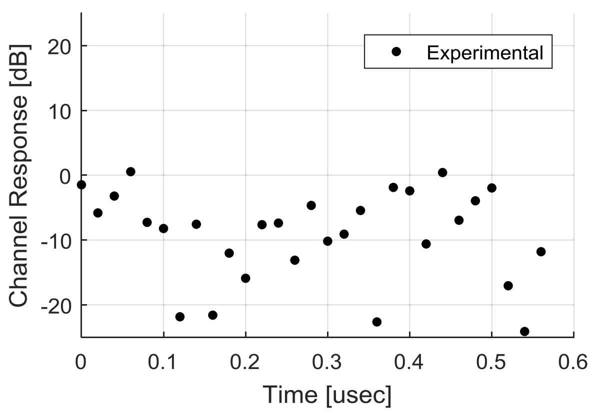

FIGURE 2. Channel response for bandwidth 50 MHz.

B. PROPOSED MODEL

To hypnotize the model from measurement data, let us consider the general form of Fourier series, which involves *sines* and *cosines*. The values of these *sines* and *cosines* can be obtained as

$$f_1(x) = \cos x \tag{4}$$
$$f_2(x) = \sin x \tag{5}$$

Which gives us the Fourier series for a function f_x as follows

$$f_x = \frac{1}{2}a_o + \sum_{n=1}^{\infty} a_n \cos(nx) + \sum_{n=1}^{\infty} b_n \sin(nx) \tag{6}$$

Where

$$a_o = \frac{1}{\pi}\int_{-\pi}^{\pi} f_x dx \tag{7}$$
$$a_n \frac{1}{\pi}\int_{-\pi}^{\pi} f_x \cos(nx)dx \tag{8}$$
$$b_n = \frac{1}{\pi}\int_{-\pi}^{\pi} f_x \sin(nx)dx \tag{9}$$

The above equations form an orthogonal system for n = 1, 2, 3, 4.........

To get the model we need to fit an equation to the collected data. After intensive experiments, it is found that the model must be of the form

$$f_x = a_o + \sum_{n=1}^{\infty} a_n \cos(xw) + \sum_{n=1}^{\infty} b_n \sin(xw) \tag{10}$$

Where a_o, a_n, b_n are the coefficients and w represents the weighting term. Which is used in the calculation of chi-square. If the value of the standard deviation σ is available, weight can be used as $w = \sigma$ which is necessary to calculate valid error bars of the fit.

To get the desired model starting from (10) which actually as a 1 term equation and can be explicitly written as

$$f_x = -134.4 + (-0.5977)\cos(xw) + 5.371 * \sin(xw) \tag{11}$$

Where $w = 31.1$.

TABLE 2. Fitted statistic results.

No of Terms	R-Squared	Adjusted R-Squared	RMSE	Weights
1 Term Equation	0.3102	0.2274	6.174	31.1
2 Term Equation	0.4524	0.3333	5.735	15.49
3 Term Equation	0.4605	0.2807	5.958	15.46
4 Term Equation	0.5279	0.3043	5.858	8.450
5 Term Equation	0.5642	0.2822	5.951	6.732
6 Term Equation	0.6664	0.3774	5.543	32.92
7 Term Equation	0.6725	0.2946	5.90	33.12
Proposed Model	0.7766	0.4312	5.297	15.24

The fitting statistics of (11) is shown in Table 2. The fitted curved using 1 term equation is shown in Fig. 3, the results were not at the desired level for which we performed number of experiments to improve the statistical results of the fitted model. The number of terms in the equation are increased by 2, up to 8 terms equations. The fitting statistics for all those

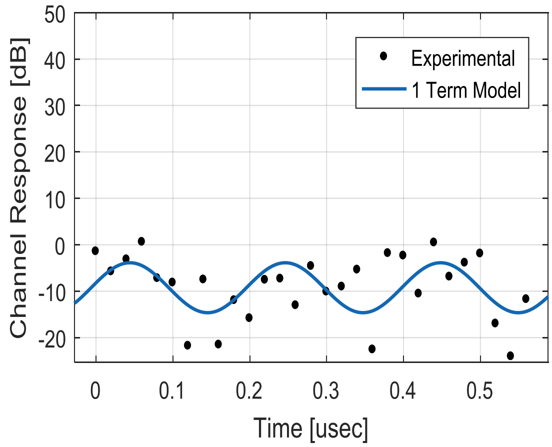

FIGURE 3. Fitted Curve Using 1 Term equation.

experiments are shown in Table 2, while Fig. 4 show the fitted model with 6 terms equation., which is reasonably a good fit but not with desired RMSE performance.

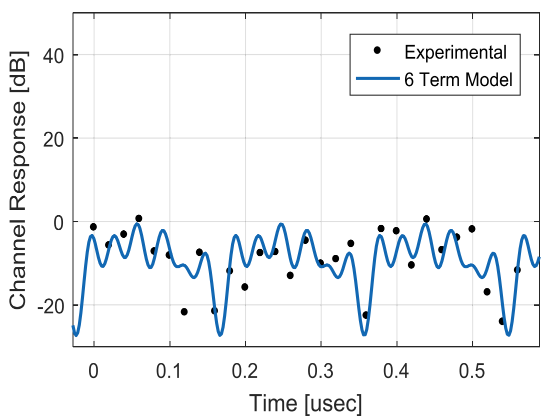

FIGURE 4. Fitted Curve Using 6 Terms Equation.

It is observed that if we proceed by increasing number of terms for the equations, the mathematical complexity is increasing without any significant amount of accuracy for the fit, so we decided to stop with the 8 terms equation, the final proposed equation (12) results in the highest RMSE = 5.297. Fig. 5(a) show the final proposed model concerning the experimental data. Finally Fig. 5(b) present the residual plot with the leftovers of the subtracted fit from the experimental data.

$$\begin{aligned} f_x = &-9.382 + 3.984 * \cos(x * 15.24) + (-0.5262) \\ &* \sin(x * 15.24) + 0.7176 * \cos(2 * x * 15.24) \\ &+ 4.324 * \sin(2 * x * 15.24) + (-0.5402) \\ &* \cos(3 * x * 15.24) + 0.4261 * \sin(3 * x * 15.24) \\ &+ 1.292 * \cos(4 * x * 15.24) + (-0.8812) \\ &* \sin(4 * x * 15.24) + 2.254 * \cos(5 * x * 15.24) \\ &+ (-1.53) * \sin(5 * x * 15.24) + 0.2745 \\ &* \cos(6 * x * 15.24) + (-0.2933) * \sin(6 * x * 15.24) \\ &+ (-0.1391) * \cos(7 * x * 15.24) + (-3.488) \\ &* \sin(7 * x * 15.24) + (-1.608) * \cos(8 * x * 15.24) \\ &+ (-2.977) * \sin(8 * x * 15.24) \end{aligned} \quad (12)$$

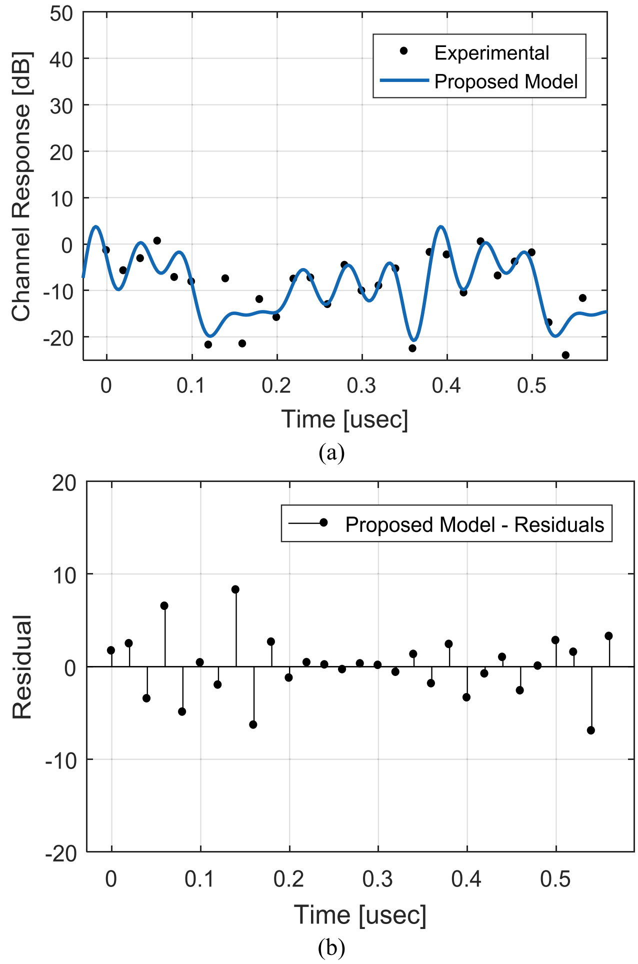

FIGURE 5. Fitted curved and residual plot. (a) Fitted Curve with the proposed model. (b) Residual Plot.

TABLE 3. 95% confidence limits.

Coefficient		95% Confidence Limits	
a_o		(-11.68, -7.085)	
a_n	Limits	b_n	Limits
a_1	(0.67, 7.298)	b_1	(-3.785, 2.733)
a_2	(-2.891, 4.326)	b_2	(1.063, 7.584)
a_3	(-3.811, 2.73)	b_3	(-2.851, 3.703)
a_4	(-1.911, 4.495)	b_4	(-4.37, 2.607)
a_5	(-1.059, 5.567)	b_5	(-5.438, 2.378)
a_6	(-2.96, 3.509)	b_6	(-3.619, 3.032)
a_7	(-4.928, 4.649)	b_7	(-6.72, -0.2568)
a_8	(-6.193, 2.976)	b_8	(-6.533, 0.5796)

Generally (12) can be written as

$$\begin{aligned} f_x = &\, a_o + a_1 * \cos(x * w) + b_1 * \sin(x * w) \\ &+ a_2 * \cos(2 * x * w) + b_2 * \sin(2 * x * w) \\ &+ a_3 * \cos(3 * x * w) + b_3 * \sin(3 * x * w) + \end{aligned} \quad (13)$$

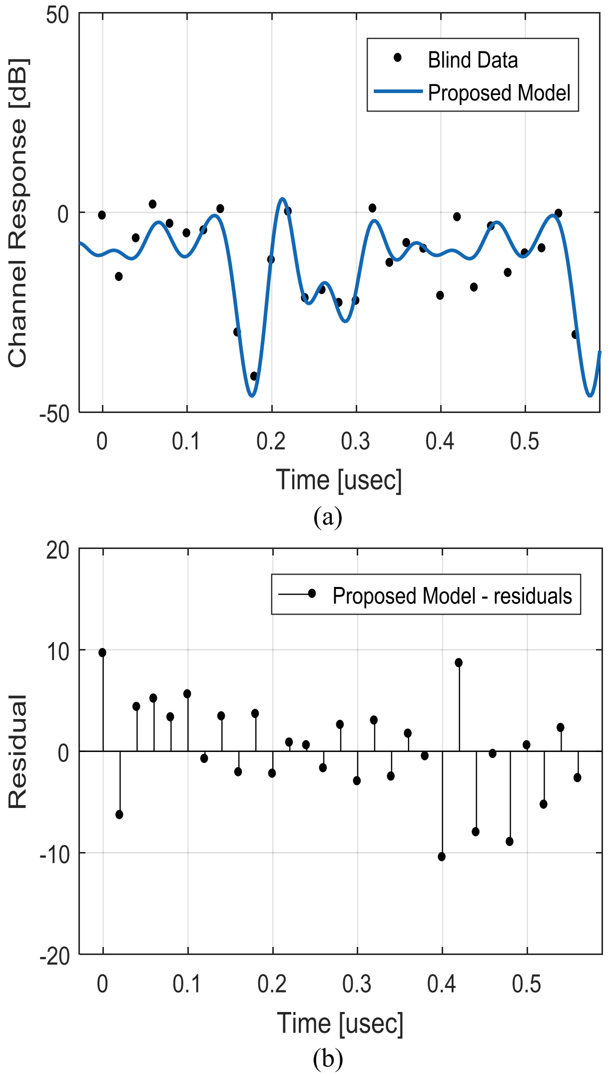

FIGURE 6. **Fitted curved and residual plot using blind data. (a) Fitted Curve with proposed model. (b) Residual Plot.**

Or

$$f_x = a_o + \sum_{n=1}^{8} a_n \cos(n * x * w) + \sum_{n=1}^{8} b_n \sin(n * x * w) \tag{14}$$

95% confidence limits for each coefficient of the proposed model can be found in Table 3. The confidence limits means that the estimate of the parameter lies between $\pm\delta$ with a 95% probability.

Using (12) we are able to get the best possible Fit for the experimental data, besides that by observing Table 2 it can be seen that we can also get reasonable RMSE values with 2 Terms and 6 Terms equations. These equations can be extracted from (12) just by reducing the no of terms to get the desired results. We used the 8 Terms equation to get the best results although from those experiments it is clear that there is a tradeoff between mathematical complexity and accuracy of the fit depending on the requirements one can easily select between 2 Terms, 6 Terms or 8 Terms equation according to the requirements.

C. BLIND TESTING

To check the success rate of the mathematical model, a blind test was conducted. The data has not been used in fitting data. A new channel response was selected for this test, the experiment was performed using the proposed model against the new channel response data. Fig. 6(a) shows the comparison of the fitted model using the proposed model for new data. Fig. 6(b) shows the prediction error of blind channel response data (i.e., data which was not used in fitting and derivation process of the proposed mathematical model) in the form of residual plot and is given as RMSE 7.76. This all indicates the high accuracy of the proposed model as compared with the experimental data from the simulation.

IV. CONCLUSION

This paper presents a novel mathematical model for UWB in-vivo communication. Blind testing is performed on the proposed model. The statistics of the error for the blind test using proposed model is RMSE 7.76. This validates the accuracy of the proposed while applying on different channel response. The presented analysis highlights a novel method to obligate the communication challenges in such environment and will help system designer to develop an accurate link budget calculation without going for costly experiments and time-consuming simulation and will open a way for further studies in this undesired environment.

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