Bit Error Rate Performance of In-vivo Radio Channel Using Maximum Likelihood Sequence Estimation

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***Abstract*—In this paper we present the Bit Error Rate (BER) performance of equalizers using in-vivo channel response measured using Vector Network Analyzer (VNA). Including the use of a Bandwidth (BW) of 50 MHz in the simulations, the results are compared with multiple equalizers and it is shown that Maximum Likelihood Sequence Estimation (MLSE) equalizer outperformed the rest of the equalizers including linear equalizers Least Mean Square (LMS) and Recursive least sequence (RLS) and non-linear equalizer Decision Feedback Equalizer (DFE). The BER performance using MLSE showed significant improvement by improving the BER and outperforming the linear equalizer from 10^{-2} to 10^{-6} and DFE from 10^{-4} to 10^{-6} at Eb/No = 14 dB for in vivo radio communication channel at ultra wideband (UWB) frequencies. Furthermore, the un-equalized and equalized channel frequency response spectrum is also part of this article which presents the overall improvement between the two spectrums.**

Keywords—Bit Error Rate (BER), Body Area Networks (WBANs), Equalization, in vivo Communication, Ultra wideband.

I. INTRODUCTION

There are many matrices to characterize the performance of a communication system. But frequently one of the most convenient and one of the most informative matrices is the Bit Error Rate (BER) of a communication system. In communication system the way of transmitting information bits from the transmitter to the receiver will make some vicissitudes on the information bits, and those information bits can be resulted as a digital stream of binary numbers in form of one's and zero's. However, there are implantable devices such as cardiac pacemaker, drug delivery devices, and defibrillators which the researchers are working on it to make it ready for the use of common man as presented in [1-2]. One of the most important issue with the implantable devices is their size as one cannot place the implant inside the human body if exceeding certain size. Researchers are trying to make the size as small as possible and make sure the reduction in size must not impact the performance of the implants. The new antenna designs are also under research which will help the device to communicate with the outside devices using different technologies including Wi-Fi, 3G, 4G and 5G. One of the design for these kind of antennas is shown in [3] for a better communication system with the wireless functionality to communicate with the external world, this scheme will help the researchers to make the size of implantable device smaller. In [4] another major issue of battery changing and charging the implants are addressed in detail as once the implant is placed, it is hard to charge it on daily basis or change the battery. Although with the advancement of fifth Generation (5G) technology, theoretically it is expected to have the battery life of those devices for up to 10 years, which will have a positive impact on those devices.

The dense structure of the human body makes it hard for a signal to travel efficiently from inside the body towards the outside receiver as it needs to cross through bones, flesh, muscles, fats and skin which make it hard for the signal to have a reliable communication and results in inter-symbol interference (ISI) as mentioned in [5]. A detailed analysis of different types of antennas are discussed in [6], which help us give an overview of what kind of antennas are available to be considered for the future implants which can help us in the reliable communication between the implantable devices and external conventional communication devices. The channel physiognomies of in-vivo communication using the experimental analysis is presented in [7]. In [8] channel model of in-vivo communication in the circumstance of antenna location of the ex-vivo device is presented where it clearly shows the location dependent characteristics of the in-vivo communication and the change in the signal propagation which is impacting the communication. As mentioned in [9] at ultra wideband frequencies a mathematical channel model is developed for in vivo communication using the measurement data collected from the experiments performed using a human cadaver, which will help the researcher to use the model without performing extensive experiments, Performing the experiments is a time consuming and costly job with the requirement of medical assistance and ethical approvals, mathematical modeling of ultra wideband for in vivo radio channel will help researchers directly get into the simulation without extensive experimental setup. The experimental analysis that is presented in [10] proves the location dependency of in vivo communication, and it is obviously different from the conventional communication channel and all the available communication models fails if applied on the in-vivo communication channel, which give a new motivation to the researcher to dig deep in the area by extracting new models. Detailed study need to be done in the near future to overcome the complications of in-vivo communication systems which will help us quickly deploy the technology and its commercialization to make it available to the end user.

II. SIMULATION SETUP AND RESULTS

A human Cadaver is used to accomplish the measurements as mentioned in [6], all the measurements were taken under the supervision of certified medical doctor who assisted us to perform all the experiments after getting the ethical approvals. In order to keep the experiments as real as possible fresh organs of sheep including heart, stomach and intestine were used by placing them inside the human cadaver at the exact places under the supervision of certified medical doctor. Two main types of antennas in-vivo (to be placed inside the human cadaver) and ex-vivo (to be placed outside the human cadaver) were used [7]. Initially the position of the ex-vivo antenna was fixed for all the experiments where the location of the in-vivo antenna were changing by placing it in different parts at different locations, both the ex vivo and the in vivo is well protected to prevent short circuit. Throughout the experiments the channel response was recorded through Vector Network Analyzer (VNA). The data was taken and normalized using (1).

$$N_{i=}\frac{x_{i}-\mathrm{m}\quad(x)}{max_{(x)}-\mathrm{mi}\quad(x)} \qquad (1)$$

Where x = $(x_1, \ldots, x_n)$ and N_i is our i^{th} normalized data.

min(x) is the minimum value of variable x.

max(x) is the maximum value of variable x.

The simulations were performed using Matrix Laboratory ($MATLAB^{©}$).

The novel data set that were used to be saved over VNA was in frequency domain (2) which has been converted to time domain (3) using Inverse Fast Fourier Transform (IFFT).

$$y(f) = H(f)x(f) \qquad (2)$$

$$y(n) = H(n) \otimes x(n) \qquad (3)$$

Here $H(f/n)$ is channel response, x y H are all functions of signal frequency f/n.

In the previous studies the researchers figured out that multiplication in frequency domain is equivalent to convolution in time domain. The whole information was composed at UWB frequencies (3.1-10.6 GHz), but for simulation, only 50 MHz bandwidth was designated, the central frequency for this UWB is 6.75 GHz.

The system performance of the in-vivo channel is discussed in details in [4] initially worst BER performance were observed due to the multipath effect a multi tap channel was observed. In order to compensate the effect of ISI different equalizers were used including linear equalizer and nonlinear equalizers. As mentioned earlier the power consumption is too critical for in-vivo channel due to multiple issues including the battery change and charging. By using (4) we can measure the power spectral density.

$$\text{S}(\omega) = \sum_{k=-\infty}^{\infty} r[k]e^{-jk\omega} \qquad (4)$$

The power spectrum for linearly equalized and DFE equalized signals are re simulated for a better comparison of the power spectrum of MLSE. Hence by taking the comparison between the power spectrums, we can notice that the (DFE) and the linearly equalized will be able to be noticed that the Maximum variation is gained in un equalized frequency response and it is with the range of 0 dB to -40 dB. Where the linear equalizer can make it less within this range 0 dB to -30 dB [4]. Meanwhile, the (DFE) decision feedback equalizer outperformed the linear equalizer and by applying the Ideal MLSE we can obviously notice that it outperformed both of the linear equalizer and the decision feedback equalizer as presented in Fig. 2. The power spectrum increases approximately by 25% using least mean square and 75% using decision feedback equalizer. Even though the analysis is created on the highest peaks but the total fluctuation of the power spectrum for linearly equalized least mean square is between 0 dB to - 10 dB and -10 to -20 dB in that circumstance a quantity of the spectrum is recuperated in the middle of 50% to 75%. Despite the fact that in the circumstance of decision feedback equalizer, it stays the same during the simulation. Which gives healthier and steady performance of decision feedback related to least mean square (LMS). All the Simulation Parameters for Equalization are shown in TABLE I.

TABLE I. SIMULATION PARAMETERS FOR EQUALIZATION

Parameters	Values/units
Sampling Frequency Fs	1
Modulation	BPSK
Symbol Rate Rs	1
Sample per Symbol	Fs/Rs
No. of Channel Taps	15
Eb/No	0-14 (dB)
No. of Weights	31

A respectable estimation technique is too significant to obtain an accurate signal at the receiver, and MLSE is one of the best estimation techniques for determining the channel response between the transmitter and the devices that are used for receiving the signal from the transmitter. Fig. 1. Presents the block diagram for MLSE.

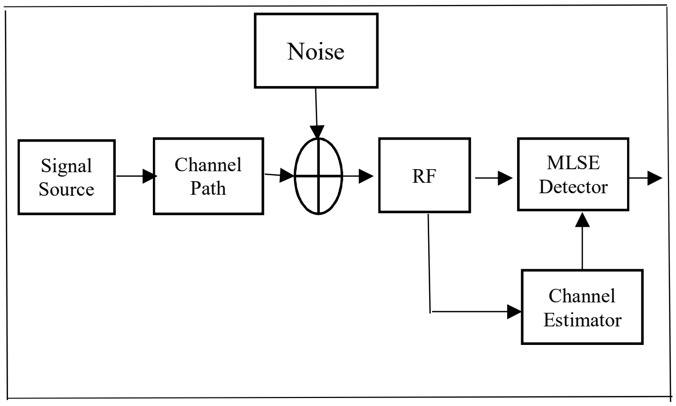

Fig. 1. A Simple Block Diagram of MLSE.

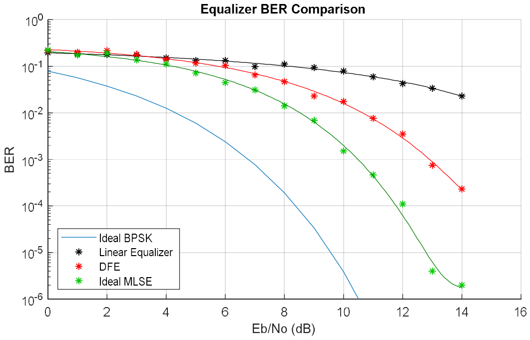

Fig. 2. Ideal MLSE applied on in-vivo radio channel communication.

As mentioned before in the previous sections, in this paper we are using the maximum likelihood sequence estimation (MLSE) to get better performance of in-vivo radio channel communication equalizers. The receivers of MLSE are working with non-stationary frequencies prerequisite channel approximation and frequently necessitate channel tracking and calculation [8].

Basically, the decision feedback equalizer (DFE) and the maximum likelihood sequence estimator (MLSE) are so important techniques for changing to a non-minimum phase condition and this change will definitely make changes on the (DFE) performance. The simulations are led to compare the performance of MLSE equalizer for its ideal MLSE and the MLSE compared to the ideal BPSK, the linear equalizer and the decision feedback equalizer (DFE) of in-vivo radio channel communication. Maximum-likelihood sequence estimator (MLSE) is an adaptive equalizer, which is a suboptimum estimation to the adaptive maximum-likelihood sensor and is having the ability of following quick time-varying inter-symbol interference (ISI) channels. The MLSE can be defined as a channel estimator and an MLSE applied by the Viterbi algorithm (VA) [9]. The original piece of the suggested adaptive MLSE is a channel estimation structure, we can see that the estimation of the channel for each state in the VA can be accomplished along the secured way that is in touch to each state. It is easier to estimate a channel impulse response by using MLSE with no effect of a decision interruption inherent in the VA, the memory length of the VA is in charge of the performance and the complexity for the suggested scenario. The bit error rate (BER) performance of the suggested MLSE is accepted by new outcomes. It is revealed that the planned MLSE has a proficiency of perfect tracking performance in a simple surroundings and it was the reason of fast time-varying ISI, for an instance a frequency selective multipath vanishing in digital mobile radio communications [10].

Finally, we can obviously notice that the Ideal BPSK which is our threshold to be approached, followed by Ideal MLSE and in-vivo MLSE as presented in Fig. 3.

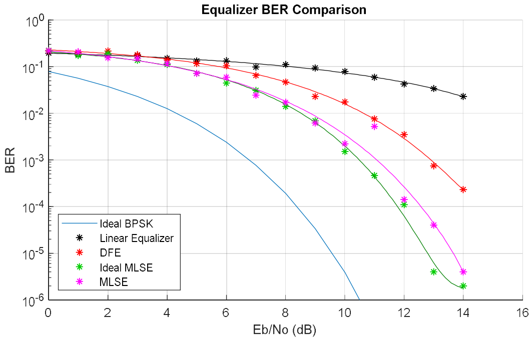

Fig. 3. BER performance of different equalizers for in-vivo radio channel communication.

III. CONCLUSION

This paper presents BER performance of in-vivo radio channel by improving the bit error rate (BER) by using MLSE and compared the results with LMS, RLS and DFE equalizers. The paper explains how those equalizers were used to test their performance to improve the BER for an in-vivo channel. BER is compared to the LMS, RLS, DFE and ideal binary phase shift keying (BPSK) at ultra-wideband frequencies between (3.1-10.6 GHz). It is concluded that in-vivo radio channel at UWB is a critical channel and will be suffered from ISI due to the complex structure of the human body. To achieve the required results one must performed equalizers to get rid of ISI. As a future work we suggest that research must continue in this area as there is still some space of improvement for this complicated channel. The use of channel coding techniques is suggested which can help improve the channel BER. The conventional channel coding techniques is also a question mark for in-vivo communication to understand if those techniques can help us improve the performance.

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