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Bit Error Rate Estimation for Galvanic-type Intra-body Communication using Experimental Eye-diagram and Jitter Characteristics*

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Abstract—**Bit error rate (BER), which indicates the reliability of communicate channel, is one of the most important values in all kinds of communication system, including intra-body communication (IBC). In order to know more about IBC channel, this paper presents a new method of BER estimation for galvanic-type IBC using experimental eye-diagram and jitter characteristics. To lay the foundation for our methodology, the fundamental relationships between eye-diagram, jitter and BER are first reviewed. Then experiments based on human lower arm IBC are carried out using quadrature phase shift keying (QPSK) modulation scheme and 500 KHz carries frequency. In our IBC experiments, the symbol rate is from 10 Ksps to 100 Ksps, with two transmitted power settings, 0 dBm and -5 dBm. Finally, the BER results were obtained after calculation by experimental data through the relationships among eye-diagram, jitter and BER. These results are then compared with theoretical values and they show good agreement, especially when SNR is between 6 dB to 11 dB. Additionally, these results demonstrate assuming the noise of galvanic-type IBC channel as Additive White Gaussian Noise (AWGN) in previous study is applicable.**

I. Introduction

Intra-Body Communication (IBC), which has the advantages of low power and secure signal transmission, is developed as a new method for data communication. Galvanic-type and capacitive-type are two main coupling-types of IBC. Galvanic-type is a relatively new technology and it has been attempting to become a front-runner candidate of IBC because of its lesser interference to the nearby environment and operation at lower frequencies with the capacitive-type [1]. However, its characteristics have not been fully known, such as the reliability of the channel.

Bit error rate (BER) quantifies the performance of entire communication system from “bit in” to “bit out” [2]. This criterion has been widely used in channel analysis. Therefore, it is one of the most obvious figures of merit to decide galvanic-type IBC channel has potential to transmit and receive data reliably. Its definition can be expressed as below:

$$BER = Number\ of\ Errors\ /\ Total\ Number\ of\ Bits \tag{1}$$

For example, if the BER value equal to 10^{-10}, it means with 10^{10} bits data being transmitted, only one bit errors is allowed. We can see the total number is quite enormous. The traditional method usually disposes all transmit and receive data directly by designing specified prototype. For low carrier frequency, low data rate transfer in a reliable channel, this measured process is extremely time-consuming and becomes impractical. Consequently, finding a new or alternate method for BER estimation is worthy and valuable.

On the one hand, jitter is one of the enemies of BER. Jitter means the deviation of a timing event of a signal from its ideal occurrence in time [3]. In other words, BER closely depends on jitter in the communication system and the BER estimation could be done from jitter. On the other hand, one way to represent the effect of jitter is eye-diagram [4]. Eye-diagram contains useful information of jitter due to its definition. From these two relationships, we can obtain the BER estimation for galvanic-type IBC from experimental eye-diagram and jitter while the traditional way will take unreasonable time to do it.

In order to know more about the performance of galvanic-type IBC channel, the works here focus on estimating its BER values by our aforementioned idea. Section II concentrates on the analysis of relationships among eye-diagram, jitter and BER. Theories will be briefly reviewed to obtain the proposed method. Section III shows the experiment of BER estimation based on galvanic-type IBC through human lower arm. Quadrature phase shift keying (QPSK) modulation scheme and 500 KHz carries frequency were employed [1]. In addition, the range of symbol rate is from 10 Ksps to 100 Ksps, with two power levels of 0 dBm and -5 dBm. Section IV discusses the experimental results compare with theoretical calculation and previous works in [1][5]. Finally, conclusions can be found in section V.

II. Methodology

Jitter is a time-domain phenomenon reflecting any errors deviate from the ideal timing. It causes edge transition to be either earlier or later compare with the ideal timing location. Traditionally, jitter can be expressed in normalized to one unit interval (UI), which means the time duration of a bit of the transmit data.

Jitter, also called as total jitter (TJ), is generally classified into deterministic jitter (DJ) and random jitter (RJ). The major

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causes for DJ include electromagnetic interference (EMI), signal reflection and dielectric loss. On the other side, the main causes of RJ are flicker noise, thermal noise and shot noise, which are related to device noise sources. It is possible to assume that both DJ and RJ are independent due to they caused by different theories. As a result, the probability density function (PDF) of TJ f_{TJ} is the convolution of DJ PDF f_{DJ} and RJ PDF f_{RJ}, which can be written as [3][6]:

$$f_{TJ} = f_{DJ} * f_{RJ} \tag{2}$$

Strictly speaking, the convolution result depends on its components. However, in most cases, TJ PDF can be characterized by Gaussian distribution function because of its RJ characteristic of unbounded noise source, though there are still some influences determined from DJ.

An eye-diagram is composed of all the time duration of the captured data bits and superimpose into a clock. The more widely open area of eye means the better performance of communication channel. Eye-diagram superimposes the edge transitions into one UI range and jitter usually occurs on the rising or falling edge of the signal [3]. Therefore, we know each eye-diagram has its associated jitter, as shown in Figure 1.

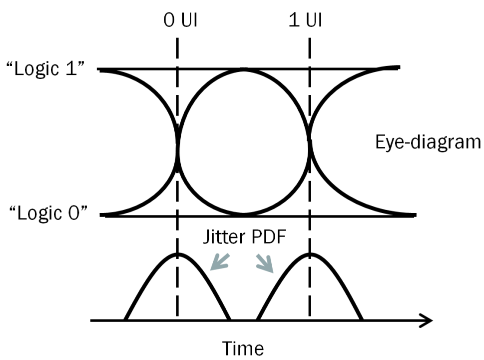


Figure 1. Eye-diagram and its associated jitter

On the other hand, to consider the relationship between jitter and BER, it is well known that a bit error will happen when the relative timing relationship between jitter and sampling time t_s is out of the expected range [3]. In other words, the jitter PDF and BER cumulative distribution function (CDF) is firmly relative to the sampling time t_S, as shown in Figure 2.

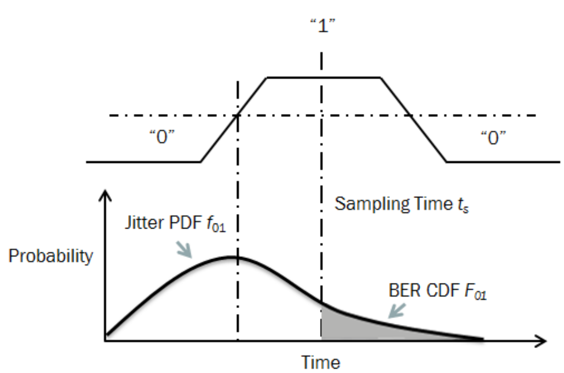


Figure 2. Relationship between jitter PDF and BER CDF as a function of sampling time t_s

From Figure 2, in the interval 0-1, for jitter PDF f_{01}, any edge transitions occur on the right side of the sampling time t_s will cause a bit error. Therefore, the BER CDF in this interval F_{01} is the integral of all the jitter values larger than the sampling time t_s in f_{01}, which as shown in the shaded part. Similarly, we know that in the interval 1-0, the BER CDF F_{10} is the integral of all the jitter values smaller than the sampling time t_s in f_{10}. In summary, the BER CDF is made up of contributions from both 0-1 and 1-0 edge transitions, which can be simplified below [3][8]:

$$\begin{aligned} BER\ CDF &= F_{01}(t_s) + F_{10}(t_s) \\ &= P_{01}\int_{t_s}^{\infty} f_{01}(\Delta t)\, d\Delta t + P_{10}\int_{-\infty}^{t_s} f_{10}(\Delta t)\, d\Delta t \end{aligned} \tag{3}$$

Please note that P_{01} in Equation (3) means the probability for 0-1 edge transition and the similar as P_{10}. For equal digital sources probabilities, these values are 0.5, which indicate "0" and "1" have the same probability of occurrence. Using Equation (3), the BER curve as a fucntion of sampling time t_s can be figured out. Moreover, when t_s equals to 0.5 UI, the sampling time has no drift and the corresponding BER values at that time is the best of the measured channel.

According to the above theories, if we get the original trace points which generates eye-diagram, the period of all the captured data bits can be found. Then to compare these periods with the known clocks, the deviations of them are jitter. In addition, if we obtain the jitter PDF after doing statistics from previous step, the BER CDF can be figured. Hence the jitter PDF can be used to estimate BER values of the communication channel. To combine these two principles, the block diagram of our proposed method is shown in Figure 3.

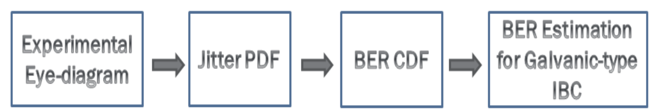


Figure 3. Block diagram of proposed method

III. Experiment

In order to evaluate the performance of galvanic-type IBC channel by BER and to demonstrate the feasibility of our proposed method of BER estimation, pilot experiments have been done in this section.

Galvanic-type IBC utilizes the human body as medium for data communication. The transmitter converts the transmitted signal into a flow of ionic current within the tissue and the receiver recovers the original signal by detecting the ionic current flow. In our *in vivo* experiment, a young healthy male was recruited. His lower arm plays as the communication channel. A signal generator (Agilent, N5182A MXG Signal Generator) was used as the transmitter. It generates and transmits the digital signal using QPSK modulation scheme with 500 KHz carries frequency. We chose QPSK because it is an efficient digital modulation to improve power efficiency and bandwidth efficiency for galvanic-type IBC from previous researches [1][5]. Moreover, the range of symbol rate is from 10 Ksps to 100 Ksps, with two fixed powers of 0 dBm and -5 dBm. A signal analyzer (Agilent, N9020A MXA Signal Analyzer) was used at the receiver to detect signal. Both the received signal and corresponding eye-diagram were demodulated and generated by its associated 89600 Vector Signal Analysis (VSA) software. Two pairs of 4cm*4cm physiotherapy electrodes (Shanghai Litu Medical Appliances

Co.,LTD, LT 01) were employed to connect the transmitter to body and the receiver to body simultaneously. The separation distance is 6 cm. As usual, the experiment done here have been performed carefully to take care of the common ground problem by using a differential probe (Agilent, 1141A) and battery-powered equipment. The experiment set-up block diagram is displayed in Figure 4.

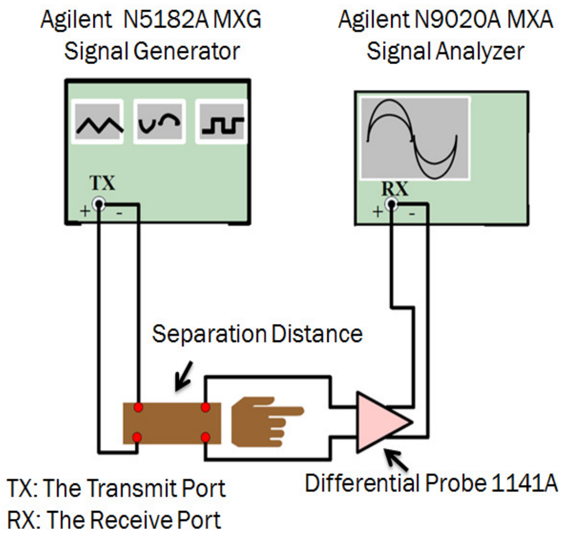


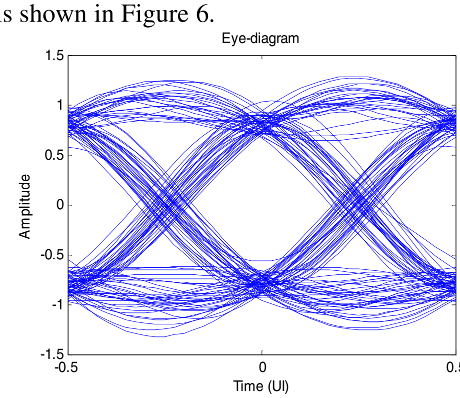
Figure 4. General block diagram of *in vivo* experiement

After cleansing the skin and attaching the electrodes, the testing digital signal (random pattern, symbol rate from 10 Ksps to 100 Ksps, step 10 Ksps, with two fixed powers of 0 dBm and -5 dBm) can be applied to the lower arm. When we complete setting the parameters of the VSA software, it automatically begins to detect and demodulate the received signal. In the meanwhile, it also records the captured trace points of eye-diagram and displays the eye-diagram on the screen of analyzer. Both the captured trace points (5100 points, every 20 points a clock, thus 255 data bits in total) and experimental information can be stored. Using the trace and information, we find out the period of all the captured data bits. Then we compare these periods with the clocks and perform basic statistics of them by Microsoft® Excel. Finally, all the jitter values of the eye-diagram can be obtained. Figure 5(a) shows the reconstructed eye-diagram based on the acquired trace points using Matlab® to indicate the experimental data is correct. Figure 5(b) shows the histogram of statistical jitter. Figure 5(c) shows the jitter PDF obeys Gaussian distribution derives from its corresponding histogram in Figure 5(b). In this case, the symbol rate is 10 Ksps and the transmitted power is 0 dBm. Moreover, one UI equal to 0.1 ms.

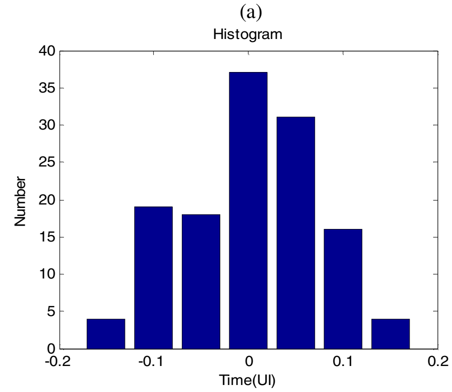
The calculation results of jitter in this case by Matlab® are: mean (μ) 0.271 μs, standard deviation (σ) 7.12 μs and variance (σ^2) 50.69 μs^2. To substitute these values into the formulation of Gaussian distribution, we get the jitter PDF equation below:

$$f(x) = \frac{1}{\sqrt{2\pi}\sigma} e^{-\frac{(x-\mu)^2}{2\sigma^2}} = \frac{1}{0.0178} e^{-\frac{(x-0.000271)^2}{0.000102}} \quad (4)$$

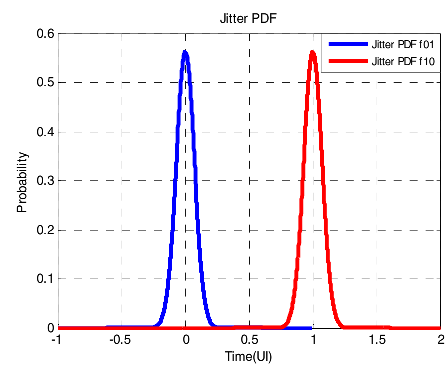
Please note that the unit of Equation (4) is ms. With Equation (4), we perform the integral using Equation (3) to find the BER CDF varied with the sampling time t_s in one UI. In this case, the range of t_s is from 0 ms to 0.1 ms. The BER curve is shown in Figure 6.



(a)



(b)



(c)

Figure 5. Resluts of jitter from experimental eye-diagram with symobl rate is 10 Ksps and transmitted power is 0 dBm: (a) Reconstructed eye-diagram using Matlab®; (b) Histogram of statistical jitter; (c) Jitter PDF based on (b)

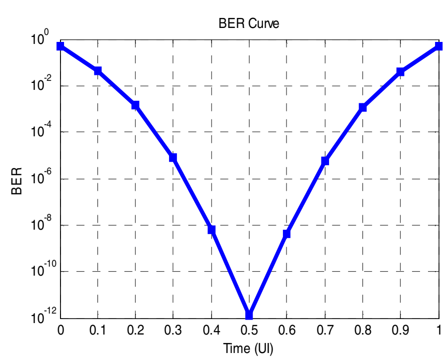


Figure 6. BER curve from jitter PDF

From Figure 6, the curve is monotone decreasing in 0-0.5 UI interval and monotone increasing in 0.5-1 UI interval. The BER performance is the best when the sampling time t_s equal to 0.5 UI and the value at that time is 1.2562×10^{-12}.

IV. RESULTS AND DISCUSSION

The theoretical BER can be calculated through signal to noise ratio (SNR), which means the ratio of average signal energy per bit to noise power spectral density E_b/N_0. In this experiment, we also record the SNR values of each measured eye-diagram by VSA software. For QPSK, the theoretical calculation can be done using the following equation, where Q(x) is the Gaussian Q-function:

$$BER = Q\left(\sqrt{2E_b/N_o}\right) \tag{5}$$

Based on our proposed method, the BER values of symbol rate from 10 Ksps to 100 Ksps, with powers of 0 dBm and -5 dBm are obtained. To combine all these values together into one figure, Figure 7 presents the performance of BER versus SNR in experiment and theoretical calculation:

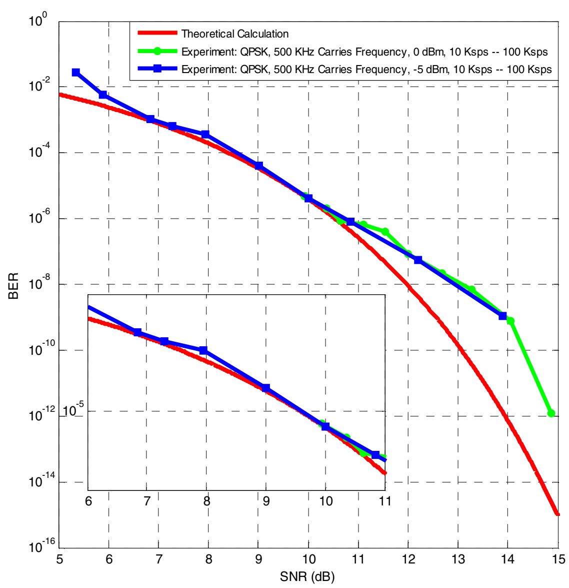


Figure 7. Performance of BER versus SNR in experiment and theroy

As depicted in Figure 7, the performance of experimental BER calculated by our proposed method shows the similar trend as theoretical values, where there exist some deviations in highly SNR region. Theses deviations may be related to the limited interval measurement between every two trace points of one UI in high SNR region, which directly affect the results of jitter and BER. When SNR is between 6 dB to 11 dB (see the inset of Figure 7), the experimental results seem consistent with the theoretical results in particular. We can find that for galvanic-type IBC channel at separation distance is 6 cm, with 500 KHz carrier frequency, QPSK have the BER performance lower than 10^{-5} under the symbol rate of 100 Ksps in 0 dBm and lower than 10^{-2} under the symbol rate of 100 Ksps in -5 dBm respectively.

V. CONCLUSION

In this paper, we have presented a new method of BER estimation using experimental eye-diagram and jitter characteristics. The details of our proposed method are discussed and analyzed. From the galvanic-type IBC channel experiment, we found out the BER performance has the similar trend with theoretical results. To investigate the process and results in the experiment, we not only verified the relationship between eye-diagram, jitter and BER, but also demonstrated the reliability and availability of our idea. Moreover, the method has better performance when SNR is between 6 dB to 11 dB compare with other interval. In addition, according to the statistical histograms of jitter, we also found out most of them obey Gaussian distribution. It means assuming the jitter PDF as Gaussian distribution function in most cases is reasonable. This phenomenon also demonstrates that assuming the noise of galvanic-type IBC channel as AWGN in previous researches [1][5] is reasonable and significant.

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