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Energy-Quality System Design for In-Body Communication

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Abstract—**With the explosive development of wireless communication technology, more and more implanted medical devices appear in everyday life. Because of the limited energy resource in implanted devices, the energy-quality wireless system design is the biggest challenge. In this paper, we update our former system level energy model and make it suitable for implantable medical communication system. In the new model, the impacts of human body tissue on the signal transmission are considered. The wireless system energy consumption is minimized by adjusting the digital base-band and RF parameters such as signal bandwidth, peak-to-average ratio (PAR), modulation levels, data rates etc. In the communication quality evaluation, we consider the effects of 1/f noise and the third-order harmonic distortion in addition to normal channel noise.**

I. INTRODUCTION

With the development of medical devices, implanted medical devices such as pacemakers, nerve stimulators and drug pumps are widely used in medical treatment and monitoring as Fig.1[1]. These implanted devices are usually battery powered and the battery is non-rechargeable. However, most implanted medical devices have lifetime requirements of many years, and the development of battery technology is often lagging behind the people's requirements. To extend battery life, we must reduce the energy consumed by communication systems.

Fig.1 Medical treatment use implanted pacemaker

As is shown in the prior work, about 75% of the power is consumed by RF front-end in an IEEE 802.11-b wireless LAN card based on Intersil's PRISM II chipset [2]. In order to accurately evaluate the RF front-end energy consumption and find the dominant power parameters that impacts the energy consumption, it is important to develop an accurate and comprehensive energy model for RF sections. It is definitely helpful to trade off energy consumption and communication quality.

Different aspects of in-body communication have been addressed in recent years. These include channel model for body area network (BAN) [3], [4], [5], the impact of the changing nature of the human body on wireless communications [6], the impact of the body electrical properties on communication parameters [7], etc. However, until now, there has not been much work on system level design of low power in-body communication. Peter has discussed the design of an in-body communication system [1], however, it has not gave out an accurate energy model that can help us know the parameters which determine the whole energy consumption of RF front-end.

In this paper, we will design an energy-quality in-body communication system. We discuss the impacts of human body tissue on the signal parameters, and propose an updated RF energy model for MQAM modulation. The system power consumption can be decreased by adjusting the digital base-band and RF parameters such as signal bandwidth, PAR, modulation levels, data rates etc. At last, we also summarize the steps for energy-quality system design.

The remainder of this paper is organized as follows. Section II describes the effect of tissue on the signal parameters. Section III updated energy model of wireless transceiver. Section IV simulates the communication quality with the consideration of 1/f noise and harmonic distortion, and the system design steps are proposed. Section V summarizes the conclusions.

II. TISSUE EFFECTS ON SIGNAL TRANSMISSION

Energy-quality wireless communication system design is always tightly related to the accurate channel model. However, the implantable medical communication channel is different from the normal free space channel. The impact of human tissue on signal transmission is serious. We must evaluate the impacts of human tissue on the communication parameters. The body electrical properties is given out in [7], and it also described the impact of human tissue on signal wavelength and the absorb effect on the signals. The body electrical properties are shown in TABLE I, where ε represents the dielectric constant, σ is the conductivity, and

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Z_0 is the characteristic impedance. From TABLE I, we can see that the two mediums, muscle and fat, have obviously different electrical properties and vary with frequency.

TABLE I
BODY ELECTRICAL PROPERTIES [7]

Frequency (MHz)		100	400	900
Muscle	ε	66.2	58.0	56.0
	σ (Sm^{-1})	0.73	0.82	0.97
	Z_0 (Ω)	31.6	43.7	48.2
Fat	ε	12.7	11.6	11.3
	σ (Sm^{-1})	0.07	0.08	0.11
	Z_0 (Ω)	92.4	108	111

The dielectric constant has an effect on the wavelength of signals. In different mediums, the relationship of the signal wavelength and the dielectric constant is as equation (1)

$$\lambda_{medium} = \frac{\lambda}{\sqrt{\varepsilon}} \tag{1}$$

where λ is the signal wavelength in air (in meters), and λ_{medium} is the wavelength in medium.

Similar to the impact of the dielectric constant, the penetration depth of signal that passes through the tissue is also impacted by the frequency. The depth that signals can penetrate in different tissue with different frequency, is illustrated in TABLE II.

TABLE II
PENETRATION DEPTH OF TISSUE [7]

Frequency (MHz)	Muscle (mm)	Fat (mm)
100	75.1	339
400	51.5	229
900	41.6	163

The characteristic impedance is relevant with the type of medium. Therefore, some signals can be reflected at the boundary of different mediums, which can be described by a term known as reflection coefficient Γ as shown in (2)

$$\Gamma = \left|\frac{Z_0 - Z_r}{Z_0 + Z_r}\right| \tag{2}$$

where $Z_0 = 377\Omega$ is the impedance of free space, and Z_r is the impedance of medium in Ω. It can be calculated that at the muscle-fat boundary, for instance, $\Gamma = 80\%$ of the signal is reflected, which means that only 20% of the signal intensity remained after crossing the muscle-fat boundary.

From above analyses, we can see that the tissue impacts the signal transmission severely. So, we have to deal with the tissue's effect when discussing the implantable medical communication system design.

III. RF FRONT-END ENERGY MODEL

In order to minimize the total energy consumption of the transceiver, it is essential to consider the energy consumption of the RF front-end. In this work, the transceiver for implantable communication is described in Fig.2. The main components of the analog signal chain include Filter, Mixer, RF synthesizer, power amplifier (PA), low noise amplifier (LNA), anti-aliasing filter, and ADC.

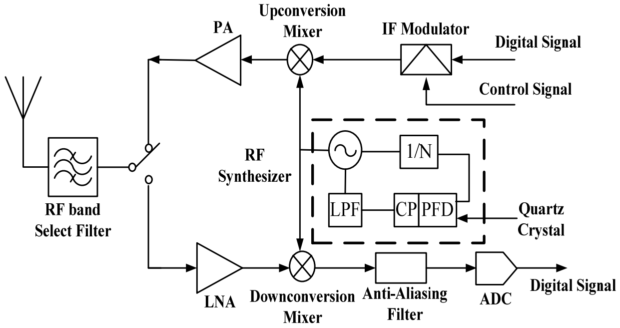

Fig.2 Block diagram of the transceiver analog signal chain

A. Preliminary

The performance of the wireless communication node with respect to energy consumption and communication quality is evaluated in this paper. Several dominant concepts and metrics are described as follows.

1/f noise is an intrinsic noise phenomenon found in semiconductor devices which is assumed -10*dB*/*dec* frequency dependency in power in this paper. We define the power spectral density of 1/f noise as $\overline{V}_n{}^2 = K_v / f$, where K_v is a device dependent constant. The 1/f noise can dominate the base-band noise budget in direct conversion receivers and degrades the communication quality.

Harmonic distortion is an important phenomenon caused by the nonlinearity of the system. The nonlinearity of the system changes the relationship between the output $y(t)$ and input $x(t)$ as [8]

$$y(t) \approx \alpha_1 x(t) + \alpha_2 x^2(t) + \alpha_3 x^3(t) \tag{3}$$

If $x(t) = A\cos\omega t$, we have

$$y(t) = \alpha_1 A\cos\omega t + \alpha_2 A^2 \cos^2\omega t + \alpha_3 A^3 \cos^3\omega t$$
$$= \frac{\alpha_2 A^2}{2} + \left(\alpha_1 A + \frac{\alpha_3 A^3}{4}\right)\cos\omega t + \frac{\alpha_2 A^2}{2}\cos 2\omega t + \frac{\alpha_3 A^3}{4}\cos 3\omega t \tag{4}$$

We call the term with the input frequency "fundamental" and the higher-order terms the "harmonics". The harmonics terms can change the system voltage, lead to a high PAR, and it can also bring out the phase rotation of the transmitted signal. So, it can increase the system power consumption and decrease the system performance. Even-order harmonics can be vanished if the system is fully differential, and higher harmonics are ignored due to low amplitude. In this paper, we only consider the effect of third harmonic distortion.

PAR is the ratio of the signal peak power to its rms value and is defined as $\mathrm{PAR\,(dB)} = 10\log(P_{peak} / P_{rms})$, where P_{peak} denotes the peak power, and P_{rms} denotes the average power, PAR gives information on how the signal is distributed over the amplitude range. PAR is an important parameter that affects both energy consumption and communication quality.

PAR is a function of both modulation level *b* and roll-off factor α . Thus

$$\begin{aligned}\mathrm{PAR(dB)} &= \mathrm{PAR}_{modulation}\,\mathrm{(dB)} + \mathrm{PAR}_{roll-off}\,\mathrm{(dB)} \\ &= 10\log\left(\sqrt{\frac{3\cdot\left(2^{b/2}-1\right)}{2^{b/2}+1}}\cdot \mathrm{PAR}_{C}\right) + \mathrm{PAR}_{roll-off}\,\mathrm{(dB)}\end{aligned} \tag{5}$$

Where PAR_C is the PAR of the carrier. If the carrier is a sine wave, PAR_C=1.4. $\mathrm{PAR}_{roll\text{-}off}$ is the PAR related to the roll-off factor α. This equation also shows that PAR increases with the modulation level *b*.

B. RF front-end energy model

In our previous work [9], we built an energy model of the RF front-end in transmit mode. The dominant power parameters for the mixers, frequency synthesizer, ADC, DAC, and analog filters are hard to be adjusted and we assume the total power consumption of these blocks is 12mW for medical wireless communication according to Zarlink products [10]. Although the ADC and DAC are also PAR-sensitive components and thus the power consumption is related to the modulation level, the power variation in the two converters is comparatively small. Hence, we consider the two converter power consumption as a constant. However, the power consumption of the PA is dominant in RF front-end and depends on adjustable parameters such as *d*, *PAR*, R_s, and *b*, allowing us to select these parameters so as to minimize the total RF circuit energy consumption.

As mentioned before, the human body tissue not only affects the signal wavelength, but also the signal penetration depth. For the characteristic impedance is various in different tissues, the signal can be reflected partially at the different tissue boundary. According to the different mediums the signal passed, the signal energy consumption can be divided into the energy consumed in muscle, fat and air.

We update our former RF energy model and have the new active energy consumption equation with the additional consideration of the effect of human tissue.

$$\begin{aligned}E_{bit} = \frac{12\times10^{-3}}{b\cdot R_s} + \frac{L}{3G_tG_rK}\left(\frac{(4\pi)^2 d_1^{\,\mathrm{n1}}}{\lambda_1^{\,2}(1-\Gamma_1)}\cdot\frac{(4\pi)^2 d_2^{\,\mathrm{n2}}}{\lambda_2^{\,2}(1-\Gamma_2)}\cdot\frac{(4\pi)^2 d_3^{\,2}}{\lambda_3^{\,2}}\right)(2^b-1) \\ \cdot N\cdot\frac{1}{b}\left(Q^{-1}\left(\frac{1}{4}\left(1-\frac{1}{2^{b/2}}\right)^{-1}\cdot b\cdot BER\right)\right)^2 PAR\end{aligned} \tag{6}$$

where G_t and G_r are the transmit and receive antenna gain respectively, *L* is the system loss factor not related to propagation, *K*=0.5 is a constant, and *BER* is the bit error rate, d_1, d_2, d_3 denote the distance of signal transmit in muscle, fat and air respectively. We can choose d_1, d_2 according to people's physique, $n1$, $n2$ are the corresponding path loss exponents, $\lambda_1, \lambda_2, \lambda_3$ represent the carrier wavelength in three different medium respectively, and Γ_1, Γ_2 are the reflection coefficients at the muscle-fat boundary and fat-air boundary respectively. The first term $12\times10^{-3}/(b\cdot R_s)$ is the energy consumption of all the components except the PA, and the second term is the energy consumption of the PA.

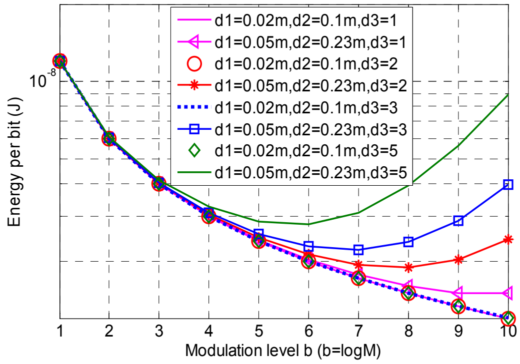

Fig.3 RF front-end active energy per bit vs modulation level with different transmit distance, $\mathrm{PAR}_{roll-off} = 10\mathrm{dB}$, $\mathrm{BER} = 10^{-3}$

Fig.3 describes the effect of the modulation level *b* on energy per bit for different transmit distance and different people. The different value of d_1 and d_2 represent different people, larger d_1 and d_2 indicate the people strong and fat, and smaller ones mean the people thin, and d_3 is the transmission distance in air. The main simulation parameters are listed in TABLE III. From Fig.3 we can see, for the thin people, the energy per bit consumed by the RF front-end decreases with the increase of *b*, but for the strong and fat one, the energy will decreases with the increase of *b* first, and when *b* increases to a certain value, the total energy consumption will increase with *b*. This is because, for the thin people, the tissue's effect on the power consumption of PA is not dominant, but for the strong and fat one, the tissue's effection is very serious, it lead the energy consumption of PA will increase with *b*, as the increase of *b*, the energy consumption of PA become dominant. So we see different trends in the curves.

TABLE III
SYSTEM PARAMETER VALUES IN DETERMINING THE OPTIMAL MODULATION LEVEL

$L = 1.25$	$K = 0.5$
$\Gamma_1 = 0.8$	$\Gamma_2 = 0.55$
$n_1 = 5$	$n_2 = 3.7$
$BER = 10^{-3}$	$PAR_C = 1.4$
$N/2 = 10^{-16}\,\mathrm{W/Hz}$	$R_s = 1\mathrm{MHz}$

IV. ENERGY-QUALITY MEDICAL WIRELESS COMMUNICATION SYSTEM DESIGN

The harmonic distortion and 1/f noise, caused by the nonlinearity of RF circuit, have a serious impact on the communication performance. And in this section, we evaluate the communication quality with the consideration of 1/f noise and the third-order harmonic distortion in AWGN channel. The figures are plot by simulations.

Fig.4 and Fig.5 are the original signal constellation and the received signal constellation which contains third-order harmonic distortion and 1/f noise respectively. Compared to the original signal constellation in Fig.4, the received signal constellation in Fig. 5 shows an obvious rotation due to third-order harmonic distortion. As a result, the BER increases. Fig.5 demonstrates that it is necessary to consider the third-order harmonic distortion, 1/f noise when evaluates the communication performance.

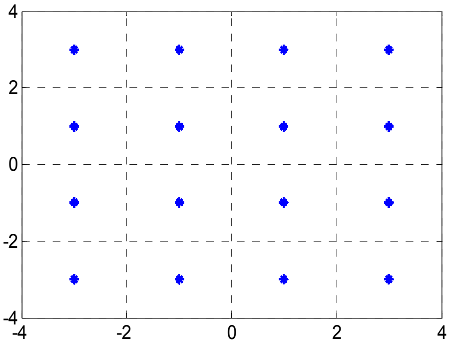

Fig.4 Original signal constellation

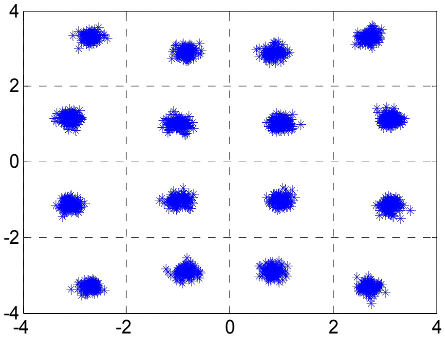

Fig.5 Signal constellation that contains
RF circuit noise and nonlinear distortion

The system BER with the consideration of the effects of the third-order harmonic distortion (-25*dBc*) and the 1/f noise (-10*dBc*/*dec*), is presented in Fig.6. In order to ensure the reliability of the simulations, each BER value in Fig.6 is calculated by the simulation results of 7.98×10^6 samples. Since the impacts of third-order harmonic and 1/f noise are also considered, our BER curves are more accurate than that of the traditional digital communications.

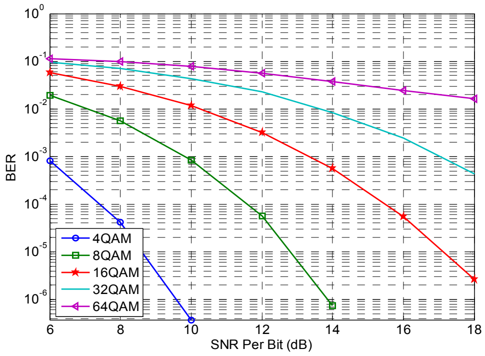

Fig.6 Communication quality

According to Fig.6 and Fig.3, we can design an energy-quality in-body communication system for required BER under certain transmission distance. For instance, if the required SNR per bit in typical wireless environment vary from 6 to 18dB and $\text{BER} \le 10^{-3}$, the candidate modulation levels are $b = 2,3,4,5$. Suppose d_3=1m, we find that the energy consumption is the smallest at modulation level b=9 in Fig.3. But b=9 is not a candidate modulation level, so we have to abandon it and choose other values in the candidate modulation levels. It is clear that b=5 is optimal according to Fig.3.

Based on the above analysis, we can summarize the steps for energy-quality implantable medical communication system design as follows:

1) Set BER threshold according to the system requirement and quality of service;
2) Choose the candidate modulation levels that satisfy the BER requirement in Fig.6;
3) According to the transmission distance value and the people's character: strong or thin, compare the active energy consumption of RF front-end in different candidate modulation levels, find the one with minimal energy value from Fig.3.

V. CONCLUSION

We propose an updated system energy model for in-body communication application in this paper. By the model, the impacts of human body tissues on the signal transmission are considered, the energy consumption of RF front-end can be minimized by adjusting the base-band parameters, such as modulation level, data rate and signal PAR etc. Besides channel noise, we evaluate the effects of 1/f noise and the third-order harmonic distortion on the communication quality. Finally, we summarize the steps for energy-quality in-body communication system design.

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