Design Methodology for Maximum Power Transmission, Optimal BER-SNR and Data Rate in Biomedical Implants

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Abstract—Using Pulse-Width Modulation Amplitude-Shift Keying (PWM-ASK) in biomedical implants enables the simultaneous transmission of wireless energy as well as data using a single inductive link. This paper approaches Pulse-Width Modulated Amplitude-Shift Keying (PWM-ASK) from a communication theory point of view. It provides a design methodology to obtain high data rate while maintaining an optimal BER (Bit Error Rate), and optimal power transfer in biomedical implants.

Index Terms—Pulse-Width Modulation Amplitude-Shift Keying, PWM-ASK, biomedical implants, wireless power.

I. INTRODUCTION

THE hearing or vision of an individual is affected when the auditory or visual nerves are damaged: the sensory information carried by the nerves can be sent to the brain using biomedical implants connected to an artificial sensor located externally [1], [2]. The data transmission requires a modulation scheme that provides a continuous carrier wave to the implant even in absence of data so that it can be powered wirelessly [3]. In addition, this modulation should be straightforward to implement and should require a reduced circuitry so as to minimize the power consumption in the implant. The Pulse-Width Modulated Amplitude-Shift Keying (PWM-ASK) modulation meets these requirements [4]: although complex modulation schemes such as DPSK, FSK and PSK can provide a considerably higher data rate, PWM-ASK modulation presents the opportunity to include both power and data transfer on the same link eliminating a separate data carrier which reduces the complexity, and therefore, the power consumption of the full system [5], [6].

This paper explores the performance of PWM-ASK modulation coding for medical implant communications, taking into account the following three requirements and the trade-offs between them, namely, continuously powering the implant, minimizing the Bit Error Rate (BER) for a given Signal to Noise Ratio (SNR) and maximizing the possible data rate. This paper is divided into three sections. Section II describes a design of a Class-E PWM-ASK modulated transmitter. Section III presents an in-depth analysis of PWM-ASK modulation, and derives the trade-offs that limit its performance. Section IV provides the simulation results of a case study conducted for power, BER-SNR and data rate of a PWM-ASK Class-E transmitter design.

II. GENERATION OF PWM-ASK USING A CLASS-E AMPLIFIER

Class-E amplifiers are used to transmit power and data to biomedical implants because of their outstanding efficiency [7]: refer to Fig. 1. The shunt capacitor \( C_2 \) neutralizes the transistor’s output capacitance, allowing a high frequencies operation. \( C_1, C_2 \) and \( L_1 \) are selected so as to ensure a minimal power consumption in the transistor [8]. Resistors \( R_1 \) and \( R_2 \) represent the equivalent series resistors (ESR) of inductors \( L_1 \) and \( L_2 \). As can be seen in Fig. 1, an extra transistor \( M_{ASK} \) shunting a constant voltage drop element is used to modulate the amplitude of the transmitted signal. However, the main issue with transmitting an Amplitude Shift-Keying (ASK) modulated signal is that a continuous sequence of zero data bits results in less power being transmitted to the implant. In order to overcome these problems, a PWM-ASK system is used: the data is encoded using PWM (Pulse Width Modulation), and the latter is used to modulate the amplitude of the carrier. The resulting signal is depicted in Fig. 2.

PWM-ASK involves a sub carrier modulation technique: the data rate is made a sub-multiple of the carrier frequency [9]. On the receiver (implant) side, a power efficient non-coherent detector with threshold crossing is used to demodulate the ASK signal. The selection of codes for the data transmission is of paramount importance, and is a trade-off between maximum...
power transmission, maximum data rate and lowest BER for a given SNR. This is examined next.

III. PERFORMANCE AND TRADE-OFFS OF PWM-ASK

A. Analysis of Maximum Power Transmission using PWM-ASK

In the case the modulation frequency is much smaller than the carrier frequency, the transmitted power contained in one PWM-ASK period is expressed as:

$$P_T = \frac{1}{T} \int_{t_0}^{t_1} A_H^2 \sin^2 (n \omega_c t) dt + \frac{1}{T} \int_{T-t_1}^{T} A_L^2 \sin^2 (n \omega_c t) dt,$$

where $\omega_c$ is the angular carrier frequency, $n$ is the number of carrier frequency cycles per data period ($T$), $A_H$ is the maximum amplitude, $A_L$ is the minimum amplitude and $t_1$ is the time that the carrier amplitude is $A_H$ (refer to Fig. 2). Working this out, yields:

$$P_T = \frac{A_H^2(t_1-t_0) + A_L^2(T-t_1)}{2T}.$$  \hspace{1cm} (2)

Let's now assume that a PWM-ASK modulated signal is comprised of random “0” and “1” bits, and that these occur on average with an equal probability. Let's call $t_1$ the time that the carrier amplitude is $A_H$ for bit 1 and $t_0$ the time that the carrier amplitude is $A_H$ for bit 0, as represented in Fig. 2. The average power per period is then equal to:

$$P_T = \frac{A_H^2(t_0+t_1) + A_H^2(T-(t_0+t_1))}{4T}.$$  \hspace{1cm} (3)

Assume a modulation index $m = A_H/A_L$. The average power per period as a function of $m$ is then expressed as:

$$P_T = \frac{A_H^2(t_0+t_1) + A_H^2}{4T} \frac{1}{m^2} (2T-(t_0+t_1)).$$  \hspace{1cm} (4)

The obtained power content can be normalized as a function of $t_0 + t_1$: this results in a plot that can be used irrespective of the PWM-ASK carrier frequency, choice of coding and amplitude. Refer to Fig. 3: this figure shows the plot of average power per period in percent as a function of $(t_0 + t_1)$ for various values of modulation index $m$.

B. Communication Performance of PWM-ASK

The energy levels of a signal play a vital role when it comes to data communication. A larger difference in energy levels between transmitted data bits simplifies the amplitude demodulation, although this reduces the average amount of power which is being transmitted. Eq. (5) expresses the transmitted energy level probability $(g)$ which is contained in a binary code which is $b$ bits long:

$$g = \frac{1}{\sigma \sqrt{2\pi}} e^{-\frac{(x-\mu)^2}{2\sigma^2}},$$  \hspace{1cm} (5)

where $\mu$ and $\sigma$ are the mean value and standard deviation of signal’s energy level, and $x$ is the energy contained in the bit combination. The transmitted energy probability level depends on the number of bits $b$ being transmitted, as there are $N = 2^b$ possible sequence combinations.

Fig. 4 shows the discrete Gaussian distribution in relation to energy levels for OOK and ASK modulation ($b = 25$). The energy spread between ASK is small compared to the one present using OOK. Fig. 5 shows the discrete Gaussian distribution in relation to energy levels for two cases of PWM-ASK ($b = 25$). Although a random binary sequence, which is encoded using PWM-ASK modulation, will contain a high average energy (e.g. the bit code having the highest probability of occurring contains more "1" bits using PWM-ASK than OOK), the spread between the energy contained between the "1" and "0" bits is smaller (e.g. the standard deviation is smaller for PWM-ASK compared to OOK). Since the energy difference between the "1" and "0" bits is correlated to the BER, the latter will increase for a given SNR.

It can be seen from Fig. 4 and Fig. 5 that PWM-ASK achieves a comparable average energy content to the one obtained with ASK modulation for similar modulation indexes when $t_0 + t_1$ is equal to 1. As expected, there is a correlation between the energy level distribution of PWM-ASK (Fig. 5) and the power per data bit period depicted in Fig. 3. However, PWM-ASK (Fig. 5) contains little differentiation between the energy contained in bits "0" and "1" and as a result has a lower standard deviation compared to OOK (Fig. 4). This is especially the case when $t_0 + t_1 > 1$, as it becomes more
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The transmitter in Fig. 1 is restricted due to the L transmitter circuit in question: the performance of Class-E versus relative energy performance. \( \Delta \) schemes having the same \( \Delta \)s can be appreciated in Fig. 2, the data rate will be restricted by the shortest time interval present in the PWM-ASK signal \( t_0, t_1, T - t_0 \) and \( T - t_1 \), as the latter needs to be larger than the rise or fall time. Clearly, the data rate handling capacity of the PWM-ASK system is more limited compared to ASK and OOK modulation. Fig. 7 shows the data rate as a function of the bit error rate (BER) derived from Fig. 6, if both \( t_0 = 0.8 \) and \( t_0 = 0.4 \) (normalized with respect to T as previously), and in case OOK and ASK are transmitting at a maximum of 100 kbps, the PWM-ASK maximum transmission would be 20 kbps. The highest achievable PWM-ASK data rate is, therefore, achieved when \( t_0 \) and \( t_1 \) are both 0.5, with a maximum data rate of which is half of the maximum data rate obtained for the ASK and OOK modulation. However, as derived from Fig. 6, if both \( t_0 \) and \( t_1 \) are equal to 0.5, the energy difference between bits 0 and 1 becomes zero, meaning that no data communication is possible.

**D. Figure of Merit**

A figure of merit (FOM) combining the three evaluated parameters (average transmitted power, BER and the maximum achievable data rate) is defined as:

\[
FOM = P_r. \Delta E. DataRate.
\]  

As can be appreciated, the data rate will be restricted by the shortest time interval present in the PWM-ASK signal. However, as derived from Fig. 6, if both \( t_0 \) and \( t_1 \) are equal to 0.5, the energy difference between bits 1 and 0 becomes zero, meaning that no data communication is possible.

**C. Data Rate**

The data rate is limited by the practical realization of the transmitter circuit in question: the performance of Class-E transmitter in Fig. 1 is restricted due to the \( L_{\text{Choke}} \), which introduces ringing when switching between amplitude levels [6]. This results in rise and fall times \( (t_{\text{rise}} \text{ and } t_{\text{fall}}) \) which, in turn, place an upper limitation on the bit transfer. Considering the PWM-ASK waveform depicted in Fig. 2, the maximum achievable data rate is equal to:

\[
DataRate = \frac{1}{t_{\text{rise}} + t_{\text{fall}}}. \tag{7}
\]

It should be observed that ASK and PWM-ASK modulation schemes having the same \( \Delta E \) and \( m \) will result in similar BER versus relative energy performance.

**IV. Case Study**

In order to analyze and validate the previously derived expressions, a suboptimal code \( (t_1 = 0.8 \text{ and } t_0 = 0.5) \) is compared to the optimal case derived here above \( (t_0 = 0.25 \text{ and } t_1 = 0.75) \). The suboptimal coding choice has been derived...
from an earlier work [10]. When $t_1 = 0.8$ and $t_0 = 0.5$, the average normalized power per period is higher (71%). However, the normalized energy difference as well as the maximal data rate is lower than in the optimal case. Table I shows the performance differences between the two cases.

It should be observed that although a conventional PWM-ASK modulation choice may yield a better performance in certain areas (average normalized power, in this case), a penalty will be incurred in the other parameters (as, in this case, the BER - which is proportional to the normalized energy difference - and the maximum achievable data rate). As an example, it can be observed in Fig. 9 that the optimal case ensures a minimal BER for a given SNR at the expense of a lower normalized average power (Table I).

V. CONCLUSIONS

This paper discusses the optimal settings for a Pulse-Width Modulated Amplitude-Shift Keying (PWM-ASK) modulated signal which is used to communicate with biomedical implants. A theoretical derivation illustrating the trade-offs between a high data rate, an excellent SNR-BER performance and an optimal power transfer has been described: a practical case study shows how the presented functional expressions are used to identify and balance the different design requirements.

REFERENCES