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A Novel Pulse-Based Modulation Technique for Wideband Low Power Communication with Neuroprosthetic Devices

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Abstract

Pulse Harmonic Modulation (PHM) is a novel pulse-based (carrierless) modulation method for wideband, low power data transmission across inductive telemetry links that operate in the near-field domain. PHM utilizes two or more unidentical pulses during each bit period to minimize intersymbol interference (ISI). In this paper, we describe the PHM concept and demonstrate its operation with a proof-of-concept prototype, which achieves a data rate of 5.2 Mbps at 1 cm coil separation with a bit error rate (BER) of 10^{-6} .

I. Introduction

Inductive links have been extensively used for short-range data and power transmission. An inductive link between two coupled coils is now one of the most common methods to wirelessly send power and data from the external world to implantable microelectronic devices (IMD).

Examples of such IMDs that need large volumes of data to operate are auditory and visual prostheses [1], [2]. There are also IMDs, such as invasive brain-computer interfaces (iBCI), which collect massive amounts of information from the central nervous system (CNS) and deliver it outside of the body for further processing and decision making [3]. Other examples of the near-field data transmission can be found in radio-frequency identification (RFID), contactless smartcards, and high throughput wireless sensors, particularly where the use of batteries is avoided due to extreme size, cost, and lifetime constraints [4].

Until now, all the data transmission techniques for such near-field applications have been carrier based. Amplitude shift keying (ASK) has been popular in the past because of its simple modulation and demodulation circuitry [2]. This method, however, is not robust against coupling variations and faces major limitations in high bandwidth data transmission, which needs high order filters with sharp cutoff that cannot be easily integrated in this low-frequency end of the RF applications. FSK, DPSK, and QPSK have also been used for the transmission of data from and to IMDs [5]–[7]. Since the data transmission in these methods has to rely on the continuous transmission of the carrier signal, these methods have high power consumption. Furthermore, these methods rely on power hungry blocks such as phase-locked loops (PLL) and oscillators, increasing the overall power consumption and complexity. Thus, we concluded that carrier based techniques are more appropriate for data

transfer from outside of the body, where size and power are less constrained, to the IMD (often referred to as *downlink*).

For wideband data transmission from the IMD to outside of the body (the uplink), most researchers so far have used active back telemetry circuits, such as voltage controlled oscillators (VCO) that utilize similar carrier based modulation techniques in the far-field domain [3]. As a result, the RF transmitter is one of the key power consuming blocks in such IMDs. An alternative method is passive back telemetry using load shift keying (LSK), which is commonly used in the RFID tags for data rates up to 0.5 Mbps [4]. Recently, Mandal et al. improved the LSK bandwidth for iBCI applications [8]. However, the LSK, which consists of a switch across the IMD power coil and an ASK receiver outside of the body, requires strong coupling between the coils and leads to a reduction of the IMD received power by the switching duty cycle, which is not desired in high performance IMDs.

Impulse Radio (IR) UWB, in which data is transmitted via sub-nanosecond pulses through wideband antennas, provides a low power method for data transmission. Low power consumption in the IR-UWB transmitters is mainly because of being carrier-less, which leads to the elimination of continuously-on, high-frequency oscillators or frequency stabilization circuitry. These features make the IR-UWB an attractive choice for the uplink in IMDs [9]. However, the caveat is that the commercial IR-UWB, which is intended for far-field interactions in the 3.1–10.6 GHz band, is highly absorbable in water and cannot penetrate or pass through tissue volume conductor.

In this paper we introduce a new carrier-less modulation technique, called *Pulse Harmonic Modulation* (PHM), for wideband, low power, and low complexity data transmission across inductive telemetry links that operate in the near-field domain at low frequencies, all of which are necessary to operate in the tissue environment.

PHM will be introduced in section II. In section III, we present our measurement results using a proof-of-concept discrete circuit implementation of a PHM-based wireless link, followed by concluding remarks in section IV.

II. Pulse Harmonic Modulation

The use of sharp and narrow pulses for data transmission, similar to IR-UWB, instead of carrier signals can reduce power consumption in the data transmitter (Tx). If these pulses are applied by a pulse generator on the Tx side to node P_1 of a transcutaneous inductive link with high quality factor (Q) LC-tank circuits, tuned at a certain frequency, F_t , on either side of the link, as shown in Fig. 1, then the link acts as a bandpass filter that only lets through a certain frequency with narrow bandwidth. The received signal at node P_2 on the receiver side (Rx) can be one of the many harmonics of the narrow pulses on the Tx, which are applied to P_1 for each data bit “1”.

The sinusoidal waveform, at frequency F_t , which appears on the Rx side at P_2 has a damping behavior. The rate of damping depends on Q_2 , the quality factor of the L_2C_2 tank circuit. In order to achieve a high data transmission rate, it is necessary for this oscillation to decay very quickly in a way that the next pulse, which represents the following data bit, can be easily detected after a short bit period. In other words, in order for one data bit, either “1” or “0”, to be distinguished from the previous data bit, the oscillation at P_2 due to the previous bit, which is also known as inter-symbol interference (ISI), must have significantly dampened at the onset of detecting the new data bit. One way to achieve low ISI is to reduce Q_1 and Q_2 . However, this can result in undesired reduction in the voltage gain across the wireless link and weakened filtering effect of the LC tanks, leading to undesired interference from the external sources, such as the power carrier. Both of these effects will reduce the

signal to noise ratio (SNR) at P_2 , making it harder to detect the serial data bit stream at a high data rate.

To facilitate the use of pulses for data transmission without degrading Q_1 and Q_2 , we must alter the oscillation pattern on the Rx in a way that it dampens much more rapidly than it would when left on its own in a high-Q LC tank circuit. For this purpose we introduce a new modulation technique called *Pulse Harmonic Modulation* (PHM).

In this method, shown in Fig. 2, instead of sending only one pulse per bit, similar to ordinary IR-UWB methods [9], a pair of successive pulses with specific timing and amplitudes is sent to create a rapidly damping pattern of oscillation that is easily recognizable from adjacent bits by the Rx circuitry. The first pulse, called the *initiation pulse*, sent at the beginning of each bit “1” period, starts the oscillation at node P_2 . After N cycles at F_t and before the end of the bit period, a second pulse, called the *suppression pulse*, is sent which causes a new oscillation that is at the same amplitude but out of phase with respect to the initial oscillation. The result is the cancellation and rapid damping of the sum of both oscillations at node P_2 after N cycles.

The amplitude and timing of the initiation and suppression pulses are determined by the data rate and F_t , to which the Tx and Rx LC tank circuits have been tuned.

$$t_d = (N + \frac{1}{2}) \times \frac{1}{F_t} \leq N < \frac{F_t}{DR} \quad (1)$$

where F_t is the resonance frequency of the inductive wireless link, and DR is the data rate. N is the desired number of oscillations on the Rx side that are allowed before the oscillation is suppressed. A larger N allows more time before the oscillation is suppressed and contributes to easier detection of each data bit at the cost of a lower DR .

Normalized amplitudes of the initiation and suppression pulses, 1 and $P < 1$, respectively, are selected based on the main link parameters: Q_1 , Q_2 , N , and the coupling coefficient between the two coils, k (see Fig. 1).

III. Discrete Circuit Implementation

A. PHM Transmitter

We have implemented a Pulse Pattern Generator (PPG) using an Altera Cyclone II[®] field programmable gate array (FPGA) to form the PHM transmitter along with the L_1C_1 tank circuit via port P_1 in Fig. 1. Fig. 3a displays the block diagram of the PPG circuit on the FPGA. Since this circuit produces pulses only at the falling edge and we intend to generate pulses for data value of “1”, $\overline{Data+Clk}$ is used as the input signal. $\overline{Data+Clk}$ goes low only when the data and clock values are “1” and “0”, respectively. The programmable delay block has been implemented to generate the necessary time delay, t_d , between the two PHM pulses based on (1). Fig. 3a also shows the schematic of the pulse generator block, which simply combines the input with its delayed version to produce a narrow pulse. The amount of this delay, t_{pw} , indicates the PHM pulse width. The PHM pulse amplitude control block has been implemented using a ladder network circuit. Alternatively, a digital to analog converter (DAC) could be used for this purpose.

B. Coils and tuning capacitors

To construct the wireless inductive data transmission link (L_1 and L_2 in Fig. 1) we used small figure-8 coils on FR4 PCB substrate [10]. The key advantage of this coil geometry in

our IMD application is its resilience against external magnetic field interference, which is important in multiband transcutaneous inductive wireless links. When a figure-8 coil is exposed to uniform or symmetrical external magnetic field, the currents induced in the two loops of each coil cancel out due to their opposing direction of winding, while the two data coils maintain a decent coupling. Coil geometries were designed for an uplink with nominal coil separation of $d = 10$ mm. L_1 is smaller to be embedded within the IMD, while L_2 will be located across the skin outside of the body. When the two coils are perfectly aligned, they have a simulated $k = 0.012$.

C. PHM Receiver

The PHM receiver, in essence, is a custom designed envelope detector. Fig. 3b shows the block diagram of the receiver. It consists of a low noise amplifier (LNA) at the front end with a total gain of 26 dB. A rectifier follows the LNA, which output is fed into a low pass filter (LPF) with 9 MHz cutoff frequency followed by a high-speed comparator to set the received high or low levels. A second Cyclone II® FPGA board oversamples the received pulses at 48 MHz and converts them to a serial data bit stream.

IV. Measurement Results

Fig. 4 shows the measurement results using the prototype PHM-based inductive data link, described in section III, at a coil separation of $d = 10$ mm. For transferring a data bit of “1”, the initiation pulse is transmitted at the beginning of the bit period, which results in an oscillation on the Rx side (P_1) at the harmonic frequency, $F_0 = 33$ MHz, to which the inductive link is tuned. The suppression pulse with $P = 0.8$ times the amplitude of the initiation pulse is transmitted with a time delay of $t_d = 106$ ns with respect to the initiation pulse for $N = 3$. This leads to the rapid damping of the oscillation on the Rx side after 106 ns (Fig. 4a). This is because the two individual oscillations caused by these two pulses, which are shown in Figs. 4b and 4c cancel each other out after $t_d = 106$ ns to significantly reduce the ISI. At this point the Rx will be ready to receive the next data bit. In other words, the waveforms in Fig. 4a are the superposition of the waveforms in Figs. 4b and 4c.

Another important observation from Figs. 4a and 4b is the comparison between the level of ISI with and without the suppression pulse, which directly affects the maximum attainable data rate. Fig. 4b shows that due to high $Q_2 \approx 45$, it takes about $2 \mu\text{s}$ following the initiation pulse for the envelope of the oscillatory waveform on the Rx side (P_2 in Fig. 1) to naturally die out in the L_2C_2 tank circuit and reach more or less the same level that is reached only after $\sim 0.2 \mu\text{s}$ with the help of the suppression pulse in Fig. 4a. As a result, the data rate at which the data link could reliably operate with a BER of 10^{-6} or lower, utilizing only the initiation pulse proved to be less than 250 kbps in our measurements, which was >20 times lower than what was achieved when we applied the PHM technique.

Fig. 5 shows the measured waveforms for the prototype PHM-based wireless data link, described in section III, operating at 5.2 Mbps, which is one of the highest rates ever reported. The serial data bit stream, shown on the top trace, is applied to P_1 in Fig. 1 in the form of the 2nd trace, i.e. two successive pulses for every bit “1” and nothing for bit “0”. The pulses are $t_{pw} = 15$ ns wide, $t_d = 106$ ns apart, and the second pulse is $P = 0.8$ times smaller than the first. The 3rd trace shows the modulated harmonics of the transmitted pulses that are received at P_2 , the input of the custom Rx shown in Fig. 3b, which amplifies, rectifies, low pass filters, and compares the envelope with a reference voltage to create the recovered data, shown on the lowest trace. Detected data is then fed into the Rx FPGA to be fully recovered and registered as a serial data bit stream by oversampling.

To quantify the quality of the prototype PHM data link, we used a Tektronix GigaBERT (GB1400) on the Tx side to generate a random serial data bit stream, and fed the received serial data bit stream into another GigaBERT on the Rx side to be analyzed. Once the two GigaBERTs were synchronized, they measured the BER in real time, which was 10^{-6} at 5.2 Mbps at a coil separation of $d = 10$ mm.

V. Conclusion

PHM tends to solve two key issues in traditional pulse based inductive wireless data links, which makes it attractive for implantable neuroprosthetic applications (IMD). First, it significantly reduces the ISI by rapidly damping the residual oscillations on the receiver side, which results in higher data rates at lower power consumption. Second, by sharpening the bandpass filtering capability of the LC tank circuits, it reduces the external interference, especially from the power carrier in multiband wireless links. Also power consumption of the transmitter can be reduced significantly by employing the carrier-less PHM technique. We have demonstrated the PHM functionality using a proof-of-concept discrete prototype by achieving a data rate of 5.2 Mbps at a distance of 10 mm with $\text{BER} = 10^{-6}$. We are now working on a PHM-based transceiver ASIC (Fig 6), which is expected to push the current limits in the near-field communication bandwidth and power consumption for IMD applications.

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Fig. 1.
A simplified model for transcutaneous inductive links.

Fig. 2.
Pulse Harmonic Modulation (PHM) conceptual waveforms, including key parameters.

Fig. 3.
Block diagram of the PHM (a) Transmitter and (b) Receiver.

Fig. 4.

Measured waveforms at nodes P_1 (blue) and P_2 (green) in Fig. 1, showing the effect of the initiation and suppression pulses when they are applied individually (b, c) and together (a) (coils distance = 10 mm).

Fig. 5.
Measured data transmission at 5.2 Mbps, using the PHM technique, across an inductive wireless link made of a pair of figure-8 coils, which are described in [10], placed 10 mm apart.

Fig. 6.
Layout of the PHM transceiver chip occupying 0.61 mm² die area.