A Wideband Telemetry Unit for Multi-Channel Neural Recording Systems

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Abstract — This paper describes a low-power design of a ultra-wideband (UWB) transmitter for biomedical applications. The transmitter is the part of a telemetry unit that is being developed for a multi-channel neural recording system. The transmitter in the telemetry is intended to be attached or implanted in the body. Meanwhile an off-shelf receiver will be replaced at a location up to 10 meters to detect the transmitted signal. We investigate the design of such a system for future neural recording systems and present some of the preliminary study herein.

Index Terms — Ultra wideband, implantable electronics, CMOS pulse generators.

I. INTRODUCTION

Recently, there have been significant advances in micro-electrode arrays and multi-channel neural recording systems \cite{1} – \cite{6}. Those systems, due to a large number of recording channels, naturally produce a huge amount of data that should be transmitted out of body to be processed or analyzed further. For example, a 128-channel neural recording system with 8-bit resolution at the Nyquist sampling rate generates 20 Mbps when recording extracellular action potentials whose signal energy spectrum is up to 10 KHz. As the number of channel increases the data rate will reach a speed of 100 Mbps and higher.

This large amount of data is usually transmitted to a receiver which is located outside the body through wires. However, using wires is not preferable in neural recording applications because those wires restrict the movement and behavior of animals or humans to be observed. In many cases, animals are anesthetized for the use of those wired-recording systems, where the behavior that can be observed is severely limited. This restriction can be solved only by using wireless telemetry. Furthermore, wireless capability is also preferred at the cosmetic point of view.

There are available standards that have been used so far for low data rate transmission and reception in some telemetry applications. There exists mainly two kinds of standards for wireless medical electronic devices. The first one is wireless medical telemetry services (WMTS). However, this frequency band is assigned for non-implantable devices and can only be used by licensed physicians, healthcare facilities, and supervised technicians \cite{7}. These regulations make WMTS devices difficult to be used for neural recording systems. Secondly, the US Federal Communications Commission (FCC) allocated 402 ~ 405MHz frequency band for medical implant communication service (MICS) in 1999 \cite{8}. On the contrary to WMTS band, MICS band is allowed for unlicensed use and implantable devices such as cardiac pacemakers, hearing aids, and neurostimulators. However, the allowable channel bandwidth is 300 kHz. It is difficult to assign enough data rate for the neural recording systems containing a large number of channels \cite{4}. It is quite obvious that there is an immediate need for higher-bandwidth data transmission for neural recording telemetry systems.

As the FCC assigned the spectrum from 3.1 GHz to 10.6 GHz for unlicensed use of ultra wideband devices to support high data rates \cite{10}, it provided an opportunity for a wideband wireless telemetry. The FCC has defined the UWB devices as one that has fractional bandwidth greater than 20% or absolute spectrum bandwidth greater than 500 MHz. Also, there are strict regulations on spectral shape and maximum power spectral density of a UWB transmitter to prevent the interference issues. Impulse Radio UWB (IR-UWB) and Multi-carrier UWB (MC-UWB) are the two general categories of UWB devices. The former is more appropriate for implantable neural recording systems because the latter is generally suitable for multiple access communication systems and thus have rather complex transmitters consuming high power. As the IR-UWB uses simple short pulses for sending data, it makes the transmitter design very simple, small-area, and low-power. Also, it can provide enough data bandwidth due to its wideband nature. Theoretically, we can achieve data rate of 200 Mbps for 1028 channels neural recording systems with IR-UWB. These features make IR-UWB the best candidate for the wireless telemetry of multi-channel neural recording systems.

II. OVERVIEW OF UWB TRANSMITTER

Fig. 1 is the block diagram of a multi-channel neural recording system with the IR-UWB wireless telemetry circuit. Neural signals are sensed by electrode arrays (MEAs) and amplified by the low-noise pre-amplifiers. Those amplified signals are then passed through filters to reject unwanted noise such as high-frequency white noise or the 60-Hz noise from environments. Analog multiplexers are used for a time-multiplexing. A buffer is required to drive an analog-to-digital converter (ADC). The ADC digitizes the incoming signal at the Nyquist rate. The digitized signal is then fed to the wireless telemetry to be transmitted wirelessly \cite{6}. The UWB telemetry link targets a data rate up to 100 Mbps and a propagation distance up to 10 m.
A-) Ultra-short Pulse Generation

In this section we will first analyze pulse generation schemes in terms of time and frequency domain characteristics. The method described here can be applied to different applications in order to meet the spectral mask of the UWB band. There are various methods to generate pulses. Among all methods using the delay-and-AND gate or delay-and-XOR gate is the least complex way in CMOS integrated circuit technology [10]. The delay unit can be realized using digital gates such as inverters, analog differential delay cells [14], flip-flops and controllable capacitors [11]. A general scheme for such pulse generations is given in Fig. 2.

The data signal $s(t)$ and the delayed replica $s_d(t)$ are passed through XNOR gate or an AND gate to obtain a UWB narrow pulse $x(t)$ (e.g. $x(t)=s(t).s(t-\tau)$). A narrow band square wave can be represented by:

$$x(t)=\sum_{n=-\infty}^{\infty} g(t-nT_b)$$

where $T_b$ is the bit period and

$$g(t-nT_b)=\begin{cases} A & nT_b < t \leq (n+\frac{1}{2})T_b \\ 0 & (n+\frac{1}{2})T_b < t \leq (n+1)T_b \end{cases}$$

where $A$ is the amplitude of the pulse and $\tau$ is the width of the UWB pulses obtained from the delay element as depicted in Fig. 2.

$$x(t)=\sum_{k=1}^{\infty} \frac{A\tau}{T_b} \sum_{k=1}^{\infty} \frac{\sin(\pi k/T_b)}{\pi k/T_b} \cos(k\pi t/T_b)$$

The signal includes a DC term and the fundamental frequency together with harmonic frequencies. As can be seen, a rectangular UWB pulse has a sinc (i.e. $\sin x/x$) envelope as a coefficient. The first zero of $\sin(x)$ will occur at $x=\pi$, that is $k=T_b/\tau$ in (3). It corresponds to a frequency of $k/T_b$ or $1/\tau$. This first zero defines the distribution of the UWB signal in frequency domain as well as the number of the discrete spectral components. Fig. 4 shows waveforms for UWB pulses with two different widths that are obtained from our circuit design. Spectrum plots are for the pulses that have the width of 2 ns (Fig. 4-a) and 500 ps (Fig. 4-c). Since our design targets a data rate of 100 Mbps, $T_b=1/100MHz = 10$ ns. If we select the pulse width as $\tau=2$ ns, the number of spectral components is therefore $T_b/\tau=5$ (Fig.4-(b)). When $\tau=0.5$ ns, the number of spectral lines is 20 (Fig.4.(d)). The distance between two spectral lines defines the data frequency (i.e. 100 MHz).
The best value for the delay is $\tau = T_b/2$. It results in the maximum power for the discrete spectral lines at the symbol rate frequency [12]. Using (3), the amplitude of the spectral lines becomes inversely proportional to their frequencies (i.e. amplitudes $= 2A/k\pi$). In the UWB transmission, the power spectrum of these discrete lines should be lower than that of the allowed spectral mask by the UWB regulations. That is why it makes it easy to have both $A$ and the delay $\tau$ in (3) to control the power level of the signal such that it will fall within the UWB spectral mask. Another observation is that once $\tau$ is arranged, increasing the bit period $T_b$ yields a large number of spectral lines, which increases the complexity of filters in the receiver as the distance between two lines becomes smaller.

The square pulses $x(t)$ are passed through a pulse shaping filter to decrease inter pulse interference (IPI) during transmission (shown in Fig. 2.). Since square waves cause higher IPI, a pulse shaping filter is generally used. A Gaussian pulse is generated after the pulse shaping filter. In practice one or more order high pass filter is used to obtain such a shape [10]. If we look into (3), we see a rectangular-shaped data extends over an unlimited frequency band. When a high pass filter (HPF) is used, the UWB frequency from 3.1GHz to 10.6 GHz frequency can be selected. However, for the UWB band of 0-960 MHz, a low pass filter should be used as illustrated in Fig. 4. It is also possible to use a band pass filter around a specific frequency. In the frequency domain, the distance between two discrete spectral lines is $1/T_b=100$ MHz. Note that the data information is contained in these discrete spectral lines at $1/T_b$. When one of UWB bands shown in Fig. 4 is transmitted, a narrow bandwidth band-pass filter (BPF) filter is used at the receiver site to obtain one of the spectral lines for the symbol detection.

**B-) CMOS UWB Transmitter Design**

There are two common transmitter categories used for UWB technology. The transmitters in the first category includes a pulse generator and an up-converter that uses a mixer and a local oscillator (LO) to transfer the baseband signal into the UWB band. The transmitters in the second category consist of a pulse generator and a pulse shaping circuitry only where the pulse directly falls in the UWB band. In those transmitters there is no need for a mixer and an LO that significantly reduces the complexity and power consumption of the transmitter [13]. Since the transmitter in our application does not require a multi-access communication protocol and the power consumption is the most critical design specification, the second type of transmitter design technique is used for our multi-channel neural recording system. For pulse generation, the method described in the previous section (II-A-) is followed.

Fig. 5 is the block diagram of the IR-UWB transmitter. The first stage of the transmitter is an encoder. The encoder is used to convert the baseband data into different formats (e.g. NRZ,

![Fig. 5. Block diagram of IR-UWB transmitter for wireless telemetry.](image-url)
Manchester). It can also be used to enable the receiver to recover clocks directly from the encoded data as well as to distinguish the data from different channels. After configuring the transmitter to a modulation scheme, the encoded data is then passed to a narrow pulse generator. The pulse generator circuit used is shown in Fig. 6. In this circuit, a pulse width is controlled by the voltage $V_c$. Generated pulses are passed through the pulse shaping filter to fit them into the FCC emission mask and to eliminate the transmission of unnecessary frequencies. Unlike other UWB applications, power amplifiers are not necessary due to the low transmitted power and the short distance range in neural recording systems. Instead, a wideband matching filter is used to regulate the transmitted power. The matching circuit together with the parasitic components from the output pad and the package pin contributes extra derivation (e.g. further filtering in frequency domain) to the UWB Gaussian pulse that makes signal more suitable for an UWB transmission [13][14].

![Fig. 6. Circuit used for pulse generation and modulation selection.](image)

Our transmitter can be configured to different pulse modulation schemes: on-off keying (OOK), pulse-position modulation (PPM), and binary phase shift keying (BPSK). A signal $OOK_{in}$ is generated by passing the NRZ and Manchester NRZ baseband signals through an AND gate. As shown in Fig. 7, when the signal $OOK_{in}$ is given to the pulse generator circuit depicted in Fig 6, $x(t)$ will be an OOK modulated signal (Fig. 7-(d)). During the bit “1”, a pulse is transmitted and meanwhile there is no pulse during the bit “0”. The PPM UWB signal is generated by using the Manchester NRZ signal and the OOK UWB signal. First, Manchester NRZ is passed through the pulse generation circuit. The resulted narrow pulses are added (using OR gate) to the OOK UWB (Fig. 7-d) to obtain PPM UWB in Fig. 7-(e). As can be seen, the pulse position for bit “1” is different than that of the bit “0”. The bits are positioned such that the bit detection will be easier at the receiver site. To generate a BPSK signal, the pulse is simply inverted by $180^\circ$ when the bit is “0”.

![Fig. 7. Time diagram for PPM and OOK modulation.](image)
III. CIRCUIT SIMULATION RESULTS

The transmitter circuit in Fig. 5 is designed, laid out and simulated using National’s 0.35um CMOS7 process and the power supply level is 3.3V. Fig 8 is a circuit simulation result that shows the input NRZ data and the OOK UWB signal at the output. Although the concept given in Fig 7 is used in the circuit for generation of modulated UWB pulses, negative edges are, however, considered in the implementation. Fig. 9 is a simulation result for a PPM-UWB signal. The PPM UWB pulses are positioned in a way that the symbol synchronization will be easier at the receiver site as a symbol clock can easily be obtained from those PPM pulses. An example of the UWB signal generation for a 100 Mbps data is shown in Fig. 10. In this simulation the pulse is passed through a BPF with 4 GHz center frequency. The circuit consumes 24 µA for a 5.12Mbps OOK UWB signal generation and 243 µA for a 100Mbps
OOK UWB signal generation. During the PPM modulation, the circuit consumes about twice as that of OOK.

Unlike other UWB applications, in our neural recording system the implanted device does not require a receiver circuit. The transmission is one directional as the information needs to be recorded and monitored only. This greatly simplifies the complexity of the implanted device and increases its lifetime. In the current recording system we need a data rate of 5.12 Mbps. The base band signal’s date rate is 20K * 16* 16 = 5.12Mbps. (16 channel, 20Ksample/ channel/sec, 16 bit/sample). However, our system together with the receiver targets a data rate up to 100 Mbps to cover a higher number of recording channels. The receiver can be designed for such a high data rate as it is built from off-shelf components by using high performance RF ICs (i.e. LNA, mixers) and high speed FPGAs. A receiver prototype system has been developed to test the concept defined in this paper (Fig. 11). The pulses have been generated using an FPGA from Altera and transmitted wirelessly. The receiver is based on the technique given by Cellonics UWB receiver technology given in [15]. The transmitted UWB signal was detected at the receiver successfully. Future works requires the fabrication of the transmitter chip and the testing with this off-shelf UWB prototyping receiver given in Fig 11.

IV. CONCLUSION

A low-power UWB transmitter architecture has been designed and analyzed for an application in a multi-channel neural recording system. The transmitter is designed in 0.35 μm CMOS technology and optimized for low power consumption. The transmitter power consumption and complexity have been traded off with that of the receiver as the receiver is located outside and its power consumption and size are not crucial. Simulation results show that the power consumption is about 24 µA from 3.3 V power supply which is extremely low for a telemetry system in addition to its high data rate capability. Generation of UWB pulses are also explained extensively when designed in CMOS technology.

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Fig. 10. An OOK-UWB modulation with 100 Mbps.

Fig. 11. UWB Receiver Prototype.