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UWB Pulse Generation and modulation for signal extraction from implantable devices

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Abstract: Ultra WideBand (UWB) communication systems have been undergoing tremendous developments over the recent past years. The areas of interests are industrial automation, identification for short range geolocational positioning systems and for extraction of signals from implants and wearable gadgets used in the bio-medical field. Such interests are the motivation of exploring this technology in terms of its utility in estimating the bit-error-rate (BER) various modulation techniques offer as performance indices. In this paper, a UWB pulse generator is designed and the performance of different modulation techniques utilizing the same pulse generator is presented. The results include frequency domain power spectral density estimates for gauging the power requirements and BER for highlighting its performance index for benchmarking purposes. The power spectral density of the different modulated streams is also compared to the Federal Communications Commission (FCC) mask to check the adherence to the FCC power emission regulations.

Keywords: UWB Modulation, Biomedical Implants, Implantable Devices, Modulation techniques

1. INTRODUCTION

Communication technologies and applications have made tremendous advances over the past half century, bringing closer than ever before communities and enabling resource sharing to wider stretches of geographical widths and to further details of geological depths. Such technologies may be requiring the use of satellites in space for that matter or the runs of fiber cables in oceans when it comes to wide ranging applications. Most communication technologies utilize the Radio Frequency spectrum. However, given the vast number of technologies utilizing a limited spectrum standardization bodies had to be formed to regulate the usage of the RF spectrum by the various technologies. Therefore, each technology is allocated a band or a certain number of frequency bands to operate at. With the rise of new technologies every day the RF spectrum has become very crowded. UWB offers a solution to this problem by providing an RF technology that would coexist with current RF technologies with little or no interference.

The International Telecommunications Union (ITU) defined UWB technology as a technology used for short range communications. A UWB device has the characteristics of intentional transmission of signal with energy spreading over at least 500 MHz at the -10 dB points. In other words, devices transmitting signals with a -10 dB bandwidth of at least 500 MHz. [1]. This is the definition of the general features of the UWB signal. However, the definition of the spectral mask or power spectral density mask or maximum power emission levels was left to national bodies to determine it within their countries. Therefore, there are currently numerous transmission masks such as the FCC mask, ECC mask, the Japanese mask, and others.

The Federal Communications Commission (FCC) is one such body, allowing the use of the unlicensed ultra wideband (UWB) devices operating in the 3.1 to 10.6 GHz frequency band with an emission limit of –41 dBm/MHz. The announcement has generated worldwide interest in exploring this low power UWB technology for abundance of applications opportunities in short-range and high speed wireless communications, radio frequency identification (RFID), vehicular radar systems, imaging systems, short-range positioning system (geolocation) and handheld applications, etc.

Ultra-wideband technology provides the solution to the spectrum problems by performing the communication task through a concept different from what is used by that of traditional communications systems. The UWB communication relies on sending streams of sub-nanosecond pulses against the traditional technologies communicating through using one analog signal as a career on which information bearing analog signal is made to ride towards its intended destination [1]. The UWB communication technology is finding applications in its ability of to penetrating the surface of the ground and other solid features such as walls for detection of through-wall and buried objects. Such applications have got the potential applications in medical diagnostic imaging and the identification of underground objects. The automobile industry is another player UWB technology is providing a ground for in terms collision avoidance and parking assistance.

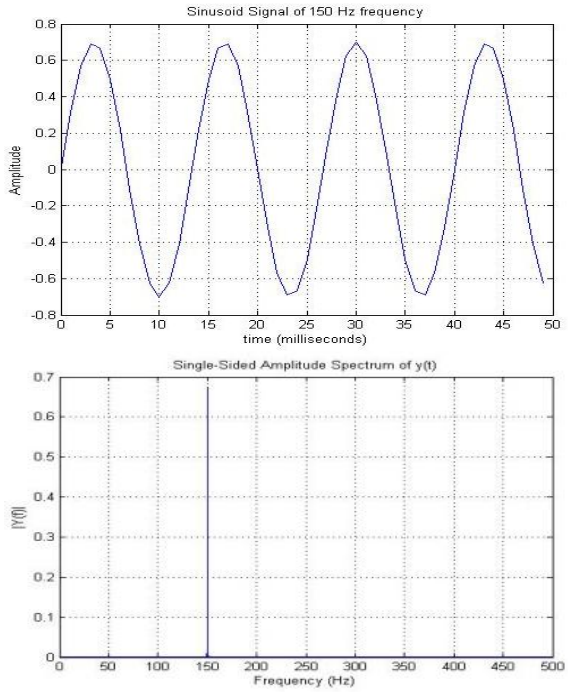
2. FREQUENCY DOMAIN CONSIDERATIONS.

The narrower the pulses are in time domain, the wideband is the emissions in frequency domain. The variation of a signal level over time in time-domain is represented by a group of sinusoidal components of varying frequencies in frequency-domain. The sharper the pulse becomes the broader goes the range of frequency components that make up the emission. The frequency contents is directly proportional to the level change over time, while a stream of similar pulses, however shows no significant change in frequency of emission in frequency domain. This point is illustrated further by the effect of scaling property an analog signal in time domain is having on its frequency contents in frequency domain.

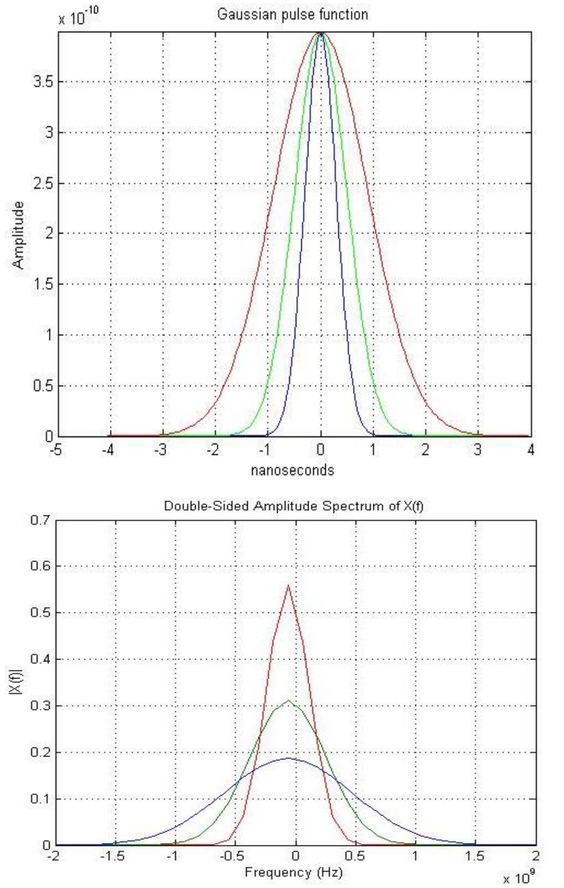
The scaling property is given by:

$$x(at) = \frac{1}{|a|} X(\frac{f}{a}). \qquad (1)$$

Where factor ‘a’ is the scaling factor, while x(t) is the function in the time domain, and X(f) is the function in the frequency domain. The scaling equation means that if a signal spanning over the entire time axis in time domain is an impulse of a length representing its magnitude and perched at zero frequency point in frequency domain. Accordingly an impulse in time domain might equivalently occupy almost the range in frequency domain. This concept is further illustrated by obtaining the following graphs using MATLAB.



(a)



(b)

Fig. 1: (a) Single frequency sinusoid and its single sided amplitude spectrum
(b) Three Gaussian pulses and their double sided amplitude spectrum

The other parameter for a UWB generator performance is pulse repetition frequency, which is the reciprocal of pulse period which does not stand to represent frequency contents at all. Thus pulses of longer rise and delayed fall times have got smaller pulse repetition frequency but not necessarily the frequency contents of the pulse I frequency domain. Such a counter balancing relationship is elaborated in Figure 1(a) and Figure 1 (b).

3. UWB MODULATION

UWB modulation does not differ a lot from the modulation techniques used in conventional narrow band communications systems. However, since UWB is based on very short pulses with the constraint of a tight power mask, only digital modulation schemes are used in UWB technology. The information signal is used to modulate specific features of sub-nanosecond pulses. The digital modulation techniques used for RF signals can be used with UWB pulses with minor modifications. For instance, the phase shift keying can be applied to UWB pulses for modulation purposes. However, high order phase shift keying is not practical for UWB pulses since the pulses are very short and hence the phase variation would be difficult to detect. Therefore, Binary Phase Shift Keying (BPSK) is one of the most popular modulation techniques used with UWB systems [2]. Other modulation techniques like On-Off Keying (OOK), Pulse Amplitude Modulation (PAM), and Pulse Position Modulation are also used. A number of hybrid modulation techniques like Pulse Position Amplitude Modulation (PPAM) have been developed for better performance [3]. Another main field of UWB modulation is the employment of the spectrum spreading techniques and frequency hopping to exploit the spectrum more efficiently and to provide multiple accesses. Another main feature of using such technique is the fact that interception is more difficult because, unless the random code for frequency hopping is known, the signal is embedded in noise. However, employing such techniques would require complex circuits with higher power consumption which is not practical for all applications. Therefore, the choice of modulation technology is vastly dependant on the intended application. Since the power consumption is one of the major limitations in implantable devices, the most popular modulation schemes are BPSK, OOK, PAM, and PPM.

4. UWB PULSE GENERATION

UWB communication requires the generation of sub-nanosecond pulses with frequency components falling within the FCC regulations requirements. There are a number of approaches to generate such short-duration pulses. One of the common methods is by using the delay in logical gates to generate those pulses [4]. As signals travel through logic gates in two parallel paths, one of the path undergoes a certain amount of delay when the two paths meet before an AND-gate, producing thus a pulse of a duration equal to the delay introduced. Short pulses can be formed by utilizing gates to add the delayed signal to the original signal. Another widely used method is utilizing the Step Recovery Diode (SDR) [5] not only to generate such pulses but to shape them too, thus reducing eliminating the ringing phenomenon considerably. The SRD is a PIN diode with a very thin intrinsic region. When the SRD is switched from the forward bias to reverse bias the carriers stored in the intrinsic region is discharged quickly producing a sharp impulse with the width of (30-150 pico-seconds) [6]. A third method is using a voltage controlled oscillator (VCO) set to oscillate at the center frequency at which the oscillator is made to operate with specified bandwidth of the signal [7].

5. RESULTS AND ANALYSIS

The results obtain from the proposed pulse generator show promising results. The pulse generator design is based on the concept of generating short rectangular pulses and filtering them using a high order bandpass filter. The pulses are generated using a Shmidtt Trigger with an RC feedback in order for it to operate in the Astable state as shown in Figure 2. Schmidt trigger is chosen because of the simplicity of the circuit and the availability of low power consumption CMOS based Schmidt trigger. The second section of the pulse generator is a PI-configuration bandpass filter based on the filter synthesis through the transformation of a prototype PI-configuration lowpass filter as shown in Figure 3.

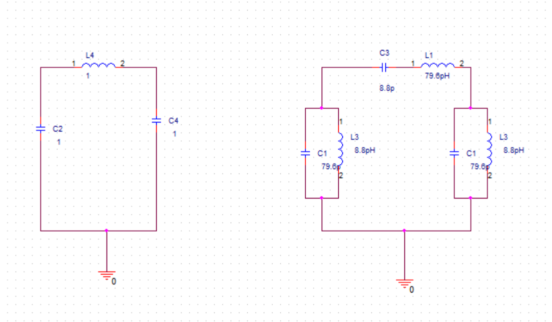


Fig. 2: The pulse shaping bandpass filter is shown on the right and the prototype filter is shown on the left.

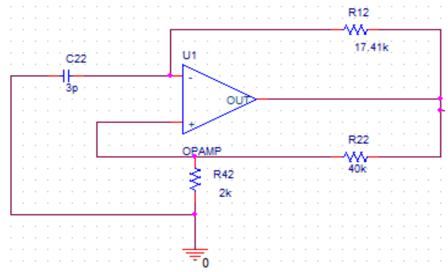


Fig. 3: Schmidt trigger rectangular pulse generator at 200MHz.

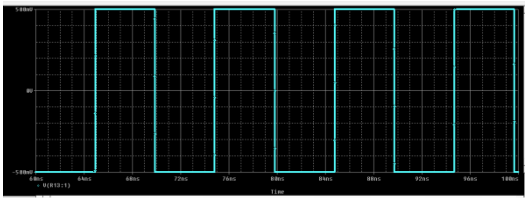


Fig. 4: Schmidt trigger rectangular pulses at 200MHz.

The pulses obtained from the Schmidt trigger are shown in Figure 4 The pulses obtained from the circuit simulation in Pspice are imported into Matlab to calculate the power spectral density of the stream. The same imported pulses are used to estimate the PSD of the different modulation schemes. The pulse stream obtained after filtering along with the PSD of the pulses is shown in Figure 5. The pulse stream is obtained through circuit simulation in Pspice and the PSD was calculated and plotted in Matlab.

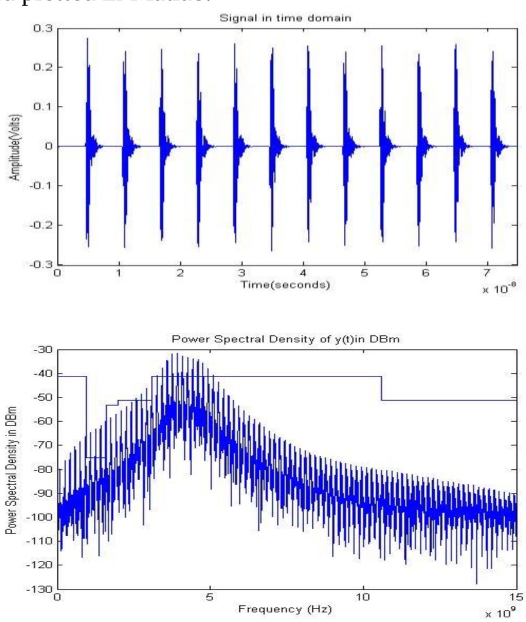


Fig. 5: Pulse stream at the output of the filter and corresponding power spectral density.

It can be observed in Figure 5 that the Power Spectral Density of the signal is not satisfying the FCC mask due to the existence of spectral lines. This effect can be reduced through using modulation schemes and a suitable pulse rate. Another feasible measure is to shift the center frequency to higher frequencies. For instance around 6 Gigahertz. The advantage of that would be the fact that the signal would be way within the spectral mask set by the FCC. However, as we move to higher frequencies the average signal power would reduce. As it is well known that the power spectral density of the rectangular pulse is in continuous decay towards higher frequencies. Therefore, a balance should be made between the center frequency and the average power level in order to clear the mask while sustaining a reasonable average signal power.

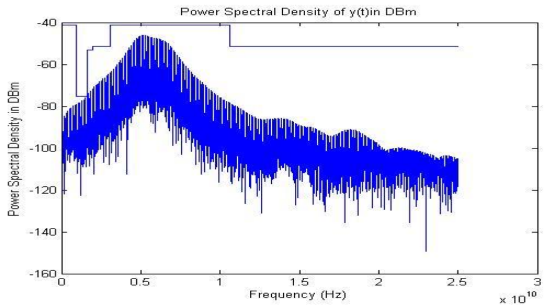


Fig. 6: PSD of the generated pulse stream

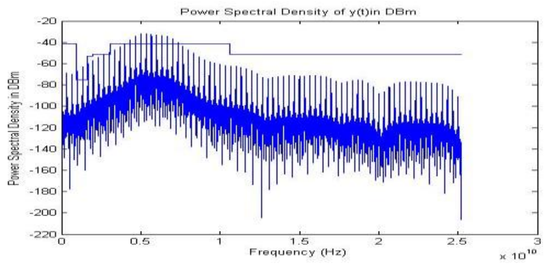


Fig. 7: PSD of simulated pulse stream

It can be observed in figures six and seven above that the pulse stream without modulation would differ between the ideal pulses generated using the mathematical equation of the Gaussian pulse derivative.

The general form of the Gaussian Pulse derivative can be recursively obtained as:

$$x^{(n)}(t) = -\frac{n-1}{\sigma^2}x^{(n-2)}(t) - \frac{t}{\sigma^2}x^{(n-1)}(t) \quad (2)$$

Where σ is the standard deviation, (n) is the order of the Gaussian derivative. x(t) is the Gaussian function.

It can be observed that the spectral lines are more dominant in the ideal pulses as compared to the pulses generated using the proposed circuit. This is due to the fact that the pulses generated are out of phase and the fact that the pulses generated are not perfectly similar like the ones simulated mathematically. The main aim of this work is to study the effects of applying the different feasible modulation techniques to the pulses generated using the proposed topology.

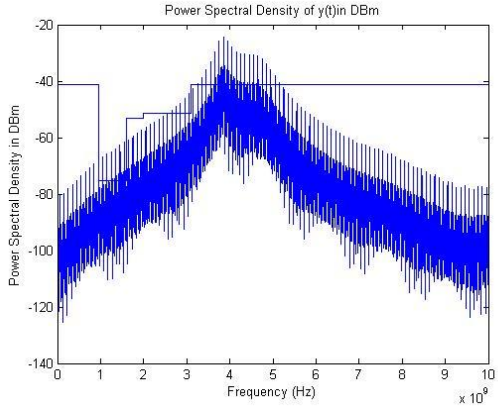


Fig. 8: PSD of simulated Pulse Amplitude Modulated pulse stream

The effect of applying Pulse Amplitude Modulation on the Power Spectral Density of the generated pulse is shown in Fig. 8. It can be observed that there is a dominant presence of spectral lines and the distribution of the average power over a range of around 10 Dbm. Both these factors make PAM undesirable due to the tight power mask imposed by the different regulatory bodies, The FCC mask is shown as an example in the previous figure and the following power spectral density figures.

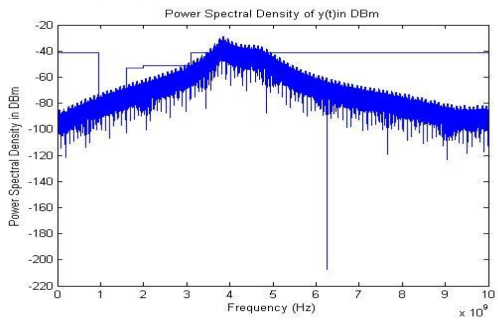


Fig. 9: PSD of simulated Binary Phase Shift Keying Modulated pulse stream

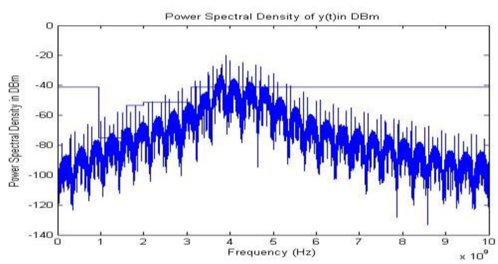


Fig. 10: PSD of simulated Pulse Position Modulated pulse stream

The effects of applying Binary Phase shift Keying and Pulse Position Modulation are shown in figures 9 and 10 respectively. As it can be observe the spectral lines disappear in BPSK and are minimized in PPM. Another advantage of those modulation techniques is a 3db advantage over other techniques in terms of Bit Error Rate as shown in figure 16. However, both modulation techniques require accurate synchronisation in order to modulate the pulses. This would make the needed circuitry more complex than other circuits and hence result in an increased size, and increased power consumption.

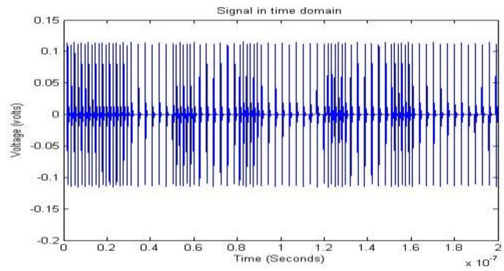


Fig. 11: Simulated Pulse Interval Modulated pulse stream

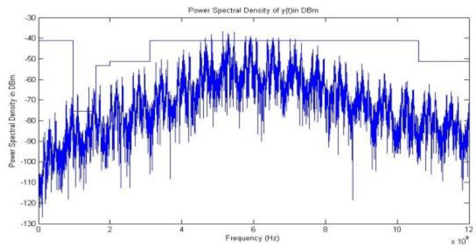


Fig. 12: PSD of simulated Pulse Interval Modulated pulse stream

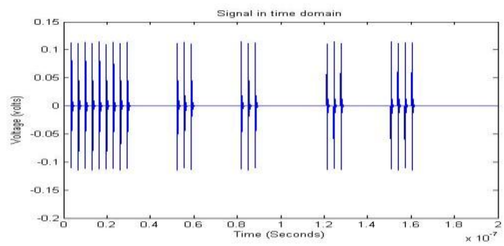


Fig. 13: On-Off Keying Modulated pulse stream

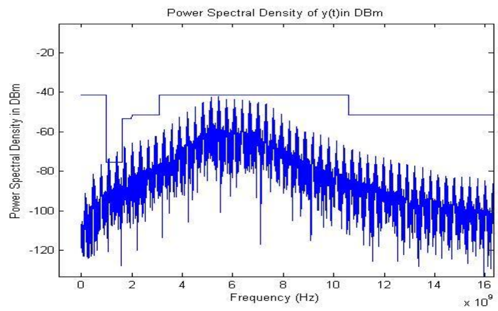


Fig. 14: PSD of simulated On-Off Keying Modulated pulse stream

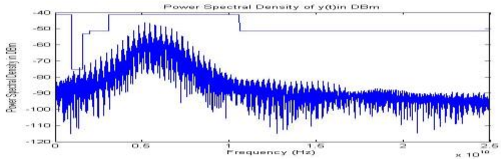


Fig. 15: PSD of simulated Unsynchronized On-Off Keying Modulated pulse stream

In figures 11-15, two important modulation techniques are shown. The first of which is the Pulse Interval modulation or Pulse Repetition Frequency modulation. The effect of this modulation technique on the spectral shape is shown in figure 12. On-Off Keying is also presented. The performance of OOK can be improved if the data is not synchronized with the pulse stream as shown in figure 15. Therefore, It is suggested that the unsynchronized OOK is implemented with the proposed pulse generator circuit.

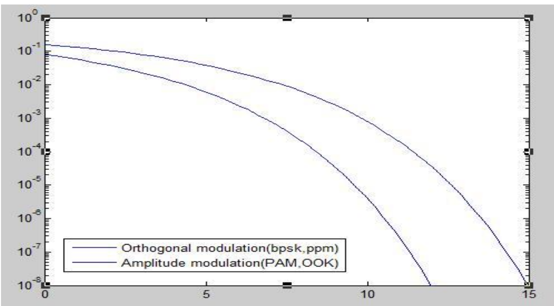


Fig. 16: Theoretical Bit Error Rate

6. CONCLUSION

In this paper, the design of a pulse generator capable of generating pulses adhering to the FCC spectral mask and consuming relatively low power for application in signal extraction from implantable devices is presented. The pulse generator is designed using a Shmidt trigger and a PI-configured Bandpass filter. The generated pulses were used to examine the performance of the pulse generator with applicable modulation schemes through evaluating the PSD effects of each modulation scheme, complexity, and the BER in AWGN environment. All previous parameters are taken into consideration in order to choose a modulation scheme most suitable for intended application. The main contribution of this work is the study of the effect of applying modulation techniques on simulated circuit generated pulses rather than the mathematically derived pulses, taking into consideration, the effects of ringing, slight amplitude variations, and the nature of the generated pulses.

A pulse generator design, adhering to the FCC mask, is presented and it is recommended that OOK is used to modulate the resulting pulses. Future work would include the design and fabrication of the Integrated Circuit for the proposed design to confirm the results obtained through simulation.

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