18

Wideband Technology for Medical Detection and Monitoring

Mehmet Rasit Yuce, Tharaka N. Dissanayake and Ho Chee Keong
The University of Newcastle
Australia

1. Introduction

Biomedical devices benefit from the recent and rapid growth of wireless technology for measuring physiological signals for both implantable and wearable systems. The use of wireless in healthcare systems provides great mobility and increases comfort level of patients by freeing them from hospital equipments. However, it is important to select a proper and safe wireless band for medical data transmission as it is crucial for the patient 's safety. Historically narrow band wireless technologies have been used in medical monitoring widely. This chapter introduces the use of wideband technology for future medical monitoring systems. The important parameters of the wideband technology are its low power transmitter design, low-interference effect in medical environment and high data rate capability. The chapter describes low power implementation of ultra-wideband (UWB) and applies the technology to some of emerging biomedical applications.

Wideband technology can find applications in biomedical monitoring especially for neural recording and multi-channel continuous signal monitoring such as Electroencephalography (EEG), Electrocardiogram (ECG) and Electromyography (EMG). The potential benefits are the low-power transmitter to increase the battery life, high data rate to increase the resolution and performance, and less interference effect on the other wireless system in medical centers. Wideband technology is particularly suitable for telemetry systems requiring high data rate transmission such as wireless endoscope and multi-channel continuous biological signal monitoring.

The design of a UWB wireless chip has been difficult for chip designers due to the difficulty in the demodulation of narrow pulses. Generally a UWB receiver circuit has demonstrated a power consumption higher than that of narrow band systems. One way to eliminate the high power consumption of an ultra wideband receiver is to use a transmitter only method for medical monitoring and detection. This chapter will address and discuss implementation of such a system. The system includes only a transmitter to send data from body to an external device for monitoring and recording. The transmitter in the wideband telemetry system is attached to or implanted in the body. Meanwhile an off-the-shelf receiver system is placed at a location between 0.5-10 meters away to detect the transmitted signal.

Methods and design techniques to use ultra wide band (UWB) technology for wearable and implantable physiological monitoring systems will be presented. The chapter covers two main applications of wideband technology: In the first part of the chapter, a band limited impulse radio and antennas based on the UWB system will be discussed to investigate the implementation of wideband signals for implantable medical devices. An example of a wireless endoscope device using an impulse based wideband radio system will be described in detail. In the second part of the chapter, a medical monitoring for wearable systems using wideband technology will be explained with implementation details.

2. Wideband Technology for Medical Telemetry

Electrocardiogram (ECG) and temperature recording have been used for more than 50 years in medical diagnosis to understand the biological activities (Mackay, 1961; Lefcourt, 1986). Electronics for biological signals (i.e. Bioelectronics) is designed taking into account very specific requirements for a a given wireless telemetry application. Wireless technologies developed in commercial domain cannot be used directly in medical implants or wearable systems because of two reasons: (1) they have been optimized for general use and are thus complex; (2) the device size exceeds the required size limitation of the current implant technology. Furthermore on-body medical monitoring devices also require miniaturization and emission constrains so that they can be wearable.

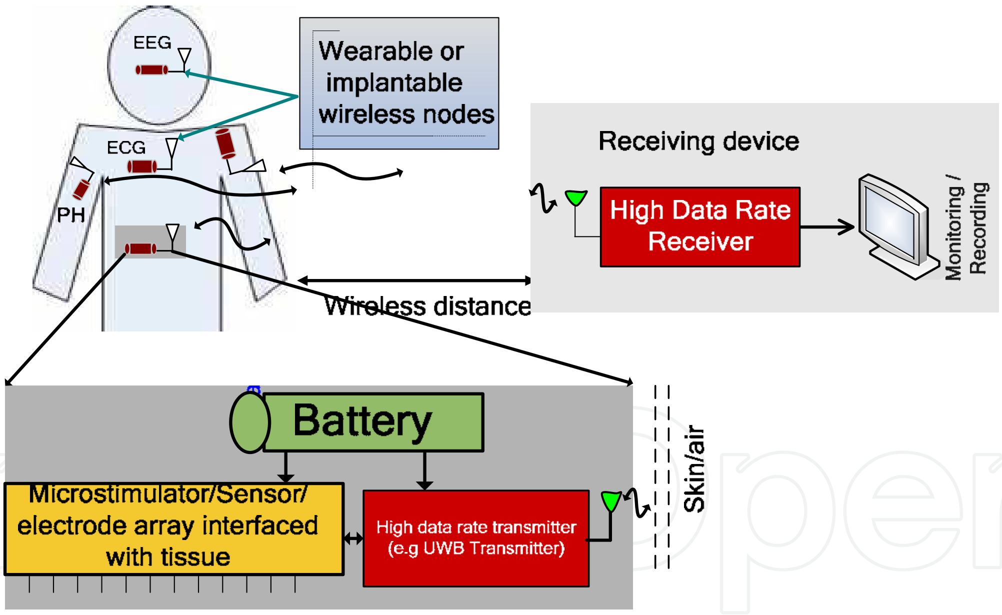

Fig. 1. A modern medical monitoring and detection system.

Fig. 1 shows a medical monitoring system that will most likely be implemented widely in medical centers in the near future. A monitoring/detection device in a telemetry system consists of sensors/electrodes that detect biological signals from the body, a battery and a transmitter to transmit signals from inside or on-body to a remote receiving device for monitoring and diagnosis. The term monitoring is used in the medical telemetry for two different functionalities: monitoring of the body signals which are used for medical diagnosis and monitoring the status of the prosthetics devices such as a pacemaker, or a cochlear implant. A monitoring device is required almost in all telemetry systems in order to send the medical status to a remote system for better treatments.

Most of implantable systems such as retina prostheses and cochlear implants have a very short transmission distance for wireless telemetry. An inductive link is constructed between the external and the implanted devices with a distance of few centimeters. In addition, implantable devices dedicate a very small size to the wireless telemetry section of an implant. Consequently a wireless system with a very simple communication scheme such as binary ASK (amplitude shift keying), FSK (frequency shift keying) and PSK (phase shift keying) modulators and demodulators can be employed (Liu et al, 2005). The transmission frequency used is usually lower than 20 MHz. The frequency 13.56 MHz in ISM (Industry, Scientific and Medical) band is usually the most common for such inductive link telemetry systems and is also used for RFID (Radio Frequency Identification) applications. A low transmission frequency usually less than 20 MHz is utilized mainly because of the simplicity in the design and to avoid the use of power hungry blocks such as mixer, oscillators. When many of such implantable systems are used in the same environment or for the same patient, such simple communication systems will face the problems of interference. Thus a more advanced wireless technology will be required in the future to accommodate better radio links for medical implants.

For some of advanced medical implants such as pacemaker, implantable cardioverter defibrillators and electronic pill (i.e. wireless endoscope), a much longer range is required for the wireless telemetry. Moving to higher frequencies is the only way to increase the range and to dedicate enough spectrums for a reliable communication in the future. However, at higher frequencies a wireless transceiver requires the use of RF blocks such as voltage-controlled oscillators (VCOs), mixer and phase-locked loops (PLLs) to down convert (or up convert for the transmitter case) the frequencies in order to process using integrated circuit technology. These blocks are constructed using inductors and capacitors on chip or off-chip which increases the physical size of the wireless chip.

Medical implants have physical limits for the electronics of the wireless telemetry and cannot afford to accommodate such blocks. Thus, in order to alleviate some of the issues mentioned above, US Federal Communication Commission (FCC) and some of international authorities have allocated a new band at 402-405 MHz with 300 KHz channels to enable the wireless communication of such implantable devices to deliver high level of comfort, mobility and better patient care (Tekin, 2008; Bradley, 2006). With the advance of radio frequency IC (RFIC) technology, this frequency band promises high-level of integration (compared to inductive link designs) which results in miniaturization and low power consumption.

Medical telemetry can be categorized into two groups: high data rate and low data rate systems. Multi channel recording (i.e. neural recording systems) for implantable system and multi-channel continuous signals such as EMG, ECG and EEG necessitate a high data rate communication. As an example, scientists aim to achieve the recording of more than 100 channels in order to simultaneously record brain functions; a data rate more than 20 Mbps is required (Yuce et al, 2007, Chae et al, 2008). A similar figure is also useful for a wireless endoscope implant to obtain higher resolution pictures and images. The MICS has channels with 300 KHz width and thus cannot provide such data rates.

	Frequency band	**Bandwidth (or data rate)**	**Trans. Power**
WLANs (802.11b/g)	2.4 GHz	>11 Mbps	250 mW
IEEE 802. 15.1 (Bluetooth)	2.4 GHz	1 MHz, 1 Mbps	4 dBm,20 dBm
IEEE 802.15.4 (ZigBee)	2.4 GHz	250 kbps	0 dBm
WMTS	608-614, 1395-1400, 1429-1432 MHz	6 MHz	≥10 dBm and< 1.8dB
MICS	402-405 MHz	3 MHz	- 16 dBm
UWB	0-960 MHz 3.1 -10.6 GHz	800 kbps, 27.24 Mbps	-41dBm
Inductive link	<20 MHz, 13.56 MHz ISM	Usually around kbps	> 0dB

Table 1. Existing wireless systems.

Although the advances in RFIC technology for wireless communication technologies have been significant in the commercial domain, these technologies are not directly transferable to medical applications due to the differing power, size, and safety related radiation requirements of medical devices. Most popular wireless technologies are shown in Table 1. These wireless systems target a wide range of applications. The existing advanced wireless systems such as ZigBee (IEEE 802.15.4), WLANs, and Bluetooth (IEEE 802.15.1) operate at 2.4 GHz ISM band and may suffer from the strong interference from each other when they are located in the same environment (Shin et al., 2007). Some of the commonly used wireless platforms (either wireless chip or complete board) from Crossbow[1], Texas Instrument[2] and Zarlink [3] are shown in Table 2. This table summarizes the properties of wireless boards or chips used in most of Today's low-power applications.

As can been seen, two chips that meet the requirement of a medical device the most are zarlink's new MICS chip and Crossbow's Mica2DOT device. Although the physical dimension of the Zarlink's device is for the chip package area, a small board can easily be designed, similar to that of Mica2DoT shown in Fig. 2 as the chip requires only few external components. Zarlink provides one of the lowest-power wireless chips available today. The low-power achieved by reducing the supply voltage to value as low as 1.2 V while most of the others operate with a voltage 1.8V and higher. When comparing the available technologies with current state of the art UWB technologies, the unique properties of UWB that outperforms others are high data rate and its transmitter power and physical size which can be extremely small. Based on the key requirements from medical monitoring, UWB could be the best choice in term of power consumption, scalability and size when a transmitter only approach is followed (Yuce et al., 2007).

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[1] http://www.xbow.com.
[2] http://www.ti.com/.
[3] http://www.zarlink.com/

Model	Company	Frequency	Data Rate	RF Power	Physical Dimension	Current	
						Tx	Rx
UWB	Ref1** Ref2***	3.1 – 10.6 GHz	20 Mbps	-41 dBm	Very small	1.6mW 2mW	16 mA*
Mica2 (MPR400)	Crossbow[1]	868/916 MHz	38.4 kbps	-24 -+5 dBm	58 x 32 x 7 18 grams (board)	27 mA	10 mA
MicAz	Crossbow[1]	2.4 GHz	250 kbps	-24 -0 dBm	58 x 32 x 7 18grams (board)	17.4 mA	19.7 mA
Mica2DOT	Crossbow[1]	433 MHz	38.4 kbps	-20-+10 dBm	25X6 mm^2 3 gram (board)	25 mA	8 mA
CC1010	TI[2]	300 to 1000 MHz	76.8 kbps	-20-+10 dBm	12X12 mm^2 (chip)	26.6 mA	11.9 mA
CC2400	TI[2]	2.4 GHz	1 Mbps	-25-0 dBm	7.1X7.1 mm^2 (chip)	19 mA	23 mA
MICS	Zarlink[3] (ZL70250)	402-405 MHz, 433 MHz ISM	800 kbps	< 0 dBm	7X7 mm^2 (chip)	5 mA, continuous TX / RX	

Table 2. Comparison of hardware designs for wireless systems
*Reference (Ryckaert et al., 2007), **(Chae et al., 2008), ***(Ryckaert et al., 2005).

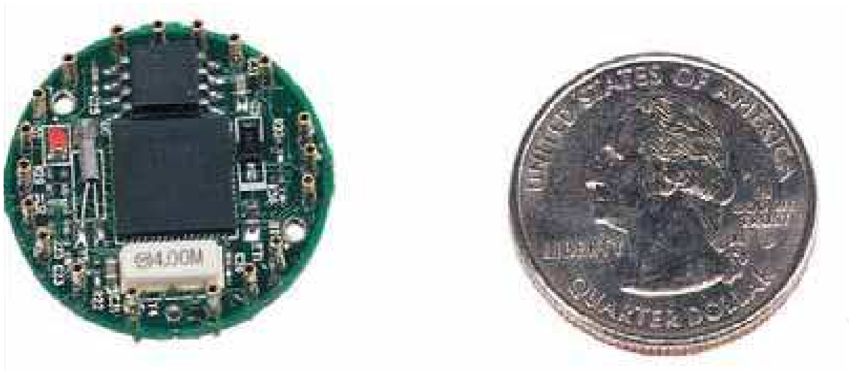

Fig. 2. A Mica2DOT board (taken from www.xbow.com).

This chapter investigates the use of wideband technology (UWB) technology for medical monitoring devices. UWB is one of the most recent wireless technologies using narrow pulses to carry data (Arslan et al., 2006). The major drawback of a UWB system is the high power consumption of the UWB receiver as indicated in Table 2. Power consumption at UWB's receiver is very high, usually higher than the narrow band wireless communications. Although recent developments have shown some promising results (Ryckaert et al.,2007), a low-power complete wireless UWB transceiver still consumes more than traditional narrowband devices. It is important to note that the transmitter part of UWB consumes very little power as it is very easy to generate pulses in a circuit (Ryckaert et al., 2005). Thus if there can be a trade off between the transmitter and receiver, medical monitoring will be one of the most attractive applications for UWB communication (Yuce et al., 2007). UWB has two major advantages, high data rate and low power consumption of the transmitter. High data rate property can be incorporated with medical sensors requiring multi channel continuous monitoring from a single patient (Especially multi channel EEG signals are used in some healthcare applications for better diagnosis) (Ho & Yuce, 2008). It may also be possible in future wideband technology to be integrated together with narrow band medical system easily for a reliable wireless communication as well as to cover different environments in medical centers. High data rate transmission, as commonly known, is not the only unique property of an UWB based telemetry system. The advantages of a wide band technology can be summarized as follows:

- **Low power transmitter design**. A transmitter circuit can be designed with few components and may consume extremely low power when designed with an integrated circuit technology. Thus if a medical monitoring device can be designed based on a transmitter only approach, significant power and size reduction can be achieved.
- Dedicated band to wideband technology is **very large, ranges from 3.1 to 10 GHz**. This range can be divided into different bands where each band can be used for one medical device. This way a multi-access scheme can easily be arranged in the case more than one medical device is used in the same environment.
- The wide band technology has **less interference effect** on other wireless devices since the regulated transmitter power is very low (i.e. -41.dB).
- **High data rate capability**
- **Miniaturized antenna** design at high frequencies.

2.1 Transmitter Design for Wideband Communication

The basis of any UWB transmitter is a narrow rectangular pulse train and some form of filtering to meet the spectrum mask requirement (Arslan et al., 2006). Wide-band communication can be broadly classified into Impulse UWB (I-UWB) and Carrier based UWB (MC-UWB). I-UWB requires fewer components and has the advantage of simple and low power transmitter designs. MC-UWB normally divides the bandwidth into channels of 500MHz; it performs better in avoiding interference from narrowband systems and useful for multi-access communications. UWB conveys information using very narrow pulses typically in the range of a few hundreds of picoseconds. For an I-UWB system, the desired spectrum shape is achieved through pulse shaping; hence no carrier is required. The Gaussian pulse and its derivatives are the most commonly used pulse shapes for UWB analysis (Marchaland et al., 2005). However, practical implementation of a higher order Gaussian pulse is difficult (Hyunseok, 2003). Therefore, most practical transmitters use a monocycle pulse, which is a first order derivative of the Gaussian pulse. As the monocycle pulse does not meet the FCC’s spectrum requirements, some form of filtering is necessary.

The narrow UWB pulses can be obtained by using completely digital or mixed digital–analog techniques. The use of analog blocks such as mixer and VCO in a UWB system is less attractive for low power, low cost medical applications. Among all methods using the delay-and-AND gate or delay-and-XOR gate is the least complex way in CMOS integrated circuit technology. Basically any type of pulse generator with a pulse shaping circuits will provide an I-UWB based transmitter. However, a transmitter design that controls the pulse width using a bandpass filter as well as controlling the energy from the frequency domain side lobes of the narrow rectangular pulse is found to be very suitable for low power medical applications. A general scheme for pulse generations is given in Fig. 3. The delay unit can be realized using digital gates such as inverters, analog differential delay cells, flip-flops and controllable capacitors (Yuce et al., 2007; Ho & Yuce, 2008; Marchaland et al., 2005). In Fig. 4, a time diagram is depicted to show how a narrow band pulse can be generated from data bits. The data signal *s(t)* and the delayed replica $s_d(t)$ are passed through XOR gate or an AND gate to obtain a UWB narrow pulse *x(t)* (e.g. $x(t)=S(t).S(t-\tau)$).

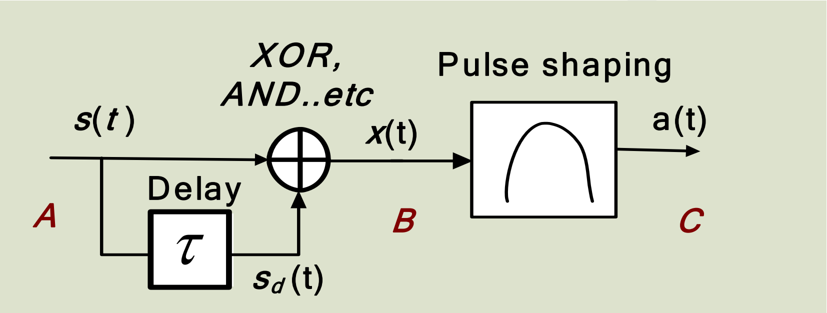

Fig. 3. Narrow pulse generator for UWB communication

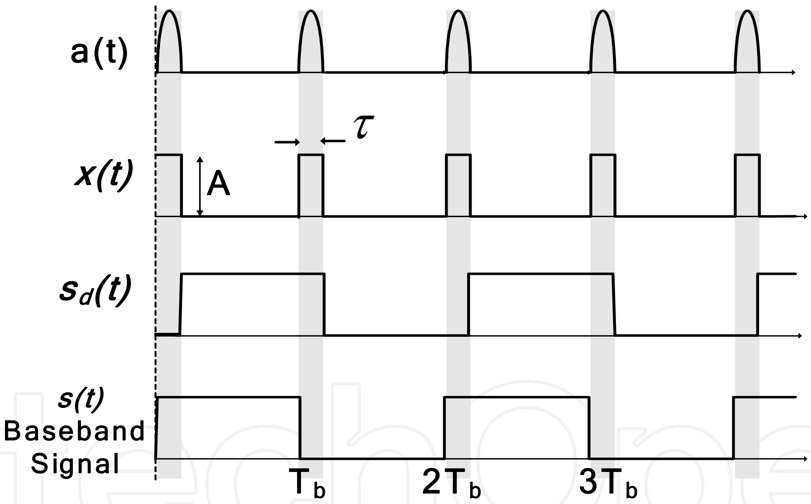

Fig. 4. Timing diagram for UWB pulse generation

2.2 Analysis of Band Limited Narrow Pulses for Medical Telemetry

In this section UWB pulse generation schemes in terms of time and frequency domain characteristics will be explained. The term "band limited " is used here because a band limited UWB signal has advantages by eliminating interference, if any, since the allocated band is very wide. It also presents the opportunity to divide the UWB spectrum into different bands when more than one device is used in the same environment a frequency hoping (different band allocations) can be applied. Assuming a UWB signal using a coding scheme such as Manchester non-return zero (NRZ) or Pulse Position Modulation (PPM), the

Fourier series expansion in terms of a rectangular pulse train can be represented by (Yuce et al., 2007)

$$x(t)=\frac{A\tau}{T_b}+\frac{2A\tau}{T_b}\sum_{k=1}^{\infty}\frac{\sin\left(\pi k\tau/T_b\right)}{\pi k\tau/T_b}\cos\left(k\omega t\right) \tag{1}$$

where A is the pulse amplitude, T_b is the bit period, τ is the pulse width obtained from the delay unit in Fig.4, ω is $2\pi/T_b$. In order to satisfy the FCC's spectrum requirements, the signal must be band limited, which can be given by (2).

$$x(t)=\frac{2A\tau}{T_b}\sum_{k=n1}^{n2}\frac{\sin\left(\pi k\tau/T_b\right)}{\pi k\tau/T_b}\cos\left(k\omega t\right) \tag{2}$$

where n_1 is ω_1/ω, n_2 is ω_2/ω, ω_1 and ω_2 are the lower and upper cutoff frequencies of the bandpass filter, respectively. Since the UWB is a power limited system, maximizing the transmission power within the spectrum mask is an important design consideration. Detailed analysis of (2) shows the impact of the various pulse parameters on the transmission power. Although this analysis is illustrated using a rectangular pulse train, the fundamental principle can be applied to all types of pulse shapes, including those used in carrier based systems.

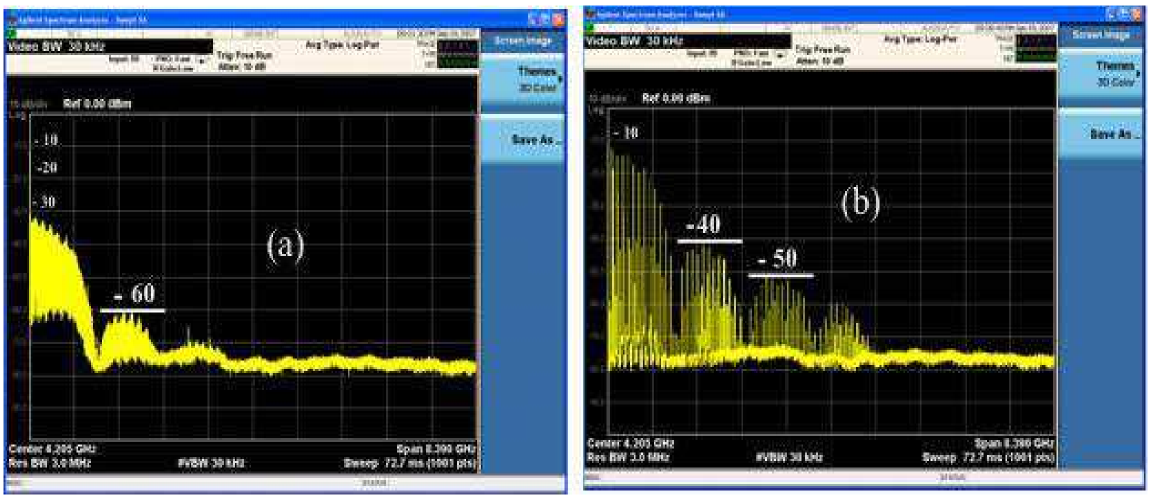
Video BW 30 kHz
Ref 0.00 dBm
Center 4.205 GHz
Res BW 3.0 MHz
#VBW 30 kHz
Span 8.390 GHz
Sweep 72.7 ms (1001 pts)

Fig. 5. Spectrums of 10MHz (a) and 100 MHz (b) pulse trains.

The key to maximize the transmitted power is to have the maximum number of approximately equal amplitude spectral lines within a given bandwidth. The maximum number of spectral lines depends on the data rate. Lower data rates contain more spectral lines but are lower in amplitude. For example, for a system with a 2 GHz bandwidth spanning from 3.1 GHz to 5.1 GHz and a data rate of 100 Mbps, the maximum possible number of spectral lines is 21. The amplitude of spectral lines is multiplied by a factor of

$2A/\pi k$ where k ranges from 30 to 51. While a system with a data rate of 10 Mbps contains 200 spectral lines (k ranges from 300 to 500). Fig. 5 shows the spectrum plots of a 10MHz signal and a 100 MHz signal with 1 ns pulse width. From the plots, it is evident that the envelope is determined by the 1ns pulse width. The amplitude of the frequency components depends on the data rate. Although amplitudes of the spectrum lines for the high data rate are higher, it does not mean that the spectrum contains higher energy in a specified bandwidth. Both signals will have the same amount of energy as the low data rate has more spectral lines.

The relationship between the pulse width (τ), the pulse period (T_b) and the number of spectral lines within a 2GHz bandwidth is shown in Fig. 6. The smallest number of spectral lines occurs when τ = 50% duty cycle where null occurs at every even integer multiple of k. To ensure a maximum number of spectral spikes in a given bandwidth, two conditions have to be satisfied. The center frequency of the desired frequency band, $(f_2\text{-}f_1)/2$, must align with $0.5/\tau$, and in addition $1/\tau$ must be greater than $f_2 - f_1$. When both conditions are met, a plot as shown in Fig. 7-(a) can be obtained. If $1/\tau$ is less than the bandwidth of the bandpass filter, the null occurs inside the band of interest as shown in Fig. 7-(b).

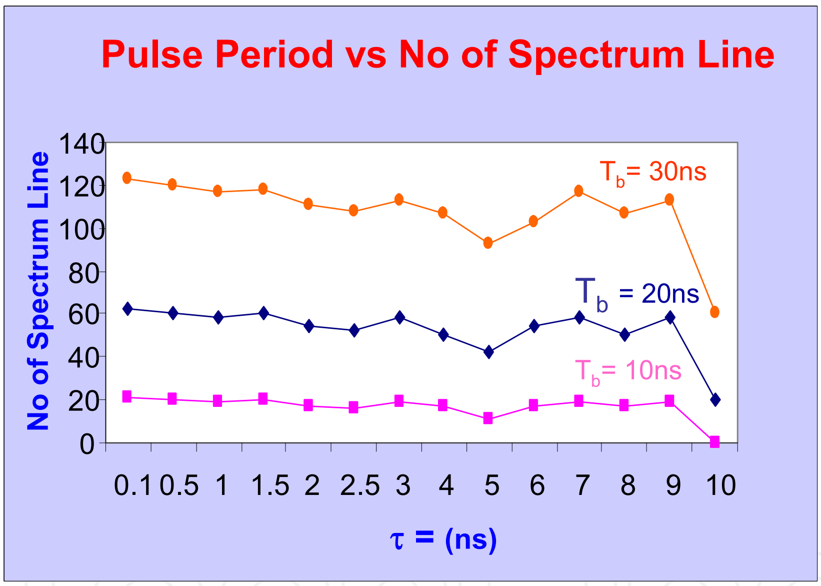

Fig. 6. Number of spectral lines vs. pulse width.

Another important factor that determines the transmission power is the relationship between the filter bandwidth (BPF) and the pulse width. Wideband filters with narrowband interference cancellation capability normally come in the form of FIR filters, which require high computing power and are power hungry. The practical implementation of wideband low-noise amplifier (LNA) and antennas is also hard to achieve. Therefore it is necessary to have a good balance between pulse widths, the filter bandwidth and the signal strength. If both τ and the filter bandwidth are large, the signal to noise ratio (SNR) will be low. A general guideline for selecting these two parameters is to maintain $1/\tau > BW$. The output of a bandpass filter resembles a high order Gaussian pulse. Fig. 8-(a) shows the output pulse from a filter bandwidth of 7.5 GHz and Fig. 8-(b) with a bandwidth of 1GHz. The wider the bandwidth, the narrower the output pulse can be obtained. Thus the width of the output pulse can be determined by the bandwidth of the bandpass filter. Sometimes this feature could be useful in the demodulation of the UWB modulated signals.

As explained earlier, the width of the input pulse determines the energy level. It is thus important to adjust the BPF such that a null will not appear within the spectrum and also the transmitted signal energy is optimized with respect to parameters explained in Fig. 6&7. It should also be noted that the distance between two pulses as shown in Fig. 8 ensures their distinction. A larger bandwidth has a finer time resolution and is thus easier to distinguish the adjacent pulses during the demodulation process at the receiver side.

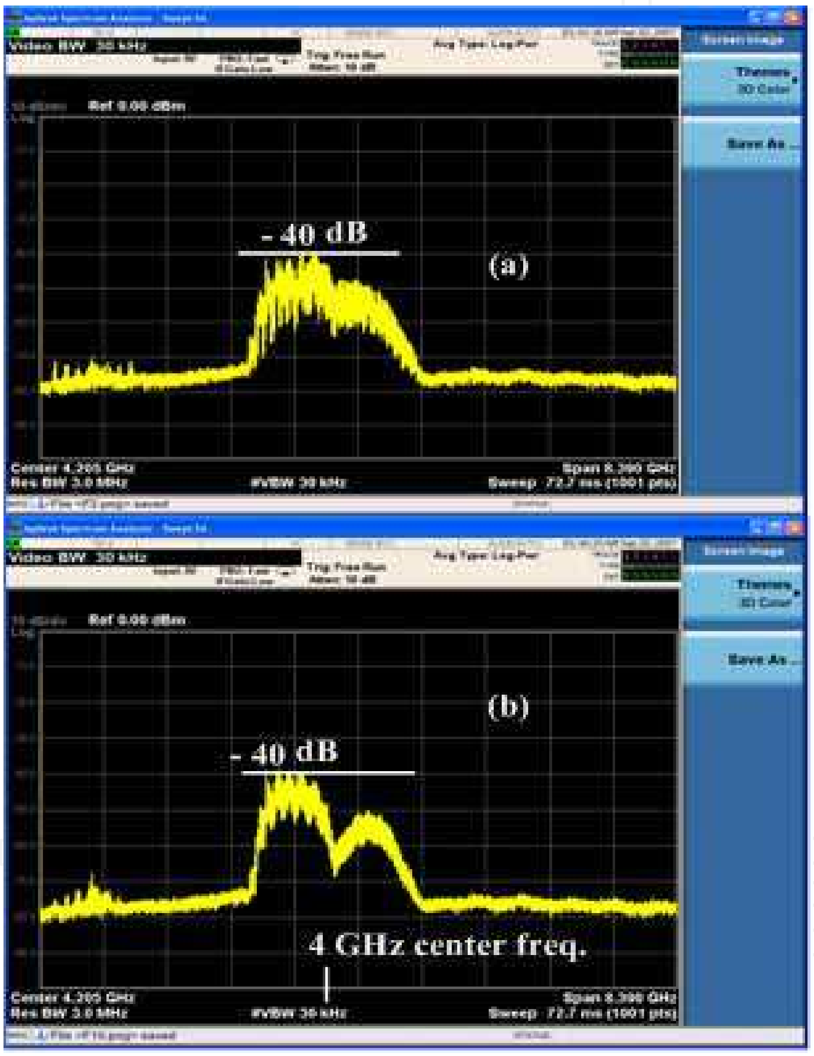

Fig. 7. Band limited pulse spectrums using 1 GHz BPF.

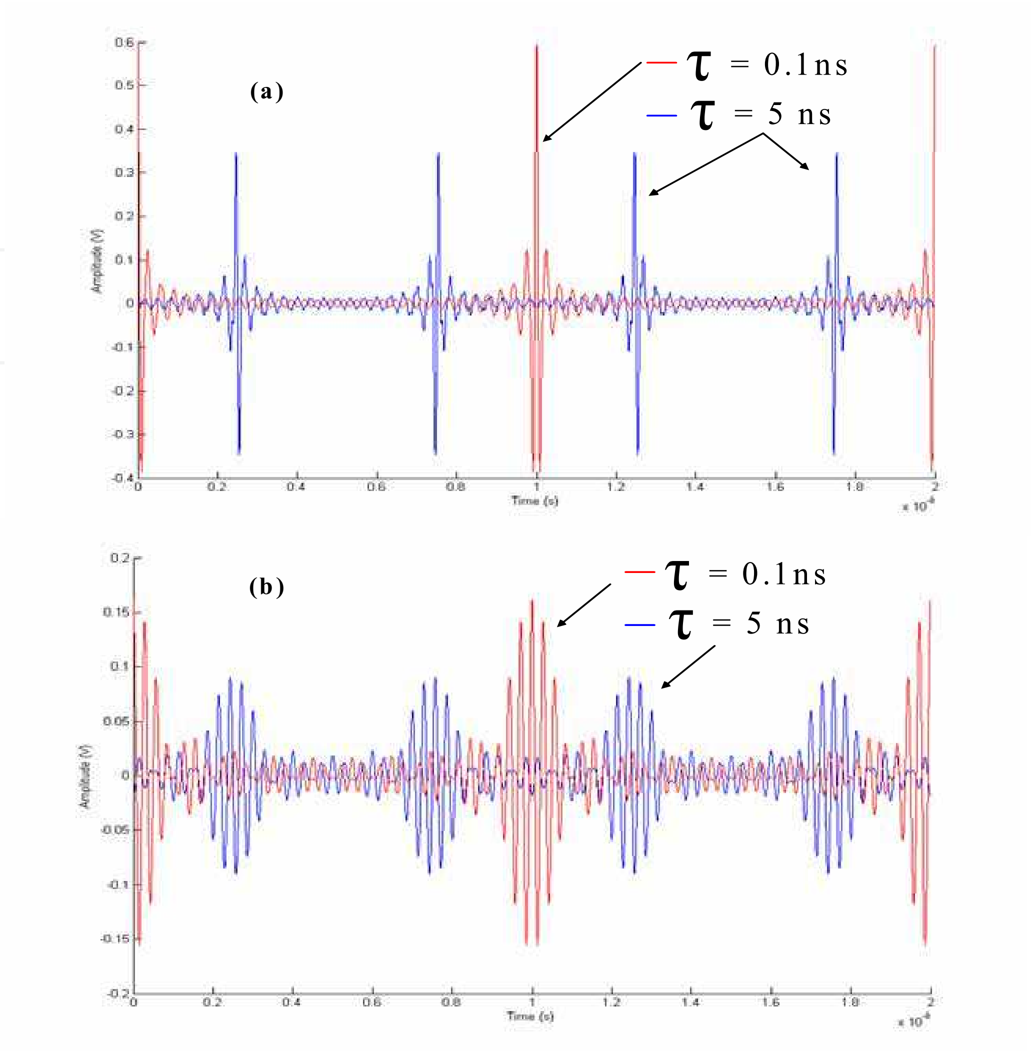

Fig. 8. The effect of bandwitdh of BPF on UWB pulse.

3. Wide Band Telemetry for Implantable Systems

Many efforts are being undertaken by scientists to understand the functions of inner organs that may be useful to diagnose and treat patients better. The early implantable[4] devices were constructed with simple electronic structures to make the device small enough so that it can be inserted in the body. A basic transmitter connected to a sensor has been used to send the signal from inside the body to external devices for tracking physiological parameters of organs (Mackay, 1961). Today's technology is able to miniaturize complex sensor devices e.g camera in order to insert inside the body so that it can travel and capture pictures for medical monitoring and detection. Prosthetic devices like Retina and Cochlear implants require a distance of few centimeters for wireless data transmission while the new implantable systems like wireless endoscope and drug delivery implants necessitate a range of 0.5-2 meters as the devices are inserted deeply inside as well as to allow patients free movement in the medical centers. In order to extend current capability of an electronic pill

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[4] The term implantable refers to devices that are inserted or ingested into the body.

technology, scientists work on the development of a high capacity radio system for better resolution as well as small enough to be swallowable or implantable in the human body.

This section will discuss the research activities for the development of a high resolution wireless endoscope device that uses wideband technology to improve medical detection and treatment. To study the feasibilty of UWB signal tranmission within a human body, a band limited UWB prototytpe system explained earlier has been tested in a laboratory environtment. Integration of antenna with UWB transmitter electronics has been considered in a capsule shaped structure. In this section the implementation details and measurement results interms of time signals and frequency spectrums at different stages of the UWB prototype system will be presented, with capsule-shaped antennas at both the transmitter and receiver ends.

3.1 UWB Technology for Wireless Endoscope

The wireless capsule endoscope is a recent implanted system that requires the integration of more complex systems on the same platform when compared to conventional implantable systems. Wireless endoscope (i.e. electronic pill) is an alternative to fiber based endoscope used in diagnosing diseases related to gastrointestinal tract, which is often inconvenient to the patient. Furthermore, capsule endoscope can reach areas such as small intestine and deliver real time images wirelessly to an external console (Meng et al., 2004). Fig. 9 shows an example of wireless endoscope used in a medical monitoring system. The device travels through the digestive system to collect image data and transfers them to a nearby computer for display with a distance 1 meter or more. A high resolution video based capsule endoscope produces a large amount of data, which should be delivered over a high capacity wireless link.

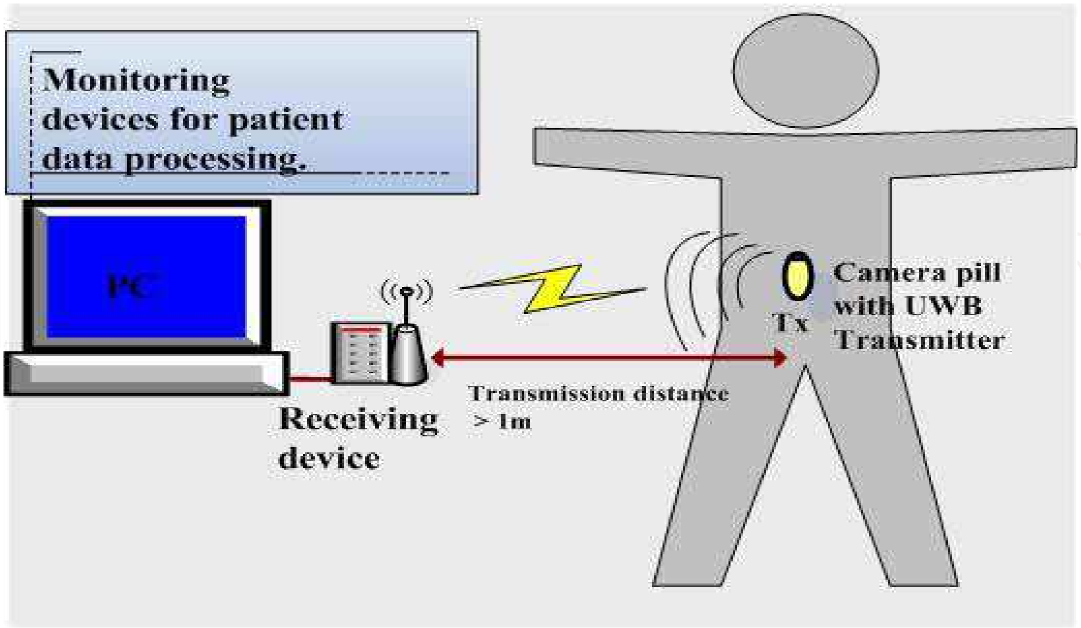


Fig. 9. A wireless endoscope monitoring system.

Since its early development, wireless endoscope designs have been based on narrow band transmission and thus have limited number of camera pixels (Nagumo, 1962; Meron, 2000). These systems are bulky due to large electronic components and batteries used. Current attempts in wireless endoscope systems or in other implantable systems have been limited to low frequency transmission. The low frequency transmission is easy to design and is found attractive due to its high efficiency. However a low frequency link requires large electronic components such as capacitors and inductors, which makes it difficult to realize a complete integrated system. Thus a high frequency link is required for better resolution and a miniaturized system. A miniaturized integrated system with a short-medium range wireless capability will make a significant impact in the performance of an electronic pill.

For low-power, high data rate and short-medium range applications of this kind, UWB (Ultra-wideband) communication is an ideal physical layer solution, which can achieve a data rate equal or higher than 100 Mbps(Kim et al., 2007; Lee et al., 2005). There have been ongoing advancements in UWB communication for short range applications (WIMEDIA, online 2009); however they cannot directly be applied to implantable telemetry because of different design and optimizations required due to stringent physical requirements and biological safety.

In recent designs (Xie *et al.*, 2006; Park et al., 2002), narrow band wireless systems have been used for bi-directional telemetry systems, with limited data rate capability. The use of wideband technology for medical implants should overcome unique challenges associated with the high frequency implementation. To address these challenges, preliminary work is presented in this section to show a complete working UWB prototype with a capsule-shaped antenna specifically designed for an electronic pill technology. The selected band is 3.5-4.5GHz (i.e. band-limited), which avoids narrowband systems operating in the ISM (Industry, Scientific and Medical) bands. Frequencies beyond 5GHz are avoided since tissue imposes strong attenuation in that range. The initial design has been tested in a laboratory environment demonstrating that an impulse based UWB system is an attractive design for wireless endoscope monitoring.

Current wireless endoscope device commercially available by “Given Imaging” is used to diagnose disorders such as Crohn's disease, Celiac disease, benign and cancerous tumors, ulcerative colitis, gastrointestinal reflux disease (GERD), and Barrett's esophagus. (Givenimaging, online, 2009). The pill uses the Zarlink’s RF chip for wireless transmission (Zarlink, online, 2009). The chip uses the MICS (Medical Implant Communication Service) band that is also allowed for unlicensed use and implantable devices such as cardiac pacemakers, hearing aids, and neurostimulators (Bradley, 2006). However, the allowable channel bandwidth for this band is only 300 kHz. It is difficult to assign enough data rate for the high quality image and video data at the moment for a real time data transfer and monitoring. It is quite obvious that there is an immediate need for higher-bandwidth data transmission for electronic pill to provide a real time data video and image monitoring that could facilitate a better diagnosis by medical professionals. This wideband technology can also be used for other medical sensing devices and prostheses such as implantable drug delivery and cochlear implants, and many other applications across the range.

3.2 Implementation and Testing

The feasibilty of UWB signal tranmission within a human body is shown in this section. A band limited UWB prototytpe system described earlier has been tested in a laboratory environtment for wireless endocsope monitoring systems. In this section the implementation details and measurement results interms of time signals and frequency spectrums at different stages of the UWB prototype system are presented, with capsule-shaped antennas at both the transmitter and receiver end. Main challenges associated with the design of microelectronics for implantable electronics are miniaturization, antenna design and saving the battery life. The microsystems will contain four main blocks, battery/power management circuitry, camera/sensors, transmitter (UWB transmitter) and antenna design. Integration of antenna with UWB transmitter electronics should be considered in a capsule shaped structure, ideally size000. Since miniaturization is important, different design approaches can be followed. As an example, each block on a separate board layer and then integrate them on top of each other as shown in Fig. 10 is a good approach to follow for a better miniaturization. In a different design shown in Fig. 10-(a) antenna can be designed such that it can easily be inserted on top of the transmitter layer. In Fig. 10-(b), the capsule shape is divided into two regions where antenna will be designed to be placed in upper-half whereas the remaining electronic units could be placed in the lower-half. Placing electronic units on one side of antenna is another possibility, Fig. 10-(c). There are commercially available mini cameras that can easily be integrated in electronic pill technology (STMicroelectronics. Online. (2009)). Small miniature rechargeable battery technologies are also being developed (smallbattery, 2009; buybionicear (http://www.buybionicear.ca/), 2009). These batteries have a dimension around 5 mm and can easily be integrated in a capsule shape structure shown in Fig 10.

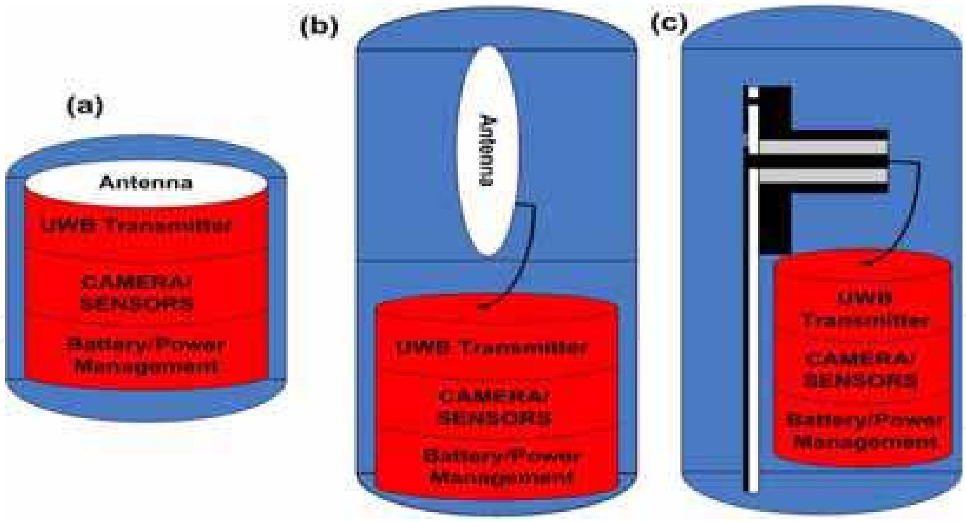


Fig. 10. Possible physical shapes for future implantable electronic pills.

The antennas that have been previously reported for endoscope applications operate in a lower frequency band (Kwak et al., 2005) A low-cost, printed, capsule-shaped UWB antenna has been designed for the targeted application (Dissanayake et al., 2009). The printed antenna presented herein demonstrates good matching in the frequency band of 3.5-4.5GHz and the radiation performance has been evaluated experimentally using a low-power I-

UWB transmitter/receiver prototype to show that it is suitable for the implantable wireless endoscope monitoring. The antenna matching has been optimized using CST microwave studio commercial electromagnetic simulation software. Proposed antenna is printed on a 0.5mm thick RO4003 capsule-shaped, low loss, dielectric substrate ($\varepsilon_r = 3.38$). It can easily fit inside a size-13 capsule (Capsule, 2000) , ingestible by large mammals. Overall length and width of the antenna is 28.7mm and 14mm, respectively. It is primarily a planar dipole, which has been optimized using simulations and printed on one side of the substrate together with a Grounded-CPW (Coplanar Wave Guide) feed as shown in Fig. 11.

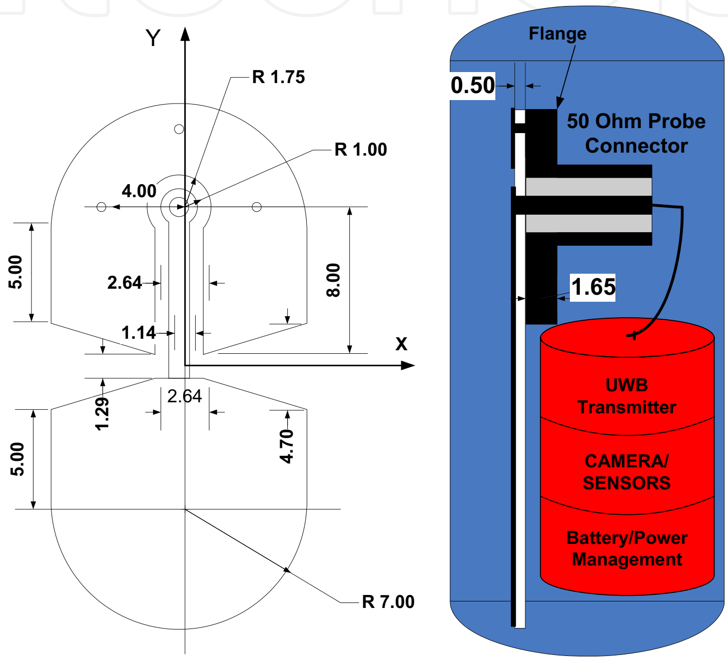


Fig. 11. A wireless endoscope monitoring system with antenna dimensions.

Grounded-CPW has characteristic impedance of 50 Ohms and the ground plane on the opposite side of the substrate is intended to support other electronics as shown in Fig. 11. This avoids performance degradation upon integration with other electronics, batteries and connectors. A panel mount SMA connector is used in place of these electronics for testing. Flange of the connector acts as a ground plane to the CPW. The circular pad in one end of the grounded-CPW facilitates broadband coaxial-to-CPW transition (Kamei et al., 2007).

The feed line has an effective dielectric constant of 2.62 at 3.5 GHz (lower end of the matched band). Therefore, the guided wavelength at that frequency is approximately 53mm, which is less than that of a CPW. The overall antenna length, 28.7mm, is close to half the guided wavelength, which is typical for a dipole. Hence the additional ground plane, which also is a part of the feed line, has contributed to the miniaturization of the antenna. As a result, largest dimension of the proposed antenna is only 0.3 times the free space wavelength at 3.5 GHz, 40% less compared to half of free space wavelength. On top of this dielectric loading of the antenna may be employed to achieve further antenna miniaturization. Three symmetrically placed vias ensure electrical connection between the patch on one side of the substrate and the flange of the connector on the other side. The radius of each via is 0.75mm. Parametric studies have shown that the distance to the vias from the center of the coaxial feed affects the input impedance of the antenna. Note that the patch, flange and each via form shorted transmission line resonators. At certain lengths, the resonant frequency of the standing waves created by via reflections can be between 3.5 and 4.5 GHz, resulting an in-band notch, which is not desirable. Thus we have selected 4mm as the optimum distance.

Two antenna prototypes have been fabricated using conventional printed circuit board design techniques. This makes the antenna low cost. Reflection coefficients of both antennas have been measured using E5071B vector network analyzer from Agilent. Measured results and simulated S11 values from CST Microwave Studio are shown in Fig. 12. There is a good agreement between measured and theoretical S11 results. Antennas have greater than 10dB return loss from 3.4-4.6 GHz. Simulations suggests that the proposed antenna has radiation patterns (not shown) similar to that of a dipole antenna. Theoretical gain at 4 GHz is 2.23dBi. It allows about -45dBm/Hz output power of the UWB transmitter under the regulations in free space. Higher transmitter power or antenna gain is possible for in-body transmission as we shall discuss shortly.

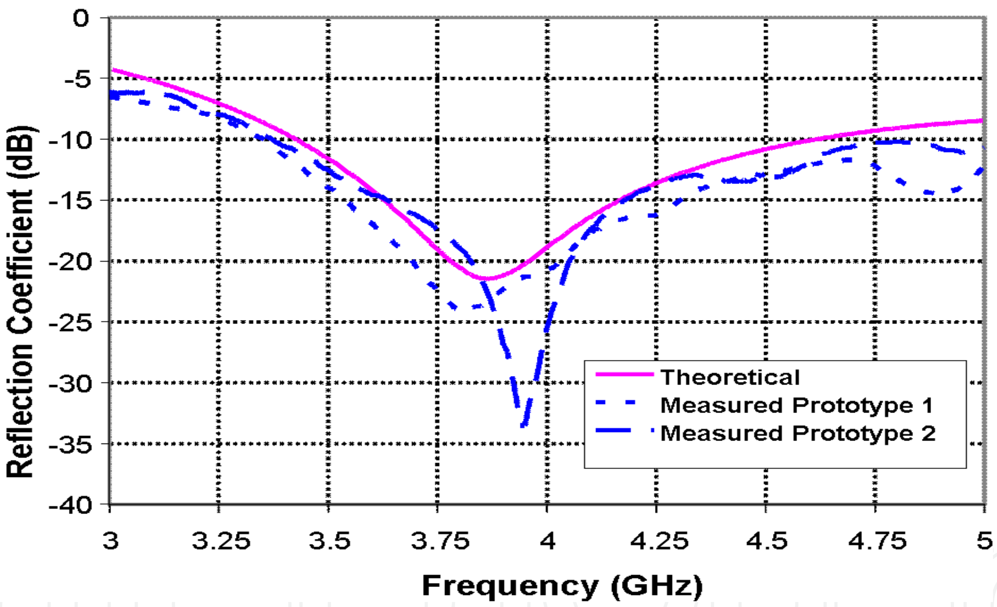


Fig. 12. Theoretical and measured reflection coefficients of the UWB antenna.

3.3 Experiments for Tissue Penetration

Our objective is to demonstrate the designed antenna and UWB prototype is capable of supporting a low-power UWB communication, which will be ultimately used to form an in-body-to-air link, without FCC violating regulations. The setup used in the experiment is shown in Fig. 13. The diameter of the plastic container is 75mm. The network analyzer (VNA) used is calibrated for full range. Salt reduced Corned Beef Silverside has been used as meat. One antenna is fixed at the bottom of the container, while the other is flushed into meat during the measurement. Both antennas were coated with clear rubber coating from Chemsearch™, to prevent any contact with meat or fluids.

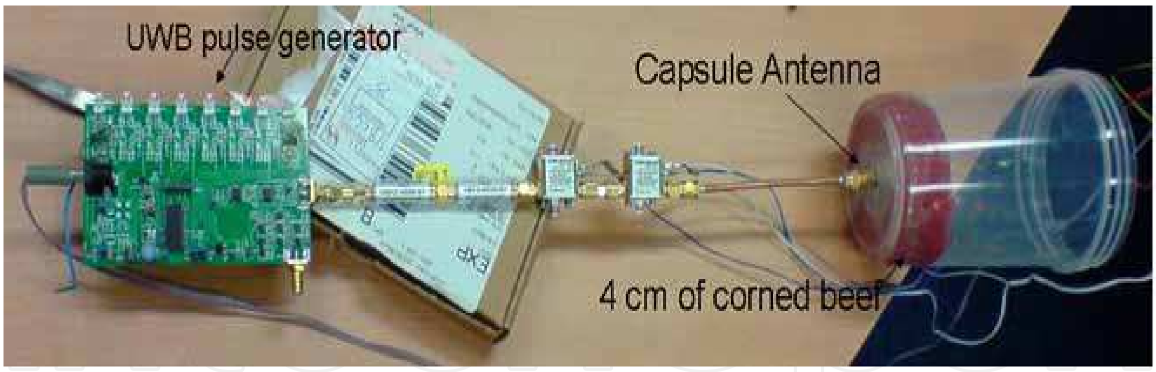


Fig. 13. Experimental setup of a UWB transmitter with capsule shaped antenna loaded with tissue material.

The coating did not have any effect on the antennas' characteristics. Antennas were held parallel so that coupling through meat is in bore sight. Prior to each measurement, jacket of aluminum foil covered the outer surface of the container to minimize outside coupling paths between the antennas. Measured S21 using the VNA is shown in Fig. 14. Coupling between antennas in the same laboratory environment and instrument calibration, for both through the meat and free space, are shown for comparison. There is about 20-30 dB attenuation through meat within 3-5GHz band for every 2 cm. This attenuation is not entirely due to absorption by meat. The antenna mismatch due to presence of meat also contributes to this.

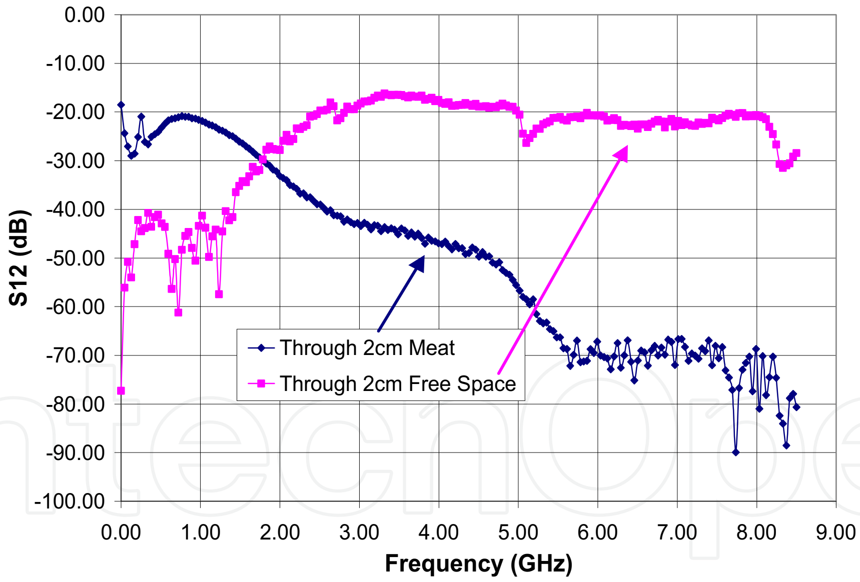


Fig. 14. Antenna coupling through meat (s21 measurement).

For a UWB transmitter, the regulation requires the signal output to be -41 dBm/Hz and lower with 0dBi antenna gain (Arslan et al., 2006). To make the UWB transmission feasible for implantable devices, higher transmitted signal levels can be used at the implanted transmitter side. The UWB signal power is arranged such that when the signal is radiated through the skin, the power level should meet the FCC mask. Fig. 15 shows acceptable transmitted power levels of the implanted transmitter for different penetration depths, approximately based on the results of our experiment. At 2cm, we can allow for as much as 20 dBm of transmitted power, which would ultimately meet regulated spectral density requirements after penetration through tissue. Thus considering the strong attenuation through body tissue, the transmitter power level can be adjusted from -20 dBm to 20 dBm in the system, without violating power levels of FCC regulation. Of course, the power levels should not reach above regulated in-body tissue absorption levels. A special case of electronic pills is that the device travels in the body, it does not stay in the same area (unlike the stationed implants), and thus increasing power levels will not increase the heat much at the tissue of a certain body part.

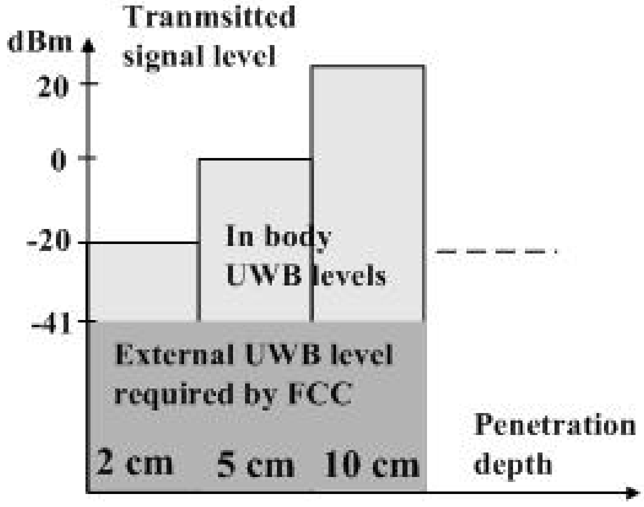


Fig. 15. Power levels of transmitted UWB signal in body.

3.4 Testing and Measurements

In the I-UWB setup, pulses have been generated based on an all digital approach described in section 2.2. Fig. 16 shows the UWB prototype with transmitter and receiver with waveforms shown explicitly. Short pulses are generated according to the on-off keying (OOK) modulated signal. At the transmitter, the pulse generator unit produces a rectangular-shaped pulse with 1ns width, as shown in Fig 16 (a). The spectrum of the rectangular pulse extends over an unlimited frequency band. Thus a Band Pass Filter (BPF) centered at 4 GHz with 1 GHz bandwidth is used to constrain the signal power under the FCC emission mask (i.e. a band limited UWB system). The energy of the side lobes is maximized within the bandwidth of the bandpass filter as discussed in Section 2.2. The filtered pulses are fed into our custom made UWB antenna. The UWB signal has shown good performance in the frequency band of 3.5- 4.5 GHz. It has also shown its ability to form a 0.6 m UWB link across the laboratory both in free-space and when loaded with meat emulating an implant once a high gain antenna is used at the receiver instead of one shown in Fig. 16-(b).

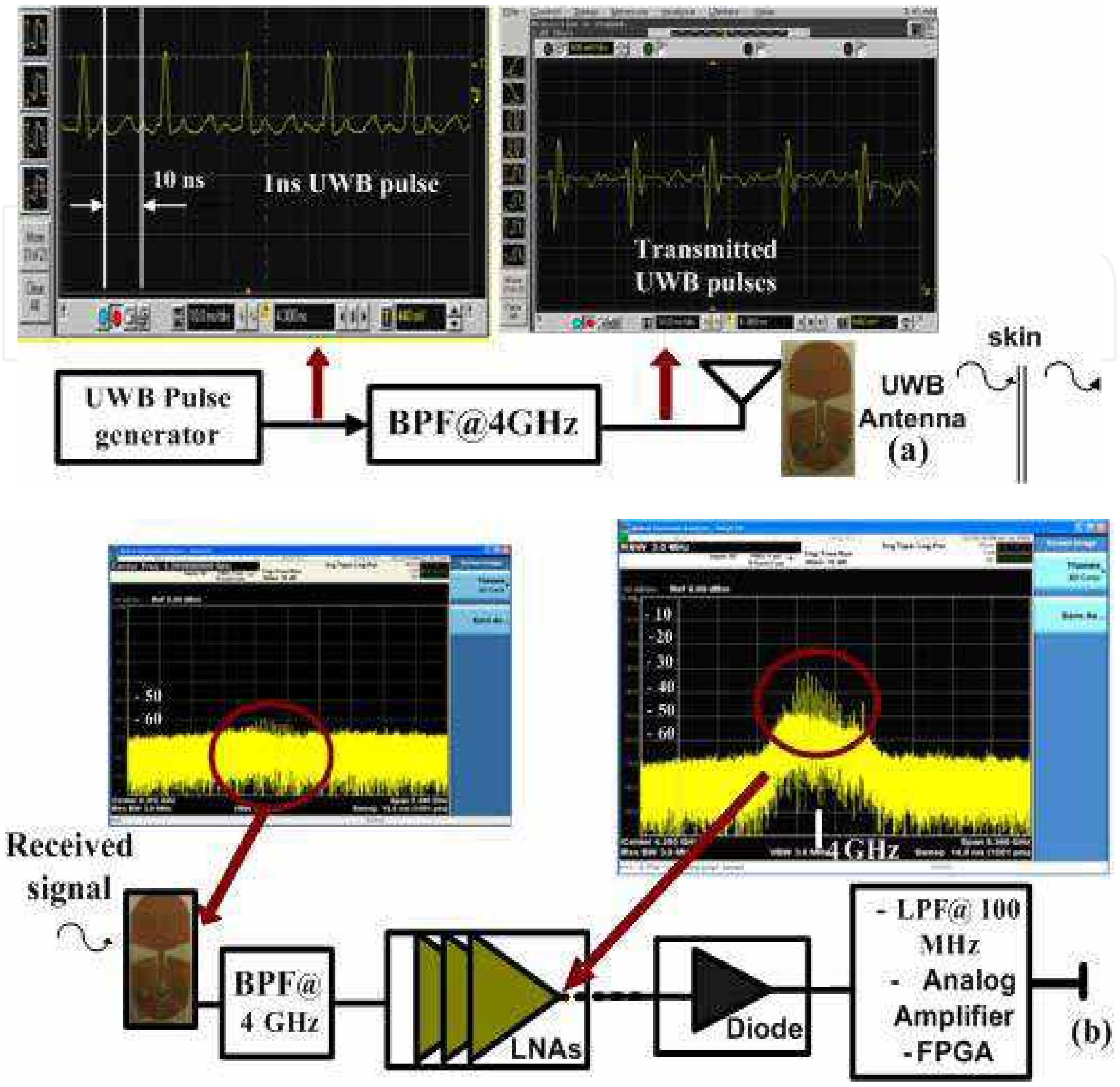


Fig. 16. A ultra wideband (UWB) wireless telemetry prototype and measurement results,(a) transmitter with 1 ns UWB pulse, and (b) receiver with spectrums at the output of antenna and after RF amplifications.

Despite the simplicity of the transmitter design, several limitations arise when designing a practical UWB receiver. A major challenge faced by an UWB receiver is its capability to demodulate the narrow pulses. A coherent receiver requires a very high speed ADC (Analog-to-Digital Converter) with a large analog input bandwidth. Secondly, it is hard to achieve precise synchronization, which is critical for the reliable operation of coherent receiver. In this experiment, a non-coherent energy detector method is used to demodulate the received signal.

There are different receiver architectures that can easily be constructed using high performance off-shelf RF components. Usually a mixer is used to down convert the high frequencies to low frequencies (Ryckaert et al., 2007). Herein a diode is used due to simplification in the successive blocks (See Fig. 16 (b)). The received signal is passed through a BPF, whose center frequency is 4 GHz, to eliminate possible interference from the frequencies of Wireless Local Area Network (WLAN) standards (for example 2.4 GHz and 5 GHz). The signal is then amplified by the Low Noise Amplifier (LNA). A diode and a Low Pass Filter (LPF) down converts the UWB signal and the baseband data is finally recovered by the FGPA.

At the receiver end, the main component is the diode detector. When small input signals below -20dBm are applied to the diode, it translates the high frequency components to their equivalent low frequency counterparts due to its nonlinear characteristics. Measurement results, shown in Fig. 16(b) are spectrum plots at the outputs of the receive antenna and the low-noise amplifiers. The transmitted narrow UWB pulses are recovered at the output of the diode. The 50 MHz data stream is obtained at the FPGA after the demodulation process. The time domain signals before and after the FPGA are shown in Fig. 17. The recovered signal is a 50 Mbps pulse obtained from pulses with width of 1ns.

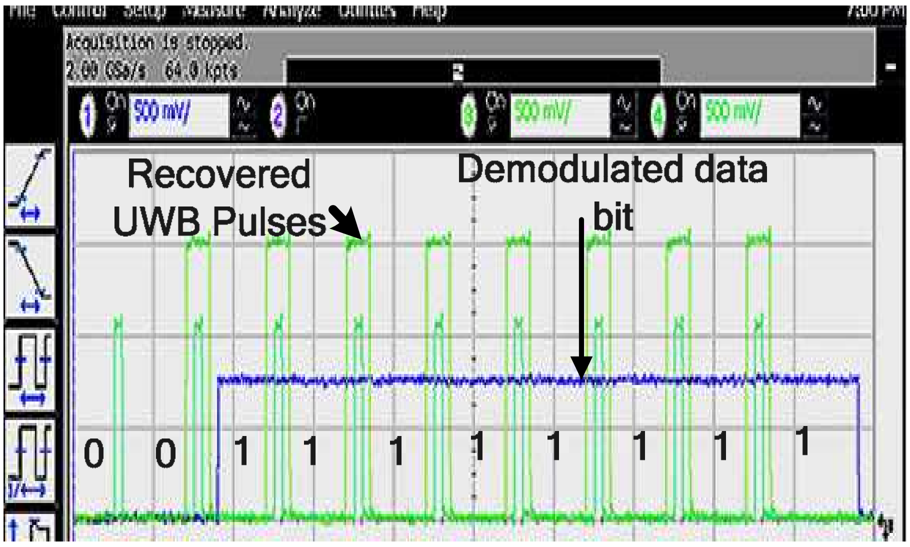


Fig. 17. Received and demodulated UWB signals.

4. Wearable Medical Monitoring System

Deployment of wireless technology for wearable medical monitoring has improved patient's quality of life and efficiency of medical staff. Several wireless technologies based on Bluetooth, ZigBee, and WLAN are available for sensor network applications (given in Table 1); however they are not optimized for medical sensor networks and lack interoperability. Therefore, there is a need for standardization to provide an optimized solution for medical monitoring systems. A group (IEEE802.15.6) was formed in November 2007 to undertake this task (WBAN standard, online, 2009). Low data rate UWB is one of the potential candidates under consideration, to overcome the bandwidth limitations of current narrowband system, and to improve the power consumption and size. In this part of the chapter, a multi-channel wearable physiological signals monitoring system using ultra wideband technology will be described.

4.1 Continuous Sign Monitoring Using UWB

An ultra wideband based low data rate recording system for monitoring multiple continuous electrocardiogram (ECG) and electroencephalogram (EEG) signals have been designed, and tested to show the feasibility of low data rate UWB in a medical monitoring systems. There has been a wide spread use of wireless monitoring systems both in hospital and home environments. Ambulatory ECG monitoring, EEG monitoring in emergency departments, respiratory rate, SPO2 and blood pressure are now performed wirelessly (WBAN standard, 2009; Ho & Yuce, 2007). The various wireless technologies adopted for medical application are shown in Table 1. Low data rate UWB is suitable for vital signs monitoring system as its transmission power is lower than those of WLAN, Bluetooth and Zigbee (See Table 1), and is less likely to affect human tissue and cause interference to other medical equipments. Furthermore, it is able to transmit higher data rates, which makes it suitable for real time continuous monitoring of multiple channels. Currently, the task group for Wireless Body Area Network (IEEE802.15.6) is considering the low data rate UWB transmission as one of the wireless technologies for the wireless devices operating in or around human body. Herein, a multiple channel monitoring system is designed and tested to show the suitability of low data rate UWB transmission for non-invasive medical monitoring applications. An 8-channel UWB recording system developed to monitor multiple ECG and EEG signals is presented in Fig. 18. Commercial off-the-shelf digital gates have been used for designing this UWB prototype system.

The system is designed to operate with a center frequency of 4 GHz and a pulse width of 1 ns, which is equivalent to 1 GHz bandwidth. An UWB transmitter is assembled using commercial off-the-shelf components for transmission of physiological signals from an on-body sensor node (Fig. 19). The UWB pulses are generated in a way to occupy the spectrum efficiently and thus to optimize the wireless transmission The transmitter as shown in Fig. 19 generates and transmits multiple pulses per bit. A clock in the transmitter is used for this

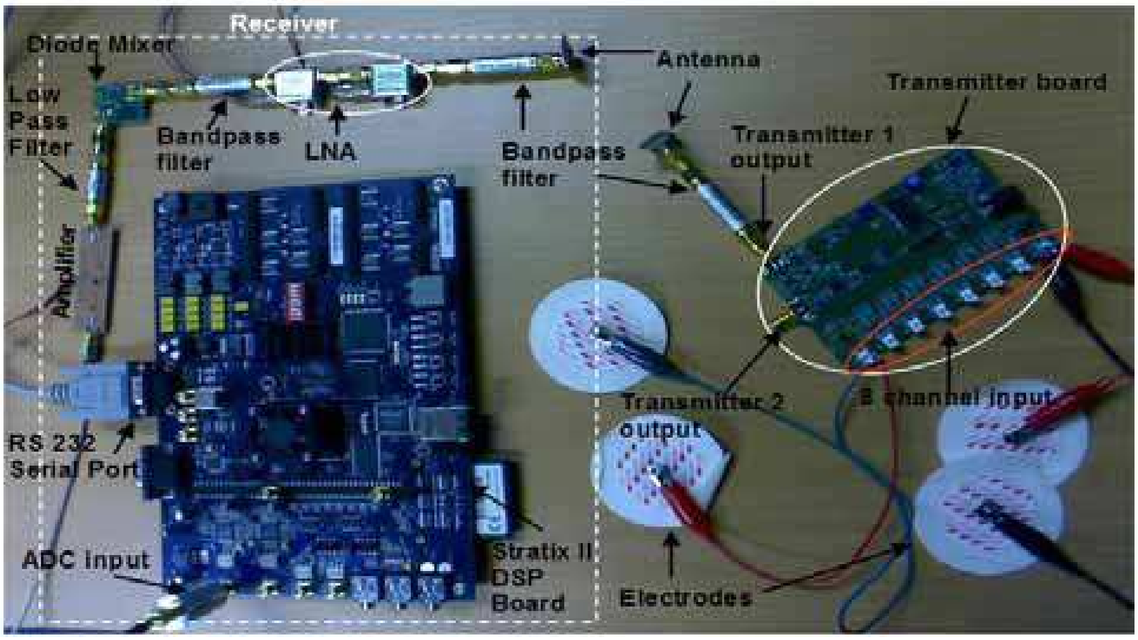


Fig. 18. Photograph of complete UWB prototype for physiological signal monitoring.

purposes and thus the number of pulses per bit can easily be adjusted. Sending more pulses per bit increases the power level at the transmitted band at 4 GHz. All the blocks (off-te-shelf components) in the transmitter consume a micro watt range power except the delay unit used to obtain very short pulses and the amplifier at the output used to arrange the output signal power for longer distances. These blocks can be designed with the recent low power integrted circuit technolgies that can easily lead to low power consumption. During the wireless transmission the ECG signal is digitised using a 10 bit-ADC in the microcontroller and the data is arranged based on the UART format in the sensor node. Each 10 bits data output from the ADC is transmitted with one start bit before the start of a byte and one stop bit at the end, which forms a periodic sequence that is used in the demodulation at the receiver.

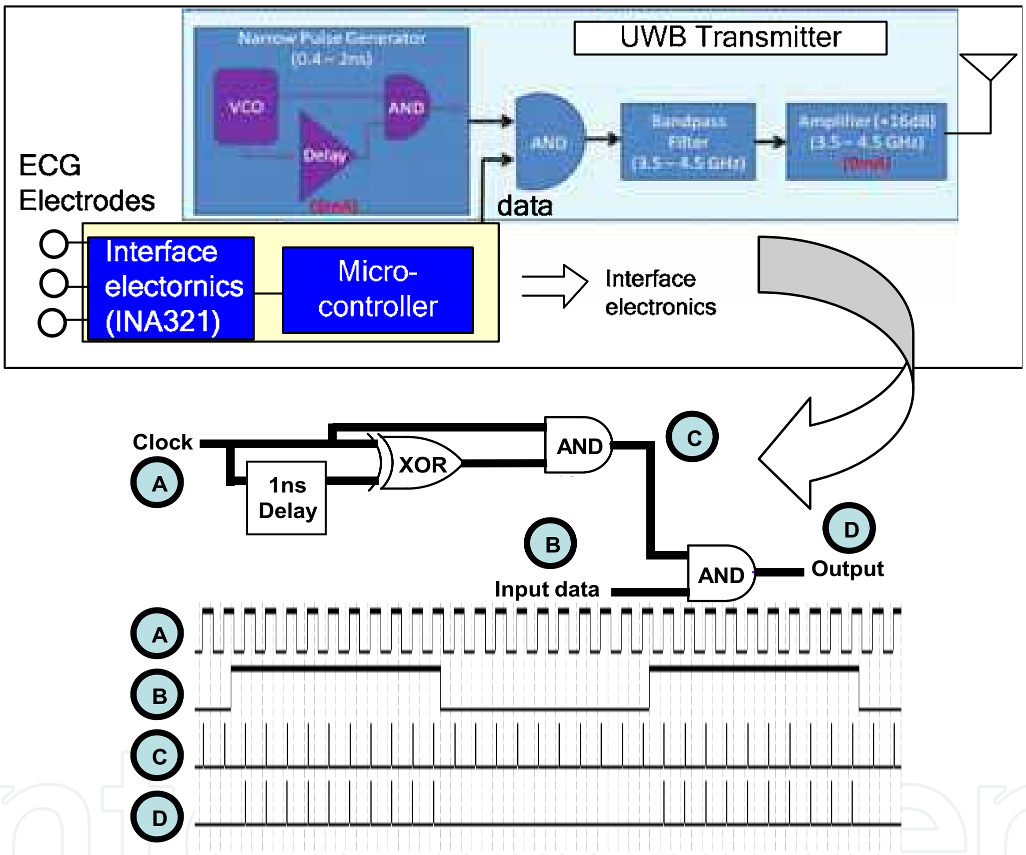


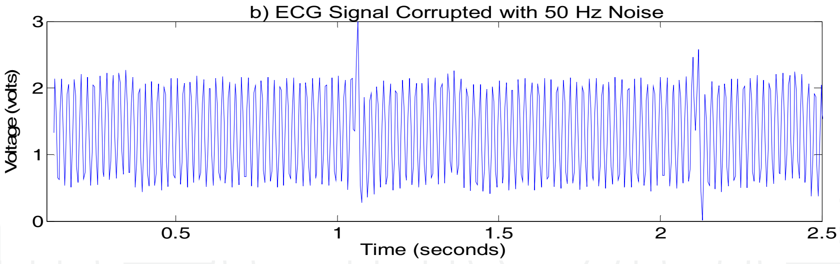
Fig. 19. ECG sensor nodes and UWB transmitter block diagram using off shelf components.

The non-coherent receiver and a field programmable gate array (FPGA) explained in the previous section is used to demodulate the data. The signals are monitored at the computer (PC) via the serial port based on UART format. Using the UWB prototype, multichannel ECG monitoring has been successfully performed showing the feasibility of low data rate UWB transmission for medical monitoring applications. Front ends for both the high data rate electronic pill system (section 3.1.) and low data rate UWB based wearable sensor system receiver for on body sensors are similar. However different data demodulation approaches are applied for the data recovery. Since here the UWB transmitter sends multiple pulses per bit to increase the processing gain, the receiver is designed to sample at a rate much higher than the data rate. The information in the bit is determined, only after performing several samples; this increases the reliability of the system.

The ECG data is obtained from the body using the instrumental amplifier (INA321) from Texas Instruments. The ECG signals are transmitted and received wireless using the UWB pulses. The result is displayed using MATLAB in Fig. 20 on the remote computer. The signal is corrupted by the 50 Hz noise as can been seen in the waveform obtained from the oscilloscope before transmitting (Fig. 20-(a)), after receiver and monitoring in MATLAB in time (Fig. 20-(b)) and the frequency domain (c). The signal is passed through a 50 Hz digital notch filter designed using a MTLAB program. The 50 Hz noise is successfully removed and the ECG signal recovered. Removing the 50 Hz noise at the PC instead of the receiver helps to reduce the complexity and the programming power required at the receiver. The whole measurement has been carried out in our lab where there were other wireless standards (e.g WiFi) and equipments operating. The ECG signal has successfully been monitoring without any error.

a) ECG Signal from Oscilloscope

b) ECG Signal Corrupted with 50 Hz Noise



c) FFT of Corrupted ECG Signal

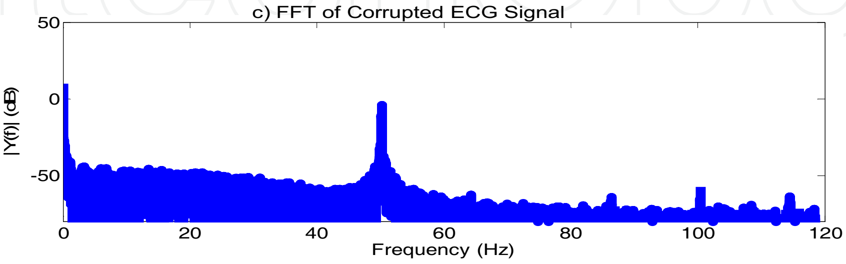
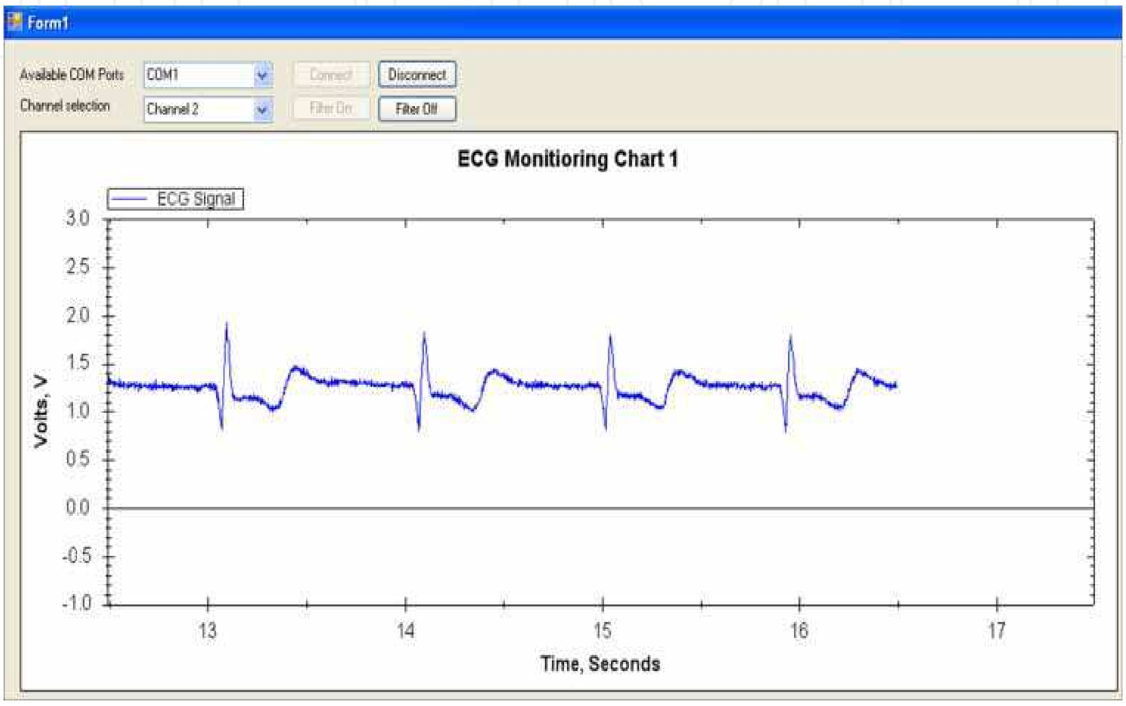


Fig. 20. Monitored ECG waveforms with 50 Hz noise

Alternatively, another program written using Visual Basic is developped to decode the data; it performs filtering as well as helps to displays the received multiple channel signals on the screen. Parity bit check is performed on the received data to ensure all data received correctly. Once the received data is decoded, it is formatted back into a 10 bit word and separated based on the information embedded in the channel bits. Digital filtering is also performed on the received signal to remove the 50 Hz noise, which comes from the power supply. The ECG signal in Fig. 21 is successfully monitored in our lab environment with other wireless devices operating. The graphical user interface (GUI) program can display any eight channels by changing the button “channel selection” shown in the window.



Available COM Ports: COM1

Channel selection: Channel 2

Fig. 21. Multi-channel ECG Signal detection via UWB wireless communication

5. Summary

This chapter has addressed the use of wideband signals in medical telemetry systems for monitoring and detection. The demonstrated UWB techniques provide an attractive means for UWB signal transmission for in-body and on-body medical applications. A band limited UWB telemetry system and antennas have been explained extensively to show the feasibility of UWB signals for implantable and wearable medical devices. The design of UWB transmitters are explained and analyzed to show its suitability for both high data rate and low data rate biomedical applications. Although the UWB system has higher penetration loss in an implantable environment compared to the conventional narrow band telemetry systems, a power level higher than the UWB spectrum mask can be used since it is a requirement for the external wireless environment. Thus an implanted UWB transmiiter should have the abilty to generate higher transmission power levels to eliminate the effect of strong attenuation due to tissue absorbtion. It should be noted that there will be a trade-off between the transmitted power levels and the desired communication range. A multiple channel EEG/ECG monitoring system using low data rate UWB technology has also been given in this chapter. The UWB receiver in the prototype is able to receive and recover sucessfully the UWB modulated ECG/EEG signals. The real time signals are displayed on PC for non-invasive medical monitoring. Wideband technology can be targeted and utilized in medical applications for its low power transmitter feature and less interference effect. When a transmitter only approached is used, the transmitter design's complexity can be traded off with that of the receiver as the receiver will be located outside and its power consumption and size are not crucial.

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The field of biomedical engineering has expanded markedly in the past ten years. This growth is supported by advances in biological science, which have created new opportunities for development of tools for diagnosis and therapy for human disease. The discipline focuses both on development of new biomaterials, analytical methodologies and on the application of concepts drawn from engineering, computing, mathematics, chemical and physical sciences to advance biomedical knowledge while improving the effectiveness and delivery of clinical medicine. Biomedical engineering now encompasses a range of fields of specialization including bioinstrumentation, bioimaging, biomechanics, biomaterials, and biomolecular engineering. Biomedical engineering covers recent advances in the growing field of biomedical technology, instrumentation, and administration. Contributions focus on theoretical and practical problems associated with the development of medical technology; the introduction of new engineering methods into public health; hospitals and patient care; the improvement of diagnosis and therapy; and biomedical information storage and retrieval. The book is directed at engineering students in their final year of undergraduate studies or in their graduate studies. Most undergraduate students majoring in biomedical engineering are faced with a decision, early in their program of study, regarding the field in which they would like to specialize. Each chosen specialty has a specific set of course requirements and is supplemented by wise selection of elective and supporting coursework. Also, many young students of biomedical engineering use independent research projects as a source of inspiration and preparation but have difficulty identifying research areas that are right for them. Therefore, a second goal of this book is to link knowledge of basic science and engineering to fields of specialization and current research. The editor would like to thank the authors, who have committed so much effort to the publication of this work.

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