UWB Wireless Link Design and Implementation Challenges in Broadband Frequency Modulated fNIR Biomedical Imaging

A. M. Khwaja, P. Daruwalla, K. Manseta, E. Sultan, L. Zhou, K. Pourrezaei+, L. Najafizadeh*, A. Gandjbakhche*, A.S. Daryoush
Department of ECE, Drexel University, Philadelphia, PA USA 19104
+School of Biomedical Engineering and Health Systems, Drexel University, Philadelphia, PA USA 19104
*National Institutes of Health, 9000 Rockville Pike, Bethesda, MD USA 20892
daryoush@ece.drexel.edu

***Abstract* — Functional spectroscopic measurements of brain matter using near IR wavelengths are characterized by absorption coefficient μ_a and scattering coefficient μ'_s. To increase the accuracy of parameter extraction, a broadband frequency modulated system is proposed and design and implementation challenges of a completely untethered and field deployable unit and a high speed wireless communication system is considered to complement a free space optical communication system.**

***Index Terms* — Functional Near Infra Red Imaging (fNIR), Ultra Wide Band Communications, System Architectures, Gilbert Cell Mixer, Fractal Antenna.**

I. Introduction

Brain Imaging has been widely considered for monitoring brain physiological condition and is proposed as a device for monitoring traumatic brain injuries (TBI). Brain inactivity's can include brain injury [1], emotional instability [2] or even pain assessment. Oxygen is essential for neuronal activity of the brain. Functional spectroscopic measurements of brain tissue at near infra red (NIR) wavelengths of 670nm, 780nm, 830nm and 980nm can be used to accurately detect levels of oxygenated and deoxygenated hemoglobin [3] from light absorption and scattering and is known as fNIR.

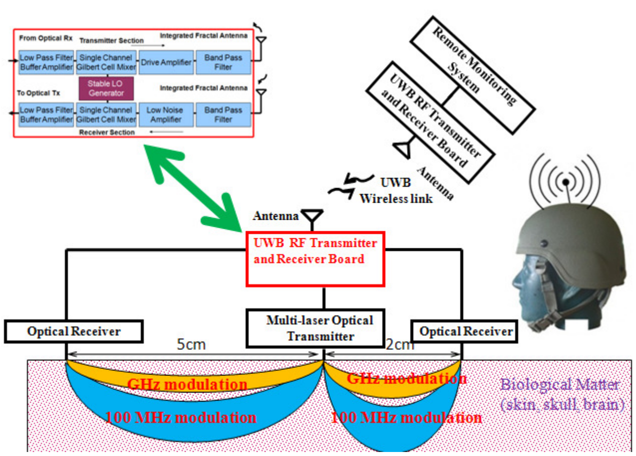

Fig. 1. Block diagram of untethered free-space fNIR brain imaging system in communication with remote monitoring using a wireless communications system. The helmet mounted structure shows the location on the human head.

A commercial system available in the market from Honda technologies are based on fiber system [4]. This system is tethered and hence not field transportable. Also this system is based on narrow-band operation. Fig. 1 depicts the basic block diagram of an untethered fNIR brain imaging system using high speed wireless system.

The system hardware consists of a number of optical transmitter and receiver modules placed in a helmet mounted structure combined with wireless transmitter and receiver building blocks. It has been demonstrated that broad band operation results in higher extraction accuracy, higher spatial resolution and higher sensitivity [5]. A practical system is based on broadband laser intensity modulation from 30 - 1000MHz. In order to have a completely mobile and field deployable system, we have a wireless communication system to communicate between the sensor and a remote monitoring device. One approach is to use a ZIGBEE unit for wireless communication [6]. However the limitation of this system is the narrow bandwidth leading to a reduced data throughput of 1Mb/s. Another approach is using raw data and employing Ultra Wide Band (UWB) spectrum, which was designated by FCC in 2002 for commercial purposes over the 3.1GHz-10.6GHz band [7]. The entire UWB band is split into 14 different channels, each having a bandwidth of 528MHz. Channel #1 starts from 3168MHz to 3696MHz while channel #14 starts from 10032MHz to 10560MHz. Each channel consists of 128 OFDM subcarriers out of which 122 contain data information while the remaining six are for control information. Since the baseband signal of the proposed fNIR system has a bandwidth of 30-1000MHz, UWB scenario has to be considered when no local signal processing is performed. The optical design challenges of the fNIR system are shown in [8]. This paper addresses design challenges of a high speed wireless data transfer system between untethered sensor and monitor systems resulting in a completely mobile and field deployable unit.

II. System Design & Modeling

The helmet mounted fNIR system is envisioned to have 18 optical transmitters and 22 optical receivers mounted in strategic locations on a helmet, which is in contact with head. The wireless system level analysis in terms of data throughput and power consumption is key in deciding the data collection method, operating frequency range, data bandwidth and data encoding scheme in an untethered helmet mounted fNIR imaging system. The system level analysis also helps in understanding the extent of local signal processing including time averaging, encoding and frequency, time or code division multiplexing is required for efficient system operation. The proposed encoding scheme in all our approaches is Manchester coding, where the self clocking ability due to zero crossing in each cycle [9] is useful for clock recovery.

A. System Design #1- Complete data transfer without any local data processing: The first approach is the brute force technique, where the entire data collected from all the optical receivers is transmitted over the wireless system. 22 optical receivers operating and collecting data over four wavelengths of 680nm, 780nm, 830nm and 980nm and over 30MHz-1000MHz bandwidth, will lead to a total bandwidth requirement of 88GHz. Assuming data of 1MHz resolution is collected from each detector every ten microseconds, a system operating at a very high switching speed is required leading to an extremely high bandwidth requirement of the order of few GHz for the transmitted information. The benefit of using this brute force system is that real time processing can be remotely performed and no information is lost due to local signal processing. The limitation of this system is the required high bandwidth and high data rate. The block diagram for this approach is shown in Fig. 2.

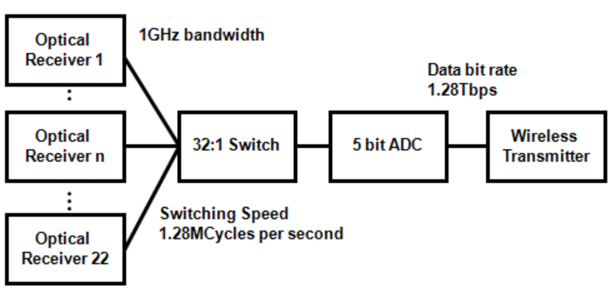

Fig. 2. System Design #1 showing data transfer using brute force technique.

B. System Design #2 – Frequency Averaging: Most biological signals vary slowly, thus, in design #2, the data collection interval from a particular optical receiver for a particular wavelength is set to every ten milliseconds. In addition, the frequency resolution of the system is reduced to time averaged information chunks of 50MHz wide bandwidth. Thus the information of every 50MHz wide signal is averaged to a single value of amplitude and phase. This information can then be digitized using a 5 bit ADC and transmitted over the wireless channel with a reduced bandwidth. The data rate for this model will be 3.52Mbps and the sweep time for each data point will be 113µs/point which matches up with the sweep time of most network analyzers [10]. In addition to throughput reduction, the signal to noise ratio is also improved by averaging out the incoherent noise sources for a 50 MHz band. Therefore, a lower data recording requirement and better efficiency is achieved. Also the bandwidth and data rate for this system is practically achievable. The averaging scheme has no active component and hence power consumption and heat generation is minimal. The block diagram for system design #2 is depicted in Fig. 3.

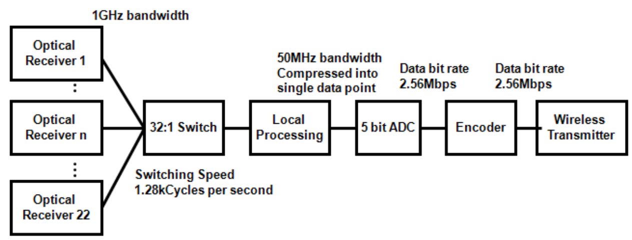

Fig. 3. System Design #2 showing frequency averaging.

C. System Design #3 –Time multiplexing and serial data transmission: This model transforms the frequency domain data from 30MHz to 1000MHz into time domain using Inverse Fast Fourier Transform (IFFT) and then this time domain information is transmitted over a wireless channel using time division multiplexing. The benefit of this approach is faster data transfer. Since data arrives from each optical receiver every ten microseconds, the data throughput for the ADC is 2.56Gbps. Real time information is transmitted in microseconds as compared to ten seconds using design #2. However the disadvantage of this approach is the high power consumption of the IFFT chips. Since the device will be placed on the human head, the increased power consumption of the system due to IFFT chips is a major concern. The block diagram for design #3 is shown in Fig. 4.

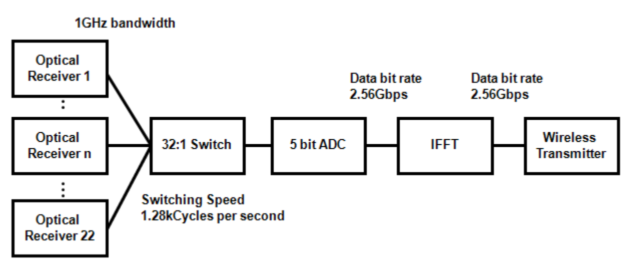

Fig. 4. System Design #3 showing IFFT chips and time division multiplexing.

D. System Design #4 – Multiple Transceivers: As the UWB spectrum is spread from 3.1GHz to 10.6GHz, we can use multiple wireless transmitters and receivers operating in different frequency ranges. Since we have 22 optical receivers, we can group optical receivers together and have six different wireless transceivers for data transfer. The first transceiver can operate in the first two channels, the second in the third and fourth channel and the sixth in the eleventh and twelfth channel of the UWB spectrum. The advantage of this approach is that it will increase the efficiency of the system by a factor of six as compared to system design #2. Thus in the same cost as of design #2, we can improve the accuracy of the system by having an averaging factor of six. The block diagram of design #4 is shown in Fig. 5. The disadvantage of design #4 is the need of multiple LO generating circuits for the conversion between baseband signal and RF signal. Also having multiple transceivers mounted on the head leads to increase in power consumption and heat dissipation.

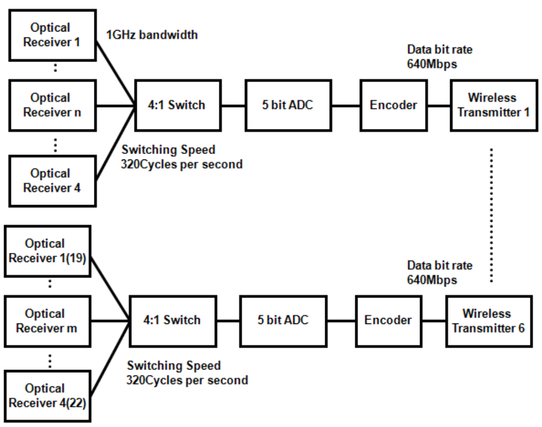

Fig. 5. System Design #4 showing multiple transmitter receiver boards using frequency multiplexing to increase throughput.

E. System Design #5 – CDMA approach: Another approach to increase efficiency is to separate different optical receiver signals using CDMA technique. Using codes to differentiate signals from different optical receivers, all the optical receivers simultaneously transmit information, each having a dedicated transceiver link for itself. The block diagram for system design #5 is shown in Fig. 6. The advantage of design #5 is that we have very high efficiency. The disadvantage of this system design is its high power consumption of simultaneously operation

A comparison between the system models in terms of performance parameters is shown in Table I. Based on the comparison of the different system designs, it appears that system design #2 has efficient data throughput and practical power consumption levels. The advantage of this system design makes it our design choice. However, we have also looked at the design requirements of system design #1, which is the lowest power consuming approach and it is discussed next.

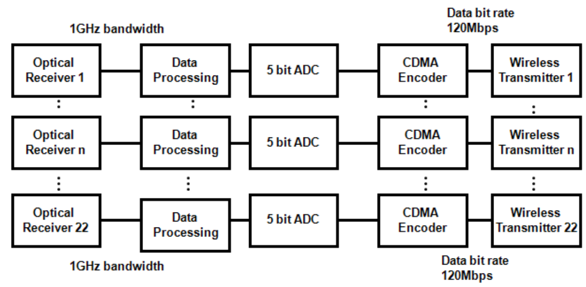

Fig. 6. System Design #5 showing CDMA technique to separate user signal and increase efficiency.

III. UWB Wireless Communications realization

In the transmit chain, the baseband signal is up converted by a Gilbert Cell Mixer (GCM), amplified by a Drive Amplifier and transmitted using an integrated printed circuit antenna as depicted in the inset of Fig. 1. In the receive chain, the signal received by the printed circuit antenna is amplified using a Low Noise Amplifier before being down converted by a GCM. The stable Local Oscillator (LO) circuit generates the LO signal for the GCM. Communication between the helmet mounted device and remote instrument control, signal processing, and imaging functions is achieved using a broadband antenna for distances up to 10m through various environments. A typical path loss exponent of n = 2.2 was selected for urban communications and the path loss of about 60dB was calculated for 3m distance [11].

As the wireless system is helmet mounted, a small size wideband printed circuit antenna, such as a fractal antenna is best suited for our broadband and small size requirements. Fractal antenna (FR05-S1-P-0-107 from Fractus Inc) was considered for the 3GHz-5GHz range in our approach [12]. The measured radiation pattern of the

TABLE I Comparison of system models in terms of bandwidth, power consumption, data rate etc

System Model	System Complexity	No of UWB Transceivers	Output Data Rate	System Bandwidth	Approximate Power Consumption
Design #1	Remote data processing	1	1.28Tbps	88GHz	800mW
Design #2	Local data processing	1	3.52Mbps	1GHz	1.2W
Design #3	Time domain data transfer	1	2.56Gbps	1GHz	1.5W
Design #4	Multiple Transceivers	6	3.84Gbps	6GHz	1.5W
Design #5	CDMA Technique	22	2.64Gbps	1GHz	2.5W

A wireless board consists of LNA, GCM, filters and LO circuits combined in a system on chip. GCM is employed for conversion between baseband frequencies (30-1000MHz) and RF frequencies. Custom built single channel GCM chip using InGaP HBT from Knowledge On (K*O) foundry services for the 2.4GHz range was reported in [13]-[14]; however, performance of a dual GCM chip is presented for first time here. This dual GCM chip is mounted in LCC carrier and mounted on a FR4 test board, as shown in Fig. 8. A conversion loss of 5dB was found for RF frequency from 4.500GHz to 5.500GHz and LO of 4.470GHz. A Low Noise Amplifier is required with gain of 20dB and Noise Figure of 0.5dB to maintain high signal to noise ratio. Custom built SOC is to be designed meeting our operating frequency requirements.

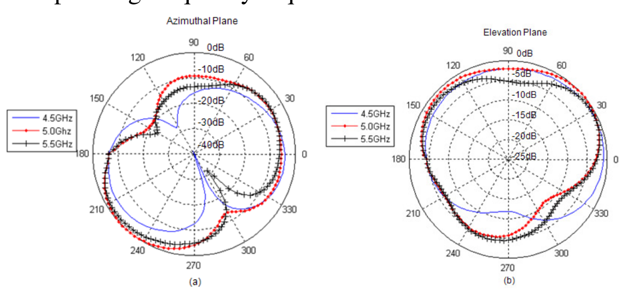

Fig. 7. Measured polar radiation pattern of a broadband Fractal Antenna in (a) Azimuthal and (b) elevation planes normalized to gain peaks of 3.5dB and 3dB respectively.

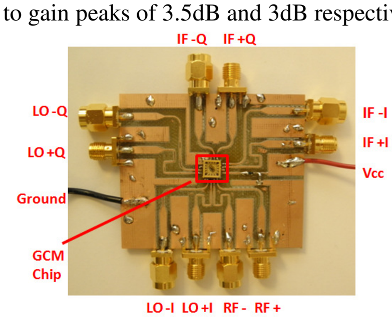

Fig. 8. A circuit board designed for dual GCM.

IV. Conclusion

A high speed wireless system is shown to complement a free space optical system in order to have a completely mobile and field deployable fNIR brain imaging device. The design challenges lie in the transfer of broadband amplitude and phase data collected at various wavelengths of light due to absorption and scattering in the brain. Various system architectures were compared in terms of data throughput, power consumption and circuit function complexity. Moreover, system on chip design topologies using integrated hardware implementation with integrated fractal antennas was discussed and preliminary experimental results were presented.

Acknowledgement

This research is partly supported by the Center for Neuroscience and Regenerative Medicine (CNRM), and the Intramural Research Program (IRP) of Eunice Shriver National Institute of Child Health and Human Development (NICHD) of the National Institutes of Health. We also thank Prathaban Mookiah from Drexel Wireless Systems Laboratory for assisting us with antenna radiation pattern measurement.

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