Comparison of Tethered and Untethered Helmet Mounted fNIR Systems for TBI Application

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Abstract—Blast or accident related damages to brain leads to traumatic brain injury (TBI) and early detection of TBI and its severity avoids disability. Broadband near-infrared spectroscopy system of 30-1000 MHz provides accurate functional imaging that could be instrumental in diagnosis of any TBI. This paper addresses design challenges and performance comparison of helmet mounted broadband functional near infra-red (fNIR) designs of both tethered and un-tethered communications with a remote analysis unit. Performance comparison of both systems in terms of size, power consumption, and data throughput are discussed and merits of the tethered and untethered helmet mounted broadband fNIR is discussed. The photon migration of NIR light is accomplished using broadband optical transmitters and reception of diffused photons at various positions on head that are 1.5 cm away from each individual optical transmitter. Optical transmitter and receiver are custom designed to perform photon migration spectroscopy through head and brain at wavelengths of 680nm, 780nm, 820nm, and 980nm. The untethered helmet structure consists of RF electronic for reception of UWB signals of 4.5-5.5GHz and transmission of 50Mb/s data after local signal processing of the received diffused photons. Low frequency electrical connections using microcoax are employed for interfacing the broadband 30-1000MHz reference source to the multi-wavelength optical transmitters and process the received RF signal component of diffused photon density waves.

Key Terms- fNIR, TBI, UWB communications, IC, LNA, GCM, LO, Optical transmitter, Optical receiver

I. Introduction

Near-infra red optical technologies have been used in many medical applications. Medical applications related to spectroscopy and therapy deploys the used of photons in the near-infrared region to penetration through biological matters. Functional imaging based on near-infrared optical technique, such as fNIR, provides information that covers more spatial and hemodynamic information than regular imaging techniques, such as MRI and CT scan [1]. It's been found that non-invasive technology of NIR provides information of functional process of Oxy- and deOxy-hemoglobin absorption rate that can relate to activities in brain [2], breast tissue tumors [3] and can be deployed as bio-tagging method of un-normal behavior of any biological process [2]. NIR therapy methods have been found its way through wound healing [4], neuronal cell growth [5], and even anesthesia during surgery [6]. However these techniques are either unmodulated (CW) or single frequency (I/Q) NIR based system architectures. It has been demonstrated that a broadband frequency modulated system significantly reduce optical parameter extraction of absorption (μ_a) and modified scattering (μ_s') coefficients [7] over CW and I/Q systems.

This invited paper reviews the broadband hardware implementation challenges for a field deployable helmet mounted fNIR and focuses on brain functional imaging related to the traumatic brain injury (TBI). Traumatic brain injury (TBI) is a neurological disorder that in most cases caused by other impacts or injuries form of blast injuries [8], emotional instability [2]. TBI can be caused by either open head injuries or closed head injuries. Open head injuries, caused by penetrating objects, creates visible brain injuries, where closed brain injuries is more difficult to diagnose, these injuries can be caused by broad reasons that leads to disorder in the neurons functionality.

Neuro-imaging have been evolving in the diagnosis of TBI that leads to changes in bone, tissue density, water content (i.e., edema), blood flow, subtle changes in the neuronal and extracellular biochemical milieu [1]. Studies show that functional imaging would give better assessment for detecting the underlying pathophysiology of the sequelae of mild TBI. Neurological conditions that are caused by blast brain injuries have been studied using invasive technique of intracranial pressure (ICP) [9]. ICP which is based on invasively placing pressure transducer to detect the brain pressure and water level (edema) have many limitations [10]. Studies shows that non-invasive optical functional imaging based on NIR scattering is very powerful and predicts an early monitoring of brain water accumulation in a similar manner as the invasive ICP method provides [10, 11]. Commercial fNIR systems are now being marketed based on fiber optic technologies. These tethered systems are extremely restrictive and due to its immobility are not suitable for in-field imaging. The current fNIR systems are designed based on optical transmitters and receivers which is CW or I/Q systems to perform photons migration through biological matters. CW system has been used in wound healing as part of the therapeutically process to monitor healing [4], and anesthesia as a tool to monitor the level of brain activity during surgery [6]. In broadband frequency modulated

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systems i) a higher optical parameter extraction accuracy and ii) a higher spatial resolution and sensitivity is achieved than narrowband systems operating at 141MHz [7]. This paper addresses design challenges and preliminary measured performance of a broadband (30-1000MHz) optical link using custom designed and novel free space optical transmitter (Tx) and optical receiver (Rx) modules that are placed in key locations of head in a helmet mounted structure. These optical Tx and Rx modules in TO-46 can packages are integrated with ultra wideband (UWB) wireless communication system for untethered or coaxial cables/USBII cables for minimally tethered systems as shown in Fig. 1.

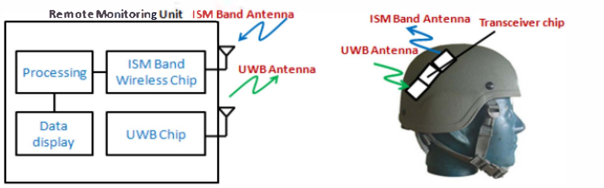
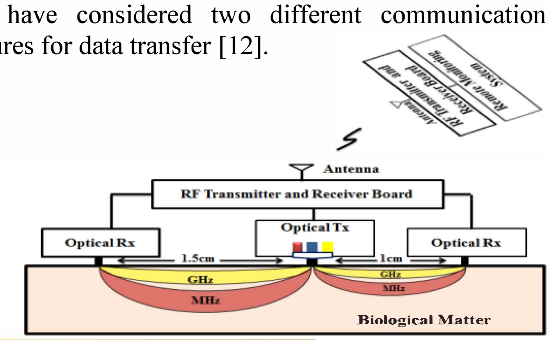


Fig. 1. Untethered helmet mounted fNIR System with remote unit.

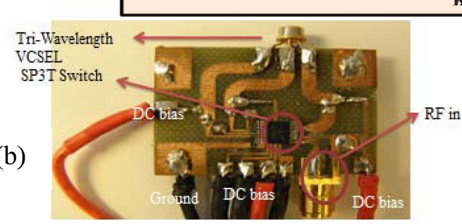
II. fNIR Hardware implementation

The overall system block diagram of a multi wavelength NIR spectroscopy system is shown in Fig. 2a. RF switch is used to drive different high power VCSEL (670nm, 795nm, 850nm). High power Multi wavelengths VCSEL from VIXAR (Module V3WLM-001) have been used with an SP3T RF switch from Hittite (HMC245QS16) as depicted in Fig. 2b. Either forward or backward scattered light from the turbid medium is collected by optical receiver shown in Fig. 2c using APD from Hamamatsu (module C5658). Phantoms that resemble brain tissue with known optical absorption and scattering coefficients are used to calibrate broadband frequency operation. Automatic Network Analyzer (ANA) could be used as RF source and a sensitive RF receiver in these experiments. The system operation and data control imposes a number of challenges that are to be addressed as part of system evaluation and performance comparison. In fact we have considered two different communication architectures for data transfer [12].

(a)



(b)



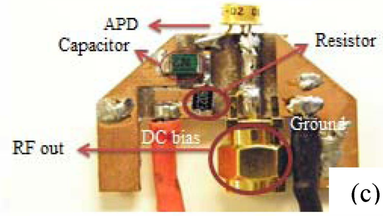


Fig. 2. a) Overall system block diagram; b) Tri-wavelength laser Transmitted with SP3T switch; c) Optical Receiver using APD from Hamamatsu.

The first approach is a wireless data transfer using custom designed untethered wireless communications between the remote control unit and helmet mounted electronics. Since our system bandwidth is about 1GHz (from 30-1000MHz), Ultra Wide Band Communications [12] protocols for distances of 3m is considered. The multiband sub-channel of each 528MHz wide is considered and particularly channel 4 (4752MHz to 5280MHz) and channel 5 (5280MHz to 5808MHz) are useful for our RF transmission. For UWB communications custom designed IC are being developed using IBM's 90nm CMOS foundry services. The 30-1000MHz chirp signal is up-converted using Gilbert cell mixer (GCM) before RF transmission.

The transistors performing the mixing between the RF signal and LO signal are biased at Vgs = 0.37V and Vds = 0.29V. The conversion gain of the single channel GCM is 1.5dB with 2.3mW power consumption. Up-converted signal is passed through drive amplifier and bandpass filter before radiation from remote monitoring and imaging system to the helmet mounted electronics. Small and conformal fractal antennas are used for efficient broadband radiation over sub-channels 4 and 5 of the UWB. The wireless receiver down-converts the RF signals to IF signal of 30-1000MHz after passing through band pass filter and low noise amplifier (LNA). To overcome the UWB path loss over 3m, at least 40dB of LNA gain is required. The designed LNA has an overall simulated gain of 32dB, noise figure of 1.5dB, and power consumption of 25mW. Once again single channel GCM is used for down-conversion of RF signals. Local oscillator (LO) signal of 4750MHz is used to down-convert RF signal of 4780-5750MHz and IF signal of 30-1000MHz out of. The LO power required for the conversion in GCM is 7dBm. The system block diagram of helmet mounted wireless communication system is depicted in Fig. 3. The output bit stream can then be sent over ISM band (3.3-3.6GHz frequency range). We can use wireless transceiver chip from Wisair to do data transfer from the sensor to monitor [13]. This chip operates in the 3.1-4.8GHz band and has data operating rate of up to 480Mbps, thus meeting our data throughput requirements by averaging over 50MHz.

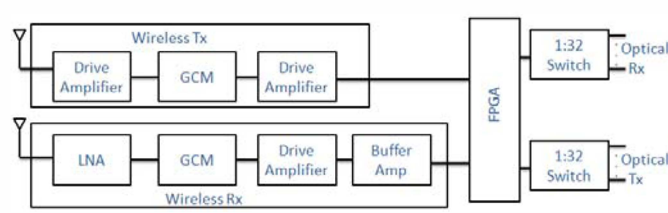


Fig. 3. Wireless and local signal processing block diagram

The second approach is to use a minimally tethered system. There are two possible solutions. In the first approach, the frequency swept signal from a frequency synthesizer is sent to the sensor unit using micro coaxial cable. At the receiver side, the output from the optical receivers is processed by a FPGA chip and transferred directly to a laptop using USB interface. The other approach is to use a network analyzer for frequency generation as well as data processing. A good frequency and time synchronization is required between sensor and monitor. Detail comparison of both untethered and minimally tethered systems is discussed in the following section.

III. System Architectures

The system composed of two sub-hardware portion one is related to the optical hardware which is optical receiver and optical transmitter to perform quantitative spectroscopy of the brain and second a portion related to the communication system and signal processing. In order to achieve full mapping of the brain a series of optical transmitters and receivers are placed 1.5cm apart as shown in Fig. 2a. Each optical receiver is interfaced to the SPMT switch and a local signal processing scheme is to be performed [12] in an FPGA. The untethered system will require a wireless chip and a local signal processing microprocessor. FPGA from Xilinx can be used in along with Wisair wireless chip. Most of the power consumption will be dominated by the FPGA and then the wireless chip as shown in Table 1. Table 2 shows system requirements and performance of two different schemes of minimally tethered systems. The untethered system design is based on performing simple signal processing by averaging signals over bandwidth of 50MHz. More sophisticated signal processing can be achieved using FPGA, but that will require more of FPGA processing speed that leads to more power consumption. We have recently developed a novel signal processing algorithm based on relative two separate positions measurement and curve fitting to the diffusion equation predictions using proposed optical parameters [14].

One of the minimally tethered systems will require digitization of analog signal using ADC and FPGA, as the data connection is provided using USB2 cable. Power consumption will be again dominated by the FPGA as shown in Table 2. The other option of the minimally tethered system relies on direct coaxial connection between the SPMT switch from the 22 optical receivers to an automatic network analyzer (ANA), similar to the calibration process. This method will rely on ANA to perform frequency generation and remote data processing, in order to sweep the frequency signal and sent to 1:32 switch using micro coaxial cable and then receive the output from 1:32 switch for data processing. This method does not consume power locally on the helmet mounted electronic, but requires the higher cost ANA at the remote unit.

Table 1. Untethered system characterization

Parameter	Untethered System
System Approach	• 1 GHz data from monitor to sensor transmitted over 4.7-5.8GHz (custom UWB chip) • After local signal processing, 50Mbps throughput data from sensor to monitor transmitted over 3.1-4.7GHz band using WSR601 chip
Hardware Requirement	• Xilinx Virtex 5 FPGA (Size 22mmx22mm, Power dissipation 450mW) • Analog to Digital Converter AD9266 (Size 10mmx8mm , Power dissipation 66mW)
	• Wisair WSR601 wireless chip (Size 55mmx55mm, Power dissipation 1000mW) • Fractal Antenna FR05-S1-P-0-107 (Operating frequency range 3-6GHz, Size 10mmx10mm)

Table 2. Minimally tethered system performance requirements

Parameter	Minimally Tethered System using frequency synthesizer and USB interface
System Approach	• 1 GHz frequency using frequency synthesizer • Frequency swept signal sent to 1:32 switch using micro-coax cable • Data from 1:32 switch sent to FPGA for processing • FPGA output (50Mbps throughput) sent to laptop using USB2 interface
Hardware Requirement	• Xilinx Virtex 5 FPGA (Size 22mmx22mm, Power dissipation 450mW) • Analog to Digital Converter AD9266 (Size 10mmx8mm, Power dissipation 66mW)
	• Xilinx Platform Cable USB 2(Size 116mmx54mmx16mm, Powered from Laptop) • Micro coaxial cable (Length of 3m, Expected attenuation over 3m length <2dB, operating frequency < 1GHz)

IV. DISCUSSIONS AND CONCLUSIONS

Previous experimental studies accurately extracted optical parameter even in the presence of fluctuations at certain frequency ranges using broadband modulation [14]. The potential extraction errors was observed below 100MHz and above 600MHz as shown in Fig. 4, where the measurement results of photons migration from optical source to optical receiver placed 1cm and 1.5cm away are depicted. At frequency ranges of below 100MHz and above 600MHz deviation from the expected behavior predicted insertion loss and phase from diffusion equation is observed in the homogenous phantom. This behavior has been observed repeatedly and attributed to the finite dimensions of solid phantoms. In communications with other fNIR experts, the fiber based broadband fNIR experiments have also resulted in similar fluctuations above 600MHz. A curve fitting method was devised to overcome the fluctuations which can be attributed to reflection from edges of finite solid phantom. This curve fitting process has led to a better extraction of optical parameters [14].

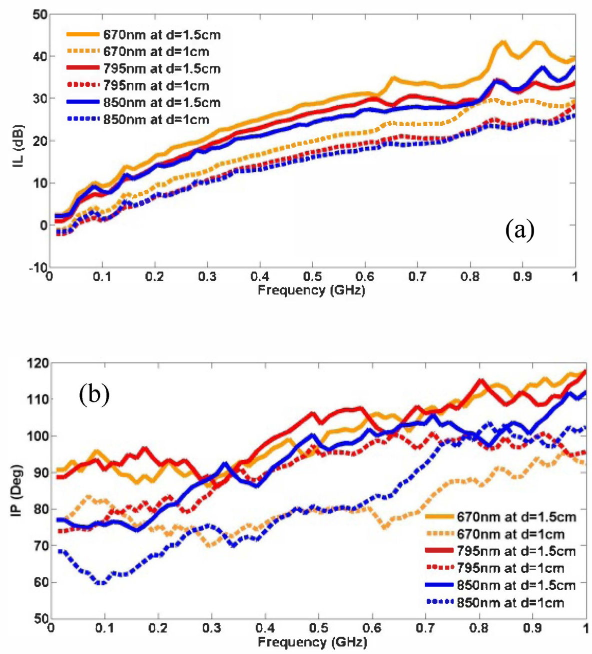


Fig. 4. a) Insertion Loss b) Insertion Phase of optical link for separation distances of 1cm and 1.5cm in solid phantom, representing optical behavior similar to brain tissue.

Error analysis is also an important factor in designing any commercially viable biomedical system, and it becomes more important when it deals with high frequency wireless communications. Random errors due to electronic component introduce noise that has been thoroughly analyzed for the optical transceivers [15], but systematic measurement errors due to calibration of ANA, incident angle of optical beam penetration, misalignment or displacements of individual optical transmitters and receivers can be analyzed as summation of various sources of error. Errors can be determined using sensitivity of each parameter to any random error from the known analytical relationship of the overall gain to various error parameters. A more detailed error analysis of fNIR system is required to identify tolerances to the manufacturing parameters.

This paper presented advantage and disadvantages of untethered and minimally tethered systems in term of data throughput, size, and power consumptions. These design schemes can provide different solutions for the helmet mounted fNIR that are applicable to field deployable units for TBI assessment and monitoring.

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