Portable Hardware for Real-time Channel Estimation on Wireless Body Area Networks

Seunghyun Oh and David D. Wentzloff
University of Michigan
Department of Electrical Engineering and Computer Science
Ann Arbor, MI, USA
austeban, wentzlof@umich.edu

***Abstract*—We present the design and implementation of a portable and economic device that can estimate wireless body area network (WBAN) channels in the 2.4-2.5 GHz frequency range. The equipment conventionally used for WBAN channel estimation is accurate, but bulky and expensive. Our channel estimator consists of multiple transmitters and a receiver, powered by consumer batteries, and small enough to fit in the palm of a hand. The transmitter includes an impulse generator fabricated in a 0.13µm CMOS process that continuously excites the channel with BPSK-modulated pulses. The receiver is implemented with COTS and records the impulse response in memory, storing up to 1.6M channel snapshots, which can be extracted later. The transmitter and receiver are described in this paper, along with experimental results. The measured data show the dynamics of WBAN channels in relation to the environment and the human body motion, in scenarios where it isn't practical to use conventional channel modeling equipment.**

I. INTRODUCTION

A wireless body area network (WBAN) consists of several mobile devices worn on the human body. WBANs have enormous potential in health monitoring systems as it eliminates the inconvenience of having wires around the patient's body, offering more freedom of movement and comfort, enhanced monitoring, and the administration of at-home treatment [1]. Low power consumption is crucial for such applications due to the limited capacity of portable batteries. The power consumption of wireless communication is especially important since it typically consumes the majority of the energy in such systems. Robustly and accurately estimating WBAN channels is a crucial task in developing more efficient communication systems that optimally sense and exploit the unique channel dynamics [2].

Figure 1 shows an example of a WBAN linking several health monitoring systems around a human body to the person's cellphone. The sensors are severely energy constrained, while the cellphone has a larger, rechargeable energy source. The WBAN channel characteristics depend heavily on the surrounding environment, body posture, and movement, which all vary with time [3]. This is unlike the channel characteristics of long distance wireless networks (e.g. cellphone to WLAN or WWAN base station), which are relatively stable irrespective of the user's posture or movement. Furthermore, WBAN channels exhibit a periodicity due to the nature of body movements, yet this phenomenon hasn't been fully characterized or exploited to save energy in any WBANs. Many studies have been performed on WBAN channels [4-8]. Most of them use a vector network analyzer (VNA) or vector signal analyzer (VSA). These are accurate, but also bulky and expensive instruments, and require wired connections around the body and to a wall outlet for power. If we want to measure the channel characteristics where this equipment cannot be carried, a portable device is necessary. Furthermore, it is desirable to log channel data as a function of time in order to characterize the periodicity of the channel. Other groups have reported implementing a portable WBAN channel estimator that relies on RSSI measurements at a fixed frequency [8,9].

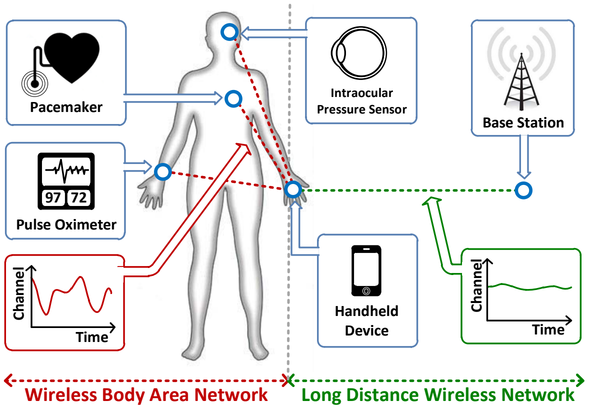


Figure 1. Communication on wireless body area networks.

In this paper, we present a portable channel estimator which can capture the impulse responses of WBAN channels. Similar to a VNA, this provides details on the multipath fading within the channel that cannot be extracted from RSSI measurements alone. The transmitter includes a custom UWB pulse generator fabricated in a 0.13µm CMOS process to excite the channel impulse response. The narrowband correlating receiver captures the response in the 2.45GHz ISM band. An impulse generator was chosen so that the transmitter excites a wide frequency range, and the receiver may be expanded to simultaneously capture multiple bands at once to observe the correlation among them. Section II describes the architectures of the transmitter and receiver, Section III presents measurement results from the hardware, and Section IV presents measured WBAN channel results.

II. ARCHITECTURE

Figure 2 depicts the entire channel estimation system. Multiple transmitters are placed on the body that generate

978-1-4577-1470-2/11/$26.00 ©2011 IEEE

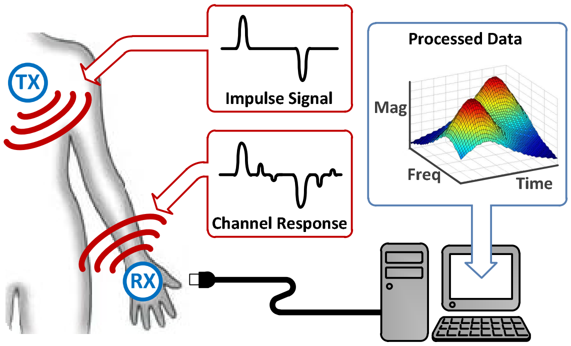


Figure 2. Channel estimation system.

impulses to excite the channel response between each transmitter and a single receiver. The impulses are BPSK-modulated with unique CDMA codes so the receiver can identify them. The receiver down-converts and samples the received signal, and an FPGA implements a correlating receiver to recover an average impulse response. Snapshots of the channel are taken at a programmable rate, and the responses are saved in a local memory. When an experiment is complete, the responses are uploaded to a PC, where an FFT is performed on them to recover the frequency response of the channel vs. time. The hardware characteristics of measured responses are de-embedded using a baseline response (with no multipath and at a known distance) in order to determine the impact of the time-varying channel.

A. *Transmitter*

Figure 3 shows the schematic of the transmitter. It consists of a custom IC fabricated in a 0.13μm CMOS process, an external power amplifier (ABA-54563 from Avago technology), and a 2.45GHz antenna (ANT-2.4-CW-RH from Antenna Factor). The IC generates BPSK-modulated, 350ps-wide pulses, and includes a gold code generator to modulate the pulses for CDMA. A 10MHz crystal oscillator is used as the clock source, and a single 9V battery is used to supply power to the entire transmitter.

The pulse generator generates pulses at each rising edge of the 10MHz clock. It consists of a NAND gate with an inverter to produce a delayed clock edge. The delay of the inverter determines the pulse width. The BPSK modulator generates a positive or negative pulse depending on the gold code bit sequence. Only one input path of the BPSK modulator is activated for each pulse, using the upper and lower paths for a positive and negative pulse, respectively. To decrease the output loading of the BPSK modulator and produce high pulse amplitudes, the output of the deactivated path is set to be floating while the activated path generates a pulse.

Gold codes are a set of binary sequences whose cross-correlation among the set is bounded into three values. Gold codes are commonly used when implementing CDMA as they allow the receiver to easily identify the corresponding transmitter which sent the signal of interest [10]. In this work, 4 different 31-bit gold codes are preset in the custom IC and can be selected by configuring external pins on the chip. Once enabled, the transmitter continuously repeats the selected code.

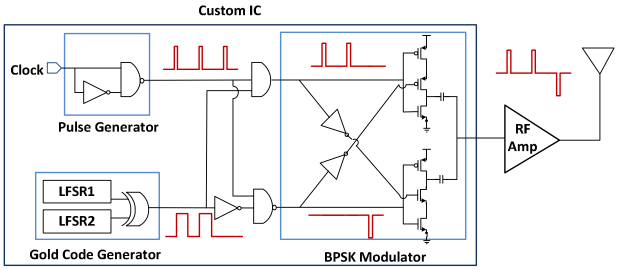


Figure 3. Transmitter architecture.

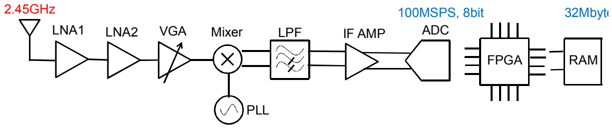


Figure 4. Receiver architecture.

The peak output amplitude of the custom IC is 300mV, which is not sufficient to excite the channel with high SNR in a WBAN; therefore, an additional PA is used to increase the peak output amplitude to 2V. Because the signals are impulses with high peak-to-average ratio, a PA with high P1dB is necessary for matched positive and negative pulses.

B. *Receiver*

Figure 4 shows the block diagram of the receiver. It consists of two LNAs (sky65047 from Skyworks), an I/Q down-conversion mixer with baseband amplifiers (AD8347 from Analog Device), a local oscillator (Si4136 from Silicon Labs), two ADCs (AD9288 from Analog Device), and an FPGA (Xilinx Spartan-3E). These components were chosen given considerations on the overall noise figure, conversion gain, frequency selectivity of the channel, and power consumption. An I/Q mixer is used to down-convert the received signal to baseband (direct-conversion receiver). A passive 5th order elliptic lowpass filter with a 50MHz cut-off frequency is added between the mixer and the baseband amplifier to avoid aliasing and reduce high frequency noise. Finally, two 8-bit, 100 MS/s ADCs digitize the I and Q signals.

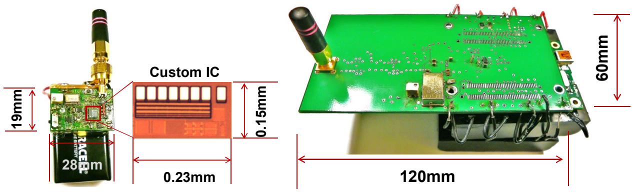
An FPGA performs all of the baseband processing on the received signals. A correlation-based receiver is implemented to correlate the incoming signal with all possible shifts of the 31-bit gold code, synchronizing the receiver to the transmitted sequence. After synchronization, 248 pulses are averaged (31 codes repeated 8 times) in order to reduce noise on the signal. The resulting signal is an average impulse response of the channel, and corresponds to one channel “snapshot.” This result is sampled at a programmable rate and saved in a 32Mbyte SDRAM, which can later be read by a PC over USB.

III. EXPERIMENT RESULT

The pictures of the transmitter and receiver, along with the die photo of the custom IC, are shown in Figure 5.

A. *Transmitter*

Figure 6 shows the transmitter output measured with a Tektronix TDS600C digital oscilloscope. Single positive and negative pulses with 2V amplitudes and 350ps widths are shown in Figure 6 (a). The positive and negative pulses are



(a) Transmitter (b) Receiver

Figure 5. Picture of transmitter and receiver.

symmetric, which is essential for BPSK modulation. Figure 6 (b) shows BPSK pulses modulated by a repeated 31 bit gold code, with a pulse repetition frequency of 10MHz. Figure 6 (c) shows the frequency spectrum of the transmitter output measured with an Agilent N9020A spectrum analyzer. The 3dB cut-off frequency is 2.0GHz; however, sufficient power for channel characterization is produced in the 2.45GHz ISM band. FCC compliance was not considered, as this is test equipment. The supply current of the custom IC, 10MHz oscillator, and RF amplifier is 27µA, 3mA, and 85mA, respectively. The supply current of the entire transmitter is 90mA, which can be powered continuously from a single 9V battery for 5 hours.

B. *Receiver*

To avoid performing operations on complex numbers on the FPGA, the receiver processes the I and Q signals separately, and saves the averaged channel responses on I and Q separately in the SDRAM. Once the values are read out, they are combined in Matlab. Figure 7 shows the recorded I and Q channel responses over a 1ms duration with a sampling rate of 40kS/s while the transmitter and receiver are 20cm apart in a lab environment. Each pulse is the result of 248 averaged pulses modulated by the gold code, and consists of 10 sample points. The amplitude of the I and Q data rotates due to the frequency difference of the transmitter and receiver clocks. When plotting the magnitude of (data I + j · data Q), only channel fluctuations are visible. The power consumption of the receiver is 1.8W, which can continuously operate off eight AA batteries for 30 hours.

IV. CHANNEL ESTIMATION

To demonstrate the capabilities of the hardware, a WBAN channel estimation experiment was performed in the EECS building at the University of Michigan. An experimenter held the receiver and transmitter in each hand, and walked into, rode, and walked out of an elevator. While this scenario seems routine, it produces highly dynamic channels and would be extremely difficult to measure with conventional equipment.

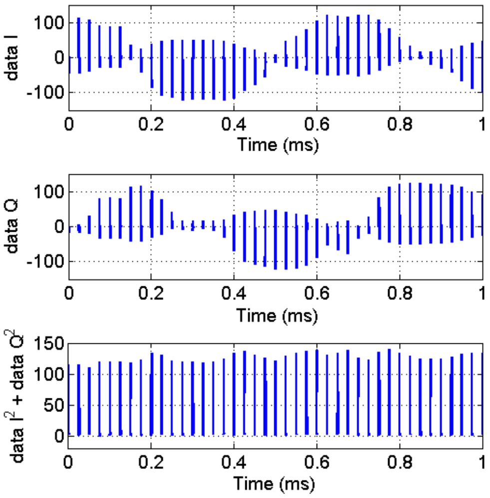
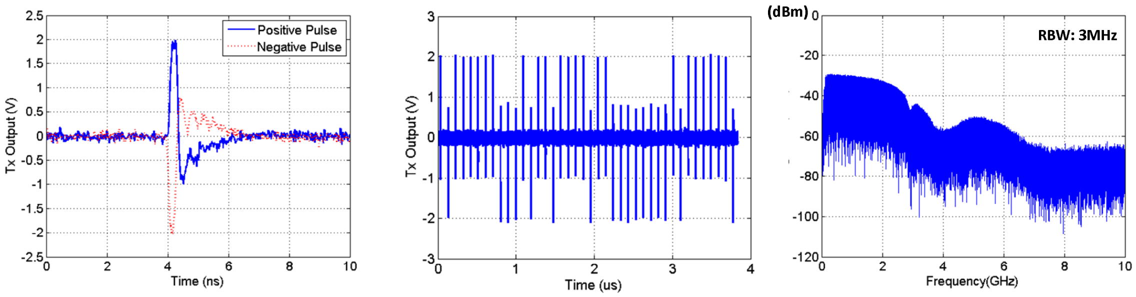


Figure 7. Receiver output.

Figure 8 is the measured frequency domain data which is taken from the averaged pulse responses. The hardware characteristics are de-embedded using the -65dBm baseline response measured outside the EECS building. The frequency axis is relative to the LO frequency; therefore, 2.45GHz ± 30MHz data is shown. The FFT axis represents the magnitude of the FFT in dB of the measured impulse response; a higher number represents a stronger received signal at that frequency. The channel was sampled at a rate of 10kS/s over a total time of 35 seconds. In this experiment, we can observe that the average channel loss varies by more than 30dB. Figure 9 shows four 1-second intervals taken from Figure 8 for (a) standing in the hallway, (b) walking in the hallway, (c) walking in the elevator, and (d) standing in the elevator. Two major observations can be found in this data. First, the channel is stable, but shows multipath fading, when the experimenter is standing, and fluctuates when the experimenter is walking. The period of this amplitude change is approximately 0.5s, which matches the period of the experimenter's hand movement while walking. Second, the characteristics of the channel depend on the location of the experimenter; the channel inside the elevator (more multipath) is different from the channel in the hallway (less multipath).



(a) Transmitter Pulse Output (b) Transmitter BPSK Output (c) Transmitter Spectrum

Figure 6. Transmitter output.

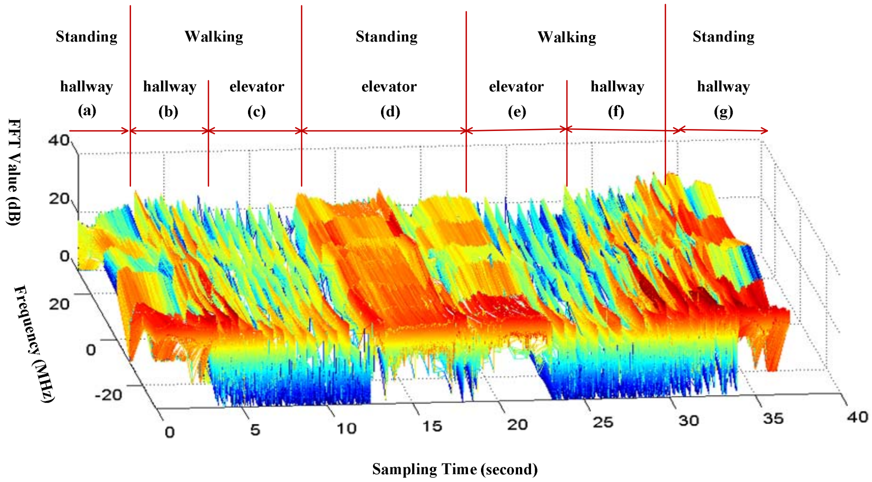
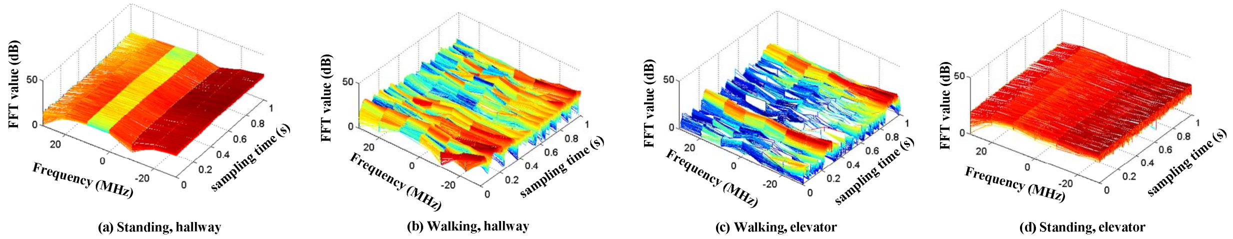


Figure 8. Frequency domain data of experiment scenario.



(a) Standing, hallway

(b) Walking, hallway

(c) Walking, elevator

(d) Standing, elevator

Figure 9. Frequency domain data for each scenario.

V. CONCLUSION

This paper presented a portable WBAN channel estimator, with specifications summarized in Table 1. The transmitter sends BPSK modulated pulses and the receiver records the averaged channel response. Experimental results of the channel response in an elevator scenario highlight the capabilities of this hardware. While the channel in this scenario appears to be highly dynamic, it also shows the periodicity and stable statistics of the channel. Ultimately, WBAN systems should exploit these properties to build better channel predictions and lower power radios.

ACKNOWLEDGEMENTS

This material is based upon work supported by the National Science Foundation under Grant No. 1035303.

Table 1. Specification of channel estimator

Transmitter		Receiver	
3dB Bandwidth	2GHz	Frequency	2.4GHz±40MHz
Pulse Amplitude	2V	Gain	18 ~ 88dB
Pulse width	350ps	Storage	1.6M channels
Pulse Repetition Frequency	10MHz	Max Channel Sampling Rate	40kS/s
Modulation	31bit BPSK	Resolution	8 bits
Size	19×28 mm^2	Size	120×60 mm^2
Power	0.81W	Power	1.8W
Life Time	5 hours	Life Time	30 hours

REFERENCES

[1] R. Schmidt, *et al.*, "Body Area Network BAN – a Key Infrastructure Element for Patient-Centered Medical Applications," *Biomedizinische Technik/Biomedical Engineering*, vol. 47, pp. 365-368, Jan. 2002

[2] H. Li, K.-I Takizawa, B. Zheri, and R. Kohno, "Body Area Network and Its Standardization at IEEE 802.15.MBAN," *Mobile and Wireless Communications Summit, 2007. 16th IST* , vol., no., pp.1-5, July 2007

[3] J. Zhang, D. Smith, L. Hanlen, D. Miniutti, D. Rodda, and B. Gilbert, "Stability of Narrowband Dynamic Body Area Channel," *Antennas and Wireless Propagation Letters, IEEE* , vol.8, no., pp.53-56, 2009

[4] A. Taparugssanagorn, A. Rabbachin, M. Hamalainen, J. Saloranta, and J. Iinatti, "A Review of Channel Modelling for Wireless Body Area Network in Wireless Medical Communications, " in *Proc. 11th Inter. Symp. Wireless Personal Multimedia Commun. (WPMC)*, 2008, pp. 1-5

[5] Q, Wang, T. Tayamachi, I. Kimura, and J. Wang, "An On-Body Channel Model for UWB Body Area Communications for Various Postures," *Antennas and Propagation, IEEE Transactions on* , vol.57, no.4, pp.991-998, April 2009

[6] A. Fort, C. Desset, P. Wambacq, and L. Biesen, "Indoor body-area channel model for narrowband communications, " *IET Microw., Antennas Propag*., vol. 1, no. 6, pp. 1197-1203, Dec. 2007.

[7] D. Miniutti, *et al.*, "Dynamic narrowband channel measurements around 2.4GHz for body area networks, " IEEE802.15.6 Technical Contribution, document ID: 15-05-0354-01-0006

[8] L. Hanlen, *et al.*, "Open-source testbed for Body Area Networks: 200 sample/sec, 12 hrs continuous measurement," *Personal, Indoor and Mobile Radio Communications Workshops (PIMRC Workshops), 2010 IEEE 21st International Symposium on* , pp.66-71, 26-30 Sept. 2010

[9] H. Liu, *et al*., "Automatic and Robust Breadrumb System Deployment for Indoor Firefighter Applications," in *Proc. 8th Inter. Conference on Mobile systmes, applications, and services (MobiSys'10)*, 2010

[10] J.K. Holmes, "Spread Spectrum Systems for GNSS and Wireless Communications, " Artech House, ISBN 978-1-59693-093-4, 2007