Experimental Analysis of IEEE 802.15.4 for On/Off Body Communications

Navid Amini[1], Wenyao Xu[1], Zhinan Li[2], Ming-Chun Huang[1], Majid Sarrafzadeh[1]
1. Wireless Health Institute, UCLA, Los Angeles, CA, USA
2. Electrical Engineering Department, Peking University, Beijing, China

***Abstract*—We target body-wearable sensor networks, in which sensor nodes are strategically placed on the human body and the wireless communications are conducted on/off the surface of the body. The results, obtained by performing multiple experiments in outdoor environments, are presented. A single on body transmitter communicates with a single receiver node, which is located on the body or off the body at various distances. Sensor nodes utilized in our experiments are equipped with XBee and XBee Pro wireless modules for on body and off body communications, respectively. The focus of our work is to observe how the Received Signal Strength (RSS) and the Packet Reception Rate (PRR) vary as we change the communication distance and transmission power level. Our experimental results can be used to perform transmission power control with high precision in order not to exceed a certain packet error rate.**

Keywords-body-wearable sensor networks; transmission power control; Zigbee; received signal strenth

I. INTRODUCTION

The incorporation of body-wearable sensor networks in sports medicine applications as well as athletic performance monitoring is emerging and opens a wide range of possibilities; athletes in different sports can greatly benefit from long/mid/short-range wireless feedback systems to improve the quality of their training. By 2014, 420 million wearable wireless devices are expected to be in use, of which 90% will be intended for sports and fitness applications [4]. Likewise, such systems can provide preventive, diagnostic, therapeutic and rehabilitative benefits through applying medical and scientific knowledge to prevent, recognize, manage, and rehabilitate injuries related to sports, exercise, or recreational activities.

The human body includes liquid, bone and flesh, which, in a selective manner, absorb, reflect or scatter wireless signals. Hence, the nodes used in body-wearable sensor networks need to cope with lossy radio transmissions around the human body. Recent findings indicate that in the range 2-6 GHz, no energy can pass through the body. Rather, radio waves transmitted from an antenna diffract around the body and can reflect from arms and shoulders [3]. Generally, attenuation rate and multipath effects increase at higher frequencies, therefore, a 2.4 GHz signal weakens faster than a sub-GHz signal, e.g., 433, 868, and 915 MHz carrier frequencies.

The nodes in a body-wearable sensor network generally use IEEE 802.15.4 radios which offer low-power consumption and are relatively immune to interference. Human body causes large signal attenuation which has a remarkable effect on wireless link reliability. RSSI is a useful link metric that represents the signal power averaged over 8 symbol periods of each incoming packet.

With most tiny IEEE 802.15.4 platforms having a nominal and practical maximum ranges of respectively 100 meters and 50 meters in line of sight scenarios, one of the shortcomings of current wireless sensors is the communication range; many applications require long-range body-wearable devices, where the transmitter and the receiver nodes are separated by large distances, giving the advantage of being able to monitor a large sports field, as well as enabling the users to move around freely while using ambulatory health monitoring systems. The problem of wireless range limitation has been poorly addressed by the research community, where most solutions propose multi-hop communications by adopting different routing strategies. However, for health monitoring applications due to a variety of reasons from reliability and transmission delay to privacy issues, such solutions are not practical. In this work, we conducted measurements from the XBee and XBee Pro wireless modules so as to find spatial impacts on the correlation between transmission power and Receive Signal Strength Indicator (RSSI).

The main contribution of our paper is twofold; first, we study the feasibility of XBee Pro wireless modules with chip antenna for mid/long range off body communications intended e.g., for athletic performance monitoring in an open sports field. Second, we study the issues confronting 2.4 GHz wireless communications around the human's body, i.e., on body communications. Our experimental results enable transmitters to control the communication power according to the anticipated channel quality.

It is envisioned that most of the sensor nodes should be able to adjust their output transmission power on-the-fly in practical applications to increase the battery lifetime, as well as to alleviate problems related to interference to/from other wireless devices. Our study facilitates the ability of dynamic power adjustment, in that we measure the impact of the human body on the wireless propagation channel and, accordingly, one can adjust the transmission power level to reduce the energy consumption of each individual wearable sensor node.

The rest of the paper is organized as follows; in Section II, we present the related work pertaining to off body mid/long range wireless communications as well as on body communications. Section III briefly explains the wireless platform used in our experiments and investigated parameters. The explanation of experiments and the analysis of results are presented in Section IV. Finally, section V presents our conclusions and future directions.

II. RELATED WORK

A. *Mid/long range off body communications*

Athlete monitoring systems must balance between size, weight and communication range. While commercially available devices such as the SPI Pro from GPSports [5] and VX Log from Visuallex Sport International [6] provide sufficient radio range to directly reach a data acquisition unit, they have sizes in the order of a large cell phone, making them impractical for monitoring athletes in sports fields. In a contrary manner, emerging body-area devices such as the Toumaz Sensium digital plasters have the form factor of a band-aid, thus well-suited for such applications. However the small form factor necessitates tiny batteries, which correspondingly reduces the communication range and makes data acquisition challenging [4].

Investigators in [4] have conducted experiments to profile the propagation of wireless signals around the body in an open soccer field. To this end, they equip each soccer player in the squad with a MicaZ mote mounted on the player's right arm. The investigators derive a rough map of the received signal strength indicator (RSSI) at various distances and directions from the body-mounted MicaZ, which transmits data every second at the highest available power level of 1 mW. To achieve connectivity, a multi-hop routing protocol was designed and utilized, which makes a balance between the competing objectives of energy consumption and delay.

B. *On body communications*

Investigators in [7] performed empirical measurements of the packet reception rate for MicaZ motes. They observed that RSSI is quite stable over a short period of time, thus being a suitable predictor of short-term link quality, and RSSI values above the sensitivity threshold correspond to a high PRR. They also found that the Link Quality Indicator (LQI) varies over a wider range over time for a given link, but the mean LQI computed over many packets shows a better correlation with PRR. They also observed that while short-term link asymmetries are common, long-term asymmetries are rare. A number of studies have discussed interference caused by the human body and dynamic environments on radio communications. Researchers in [8] substantiated the effect of subjects crossing a link between a transmitter and a receiver operating at 2.4 GHz. They use a customized RF transmitter that generates signals with transmit power of 20 dBm. The shadowing effect caused by a human body crossing the line of sight (LOS) links between a transmitter and receiver for transmissions have been discussed in [9]. The degradation of the radio signal when passing through the human body is researched in [10]. The indoors and outdoors evaluation of IEEE 802.15.4 radio for static sensing platforms through a characterization of the RSSI for different transmitter-receiver distances has been discussed in [7]. In [11] the authors stress the importance of antenna orientation in changing the RSSI values and in the incidence of the asymmetric links.

Jea and Srivastava [12] present results on connectivity in a body-wearable sensor network using the Mica2Dot motes. Their results suggested fair connectivity among all nodes on a body beyond a certain transmit power. They used PRR as a metric for wireless communication quality. The factors that they explored in the experiments were the relationships between transmission power values by placing nodes on different parts of the body. They considered two scenarios of standing and walking with different setups for the antennas.

The authors in [13] examined the performance of IEEE 802.15.4 through and around the human body using network layer metrics such as PRR and latency. They observed that the human body is similar to aluminum, in that it acts like a fine RF shield, such that no packet can get through without creating a multipath. They suggest that a star topology operating at low power levels might suffice in an indoor environment, whereas in an outdoor environment, nodes would have to operate at higher power levels. They also identify design goals and evaluate them against the star and multi-hop network topologies.

Ren et al. [14] performed experiments to observe how the quality of sensors is affected by surrounding factors. Varying the postures of the body, they performed experiments varying the power level in different environments. They attached a single sensor on the left arm and varied the distance from the receiver and found the correlations between PRR, distance and transmission power.

Shah et al. [15] conducted experiments on multiple subjects to measure the effect of human body on the performance of Bluetooth and IEEE 802.15.4 radios. They consider different locations on the body such as the ankle, ear, knee, and chest, while the on-body data acquisition unit is always attached to the waist. They allowed mobility of the subjects, while measuring the effect of IEEE 802.15.4 and Bluetooth. [16] evaluates the characteristics of the links in and on-body IEEE 802.15.4 network and the factors that influence link performance. The investigators used Intel Mote 2 nodes and placed them on three locations: the chest, the right side of the waist and the right ankle, while setting the transmission power to 0 dBm. They observed that the wireless links among nodes in an on-body IEEE 802.15.4 network are not as promising as expected. While 802.15.4 radios typically have a range of at least 10 meters in most indoor environments, when placed on a body, the range was observed to be less than a meter.

III. EXPERIMENTAL PLATFORM

We have used Digi's XBee and XBee Pro RF Modules [1] to conduct our experiments. The XBee and XBee modules (shown in Fig. 1) have been engineered to meet IEEE 802.15.4 standards and support the unique needs of low data rate, simple connectivity, and low-power sensor networks. They operate at the ISM 2.4 GHz frequency band, with a maximum nominal data rate of 250 kbps. Furthermore, both XBee and XBee Pro modules provide an RSSI measurement tagged to a specific packet. As for the transmission power, these modules can be configured to operate using five different transmission power levels ranging from 0 to 4. For XBee modules, the levels 0 to 4, respectively correspond to power outputs of -10 dBm, -6 dBm, -4 dBm, -2 dBm and, 0 dBm. For XBee Pro modules, the levels 0 to 4, correspond to power outputs of 10 dBm, 12 dBm, 14 dBm, 16 dBm and, 18 dBm, respectively. Although a chip antenna demonstrates limited reliability and lower transmission range than a whip antenna, on account of its small form factor, we decided to use the modules equipped with chip antennas in both the transmitting and the receiving nodes. As a matter of fact, using a chip antenna has helped us to improve the repeatability and reproducibility of our experiments as well. With respect to radiation patterns, both antennas, albeit not perfectly, exhibit omnidirectional radiation patterns. XBee modules provide up to 30 m ranges for indoor and urban environments and up to 100 m for LOS outdoor conditions (with dipole antennas), both for a 0 dBm output power, whereas XBee PRO modules provide, for a 20 dBm output transmit power, up to 100 m ranges for indoor and urban environments and up to 1200 m for LOS outdoor conditions (with dipole antennas). Furthermore, both modules provide 16 channels, numbered 11 through 26. The channels are 5 MHz apart in the 2.4 GHz band (i.e., 2405 MHz - 2480 MHz), overlapping with both 802.11b (WLAN) and 802.15.1 (Bluetooth).

Table I lists basic characteristics of XBee and XBee Pro modules.

Figure 1. Dimensions of XBee Pro and XBee wireless modules.

TABLE I. COMPARISON OF XBEE AND XBEE PRO MODULES

Module/Characteristic	**XBee**	**XBee Pro**
Indoor range (m)	30	100
Outdoor line of sight (m)	100	1200
Transmit Power	1 mW (0 dBm)	100 mW (20dBm)
Receiver sensitivity	-92 dBm	-100 dBm
Tx Current Max	45 mA (Vcc = 3.3 V)	270 mA (Vcc = 3.3)
Rx Current	50 mA (Vcc = 3.3 V)	55 mA (Vcc = 3.3 V)
Sleep current	10 uA	10 uA
Communication channels	A total of 16	A total of 16
Modulation	OQPSK	OQPSK

Packet Reception Rate (PRR) is one of the parameters used to determine the link quality. PRR is the ratio of the number of successful packets to the total number of packets transmitted over a certain course of time. Higher PRRs are indicative of a better link quality. In some situations, the probability that a packet will be dropped is independent of the success rate of the packets that are sent before and after the packet. However, there are situations where the errors are more likely to occur in bursts. These groups of errors usually prove to be more detrimental in networks as opposed to cases where the errors are independent and uniformly distributed. Receive Signal Strength Indicator (RSSI) measures the strength of an incoming signal by averaging over 8 symbol periods of each incoming packet. The ability of the receiver to pick the weakest of signals is referred to as receiver sensitivity. The higher the receiver sensitivity, the better is the link quality. RSSI value is an integer range roughly from -100 dBm to 0 dBm for IEEE 802.15.4 radios. By means of sequence numbers it is possible to trace lost packets in a sequence of packets, which allows for verification if there are bursts or striking patterns of packet losses.

IV. EXPERIMENTS AND RESULTS

A. *Open field off body communications*

At an early exploratory stage, we conducted our open field experiments on a well-groomed grass field (UCLA's Intramural Field) with both receiver and sender nodes located at the height of 1.5 m above ground. Communication distances in our experiment ranged from 0 m to 250 m with steps of 25 m, i.e., a total of eleven distances. Measurements were performed on one male subject on a partially cloudy day in March 2011. The transmitter was attached to the chest of a male subject, while the receiver was mounted on an adjustable stand. The XBee Pro module in the transmitting node is connected to an Arduino Pro Mini 8 MHz microcontroller [17]. The XBee Pro chip on the receving node is connected to a laptop via a USB port and another Arduino Pro Mini. The lack of human activity ensured a human interference-free environment. However, due to the presence of IEEE 802.11 signals, all communication channels were suffering from the 802.11's interference, deteriorating the PRR. It should be noted that, even for athletic performance monitoring applications, it is not realistic to assume the existence of IEEE 802.11-free environments. The sender and the receiver are always kept in line of sight in the experiments. The data baud rate is set to 115200 bps, which is applicable for most of the scenarios. In each experiment, the transmitting node sends 1000 packets at five different power levels and the receiver records the packet's sequence number and the RSSI reading. More details regarding the experiment setup are summarized in Table II.

In transmission of radio signals between two nodes, height above the ground becomes a very influential factor, in the sense that solely guaranteeing line of sight communications does not suffice. The strongest signals are on the direct line between transmitter and receiver and always lie in the Fresnel zone. Fresnel zone defines volumes in the radiation patterns surrounding the direct signal path, which represent a reflection-free zone. It is generally accepted that antenna heights less than

60% of the Fresnel zone radius ($FZR = 17.32\sqrt{d(km)/4f(GHz)}$) will lead to significant signal attenuation and fading [18]. In our experiments for communication distance of 200 m, FZR is equal to 2.48 m. For this FZR value, the height of 1.5 m is marginal and hence, we anticipate significant signal attenuations for communication distances beyond 200 m.

Fig. 2 shows the average RSSI measurement results for different separation distances at different transmission power levels. Due to the fact that the XBee Pro's receiver sensitivity is -100 dBm and the maximum receiver signal strength is -40 dBm, the measured RSSI range is in the interval [-100 dBm, -40 dBm]. For distances above 200 m only the maximum transmission power, i.e., PL-5, is able to convey data packets to the receiver with about 50% of the packets being lost. As shown in Fig. 2, as a result of antenna height becoming smaller than FZR, significant deterioration of RSSI is observed as we increase the separation distance from 225 m to 250 m. The minimum and maximum transmission powers are 10 dBm (~10 mW) and 18 dBm (~63 mW), respectively, which is indicative of a large optimization room for power control, capable of energy savings of six-fold in energy consumption. Per our experimental results, RSSI values more than -90 dBm signify high quality links with more than 90% of the packets being delivered to the receiver.

TABLE II. BASIC CONFIGURATION/SETUP FOR OFF BODY EXPERIMENTS

Experiment Configuration	Transmitter	Receiver
Address	1	2
Height (from ground)	1.5 m (chest)	1.5 m (on stand)
PAN ID	70	70
Channel	11	11
Destination Address	2	1
Paylod	30 bytes	n.a.
ACKs	No	No
Receiver's sensitivity	n.a.	-100 dBm
Transmit/Receive current	270 mA at 18 dBm	55 mA

B. *On body communications*

In another set of experiments, we have evaluated the effect of human body on 802.15.4 communications by attaching transmitting sensor nodes to six different body positions namely, the head, upper arm (left and right), the forearm (left and right), the waist, the thigh (left and right), and the shin (left and right). The receiver node was taped to the subject's waist. The experiments were repeated with three different pairs of nodes in the same environmental conditions to achieve statistical confidence. Measurements were performed on two male subjects on an open grass field to prevent radio wave reflections from the environment.

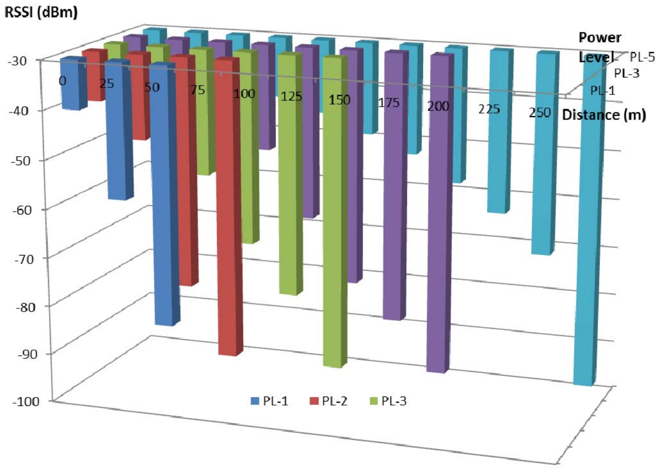


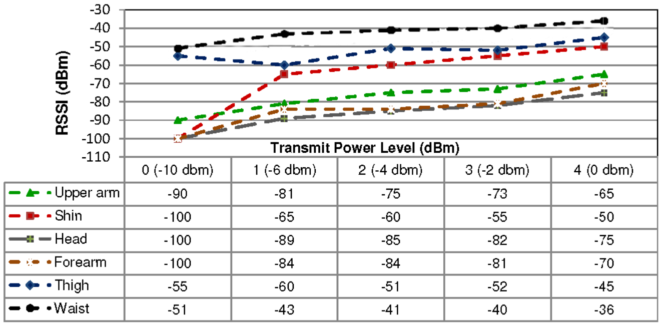
Figure 2. Average RSSI measurements for different distances at different transmit power levels.

The subjects were asked to fully extend their arms horizontally while performing the experiments pertaining to upper arms and forearms. In each experiment, the transmitting node sends 1000 packets at five different power levels and the recipient logs the packet's sequence number and the RSSI reading. More details regarding the experiment setup are listed in Table III. As shown in Figure 3, the average RSSI values gradually increase with the transmission power level.

TABLE III. BASIC CONFIGURATION/SETUP FOR ON BODY EXPERIMENTS

Experiment Configuration	Transmitter	Receiver
Address	1	2
Position	Six on body location: head, upper arm, forearm, waist, thigh, shin	Waist
PAN ID	70	70
Channel	11	11
Destination Address	2	1
Paylod	30 bytes	n.a.
ACKs	No	No
Receiver's sensitivity	n.a.	-92 dBm
Modulation	OQPSK	OQPSK
Transmit/Receive current	45 mA at 0 dBm	50 mA

At the transmission power level of -10 dBm, in experiments where we attached the transmitter nodes to the shin, head, and forearm, the resulting packet drop rate was dramatically high (more than 50%). As a result of such a high packet drop rate, we inevitably report the RSSI value as -100 dBm, which is lower than the receiver's sensitivity level. Expectedly, the experiment concerning the waist yields the best RSSI values, since the receiver is in the transmitter's line of sight. Indeed, the physical distance between the transmitter and the receiver in this case is only 10 cm. This is why the data success ratio was always 100% even when the XBee modules operate at the lowest transmission power level.



	0 (-10 dbm)	1 (-6 dbm)	2 (-4 dbm)	3 (-2 dbm)	4 (0 dbm)
▲ Upper arm	-90	-81	-75	-73	-65
■ Shin	-100	-65	-60	-55	-50
■ Head	-100	-89	-85	-82	-75
● Forearm	-100	-84	-84	-81	-70
◆ Thigh	-55	-60	-51	-52	-45
● Waist	-51	-43	-41	-40	-36

Figure 3. Average RSSI measurements for different body parts at different transmit power levels.

On the basis of our experimental results as well as similar studies such as [3] and [2], RSSI values higher than -80 dBm are indicative of reliable communications. In fact, choosing such a conservative threshold of -80 dBm always allowed for communications with packet drop rates less than 5%. Thereby, when we attach the nodes to the thigh, shin, and waist, as Fig. 7 suggests, there is enough room to reduce the transmit power level without compromising the reliability of communications. For instance, transmission power reduction for data communications between the thigh and the waist will bring about up to 50% energy savings.

The shins and generally the lower part of legs turned out to be very favorable locations for on-body wireless communications. This is because, the legs are relatively close to the ground, where reflections increase the total received power with major contributions from the multipath components rather than the direct received signal, which in turn leads to less steep changes in the RSSI values.

V. DISCUSSIONS AND CONCLUDING REMARKS

The human body adversely affects the radio propagation and communication such that nodes on some parts of the body have limited connectivity to nodes on other parts in certain scenarios. Our experiments verify that the human body by itself, not only affects the radio propagation, but also causes attenuations in signal levels received by on-body sensors, as a result of which the nodes experience varied connectivity.

Two most common applications for body-wearable sensor networks placed on the human body are ambulatory health monitoring and athlete's performance monitoring. In these applications, body-wearable sensor networks are expected to perform long-term monitoring, thus it is sensible for such systems to communicate their data at a lower transmission power. Performing transmission power control has several other advantages such as: reducing inter-network interference and thus improving the spatial reuse of wireless resources, increasing security as a packet with lower transmission power is not easy to intercept, and reducing the average contention at the MAC layer. Based on our experiments, the body location to which the node is attached significantly affects the radio propagation channel. Examples of the systems benefiting from our on/off body experimental results are the personalized ultraviolet monitoring [19] and the smart shoe systems [20].

RSSI measurements are simple and inexpensive, but they suffer from inaccurate measurements or delays due to the random nature of fading channels. Throughout our experiments regarding both on body and off body scenarios, we learned that weak signals in the presence of noise will yield low RSSI values; weak signals in the absence of noise will lead to low RSSIs; a strong signal without noise being present achieves high RSSI values; and finally strong signal in a noisy environment will achieve high RSSIs.

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