Radio Characterization of 802.15.4 and Its Impact on the Design of Mobile Sensor Networks

Emiliano Miluzzo, Xiao Zheng, Kristóf Fodor, and Andrew T. Campbell

Computer Science Department
Dartmouth College
Hanover, NH 03755, USA
{miluzzo,zhengx,fodor,campbell}@cs.dartmouth.edu

Abstract. Future mobile sensing systems are being designed using 802.15.4 low-power short-range radios for a diverse set of devices from embedded mobile motes to sensor-enabled cellphones in support, for example, of people-centric sensing applications. However, there is little known about the use of 802.15.4 in mobile sensor settings nor its impact on the performance of future communication architectures. We present a set of initial results from a simple yet systematic set of benchmark experiments that offer a number of important insights into the radio characteristics of mobile 802.15.4 person-to-person communication. Our results show that the *body factor* - that is to say, the human body and where sensors are located on the body (e.g., on the chest, foot, in the pocket) - has a significant effect on the performance of the communications system. While this phenomenon has been discussed in the context of other radios (e.g., cellular, WiFi, UWB) its impact on 802.15.4 based mobile sensor networks is not understood. Other findings that also serve to limit the communication performance include the effective contact times between mobile nodes, and, what we term the *zero bandwidth crossing*, which is a product of mobility and the body factor. This paper presents a set of initial findings and insights on this topic, and importantly, we consider the impact of these findings on the design of future communication architectures for mobile sensing.

1 Introduction

Wireless sensor networks have gained remarkable interest among researchers and application developers in the past ten years. Several studies have been conducted in order to best understand and characterize the radio environment of cheap low-power wireless sensor nodes and their impact on communication protocols such as the media access, routing, and transport. Early sensing platforms [1] presented a number of challenging radio issues. In [2] [3] the authors studied the performance of low-power radio transceivers found in sensor networks where nodes were static, closely situated, and presented obstacle-free communications in the same neighborhood. These studies demonstrated the existence of grey areas and strong asymmetric links among other findings which have had considerable impact on the design of robust MAC and routing protocols for static sensor networks. While these findings have had an important impact for the design of static sensor networks there has been no equivalent study in the case

R. Verdone (Ed.): EWSN 2008, LNCS 4913, pp. 171–188, 2008.

of mobile sensor networks, particularly, for a class of emerging people-centric, mobile sensor networks [4] [5] [6] [7] [8] that are built on low-power short-range radio such as 802.15.4 [9]. Many of these applications use mobile-to-mobile and mobile-to-static communications using a variety of devices including sensor-enabled cellphones and embedded sensors.

In this paper, we study the impact of 802.15.4 radio characteristics on the communication performance of mobile sensor networks. We aim to answer two questions in this study: what are the dominant factors that impact the overall communication performance of mobile-to-mobile, and mobile-to-static people-centric sensor networks? And, what is the impact on the design of future communication architectures based on these findings? We take a systematic approach and analyze inter-node communications when people are mobile (e.g., at walking speed of 1.5-2 meters/sec) in different radio environments such as indoors (i.e., walking along the hallway in an office building), in an unimpeded outdoor space (i.e., a soccer field), and walking in an outdoor urban environment (i.e., along a sidewalk). We consider a number of positions on the body that a sensor could be placed including around the neck and in the pocket. We characterize the performance of the radio link based on a number of known metrics including throughput between devices, received signal quality and signal strength for mobile-to-mobile and mobile-to-static communications under the different radio environments discussed above. For all experiments we use Tmote Invent nodes, based on the Telos platform [21], and their 802.15.4 radio as representative of a class of 802.15.4 devices that could be used in cellphones [11] and embedded sensor devices. Note, in our project we integrated the Tmote Mini [10] into the Nokia N800 and have recently acquired Intel/Motorola PSI [24] 802.15.4 linux phones. We plan to further extend our study to these devices as part of future work. To the best of our knowledge this is the first paper to present a set of detailed benchmark experiments to characterize 802.15.4 in a mobile people-centric setting and its impact on communications.

Our results show that the *body factor* - that is to say, the human body and where sensors are located on the body (e.g., on the chest, foot, in the pocket) - has a significant effect on performance of the communications system particularly in outdoor experiments where it effectively halves the transmission range of a device. While the body factor has been discussed in the context of other radios its impact on 802.15.4 based mobile sensor networks is not understood. Other findings that also serve to limit the communication performance include the effective contact time between mobile nodes, and, what we term the *zero bandwidth crossing*, which is a product of mobility and the body factor. In summary, the contribution of this paper is as follows:

– We present the first detailed set of empirical 802.15.4 benchmark experiments for mobile sensor networks where the nodes are carried by people;
– We present experimental results showing that the body factor, mobile-to-mobile contact times, and zero bandwidth crossing are dominant in mobile, people-centric sensor networks; and
– We discuss a set of architectural considerations to be taken into account when designing protocols, applications, and radio models for mobile sensor networks, when the nodes are carried by people.

The data traces collected during our study are publicly available at [36].

The paper is structured as follows. In Section 2 we present the related work followed by a detailed description of our experiments and results in Section 3. We present a short discussion on the impact of our findings on the design of future communication architecture for mobile sensor networks in Section 4 and finish with some concluding remarks and future work in Section 5.

2 Related Work

A number of studies have discussed interference caused by the human body and differing environments on radio communications. In [14] the authors model the influence of the human body for cellular radio as a function of the terminal-person distance. However, the model only holds for the cellular devices discussed and the cellular frequencies used. In other studies, models of human body shadowing for indoor radio environments that apply to humans crossing the line of sight (LoS) links between a transmitter and receiver for transmissions in the 10 GHz [15], 900 MHz, and 60 GHz [16] have been developed. The specifics of the devices, cellular radio, operating frequencies and models differ from what we study in this paper.

A number of papers discuss issues more closely related to our work. In [17] the authors show the effect of people crossing a link between a transmitter and a receiver operating at 2.4 GHz. However, they use a customized RF transmitter that generates signals with a power of 20 dB, which is very different from the low power devices (i.e., 2.4 GHz based Tmote Invents [21]) that we consider in this study. The authors found that a person's body causes signal attenuation at the receiver. The shadowing effect caused by a person's body has also been discussed in [18] for the 802.11 radio. Even in this case the experiments consist of having a person crossing the transmitter-receiver link. It is shown that the body creates severe attenuation and that the transmitter-receiver orientation matters. Our work differs from both [17] and [18] in that we present results for a different class of devices, low power, short-range radio 802.15.4 nodes, in a broader set of environments (outdoor open space, outdoor urban environment, indoor) adopting realistic mobility patterns to characterize the radio behaviour as a function of the transmitter-receiver distance, and considering different position of the nodes on the body. In [28] the degradation of the radio signal when passing through the human body is described.

A large body of work discusses the impact of the surroundings and interference on the same radio bands as 802.11, 802.15.4, and Bluetooth technologies proposing in some cases radio models for these environments. In these studies only the impact of obstacles such as buildings, trees, foliage, walls, etc., in outdoor and indoor environments is presented. The authors of [25] analyze an indoor home deployment of six 802.11a and 802.11b nodes. The study highlights the predominance of asymmetric links, the effect of obstacles being more severe than distance between nodes, the impact of the node orientation, and the interference caused by microwaves radio sources. The result of an investigation to characterize Bluetooth propagation in an indoor environment is presented in [27] showing the impact of the receiver's speed on the bit error rate.

The work in [19] [20] [21] [26] discuss the indoors and outdoors evaluation of 802.15.4 radio for static sensing platforms through a characterization of the Radio Signal

Strength Indicator (RSSI) and Link Quality Indicator (LQI) for different transmitter-receiver distances. RSSI and LQI are both parameters retrievable from the 802.15.4 hardware upon the reception of a radio packet [21] [20]. In [26] [25], the authors state that the antenna orientation greatly impacts the RSSI and the incidence of the asymmetric links. In [26] [30] the authors show that multipath fading is another important cause of indoor performance degradation. Impact of 802.11 on the Zigbee radio is analyzed in [29]. In [2] [3] the authors present a detailed study of communication limitations for static sensor networks including findings associated with grey areas and link asymmetry. In [23] the authors also discuss the radio irregularities in wireless sensor networks and show that the battery level of a node impacts the signal strength at the receiver.

Within the context of pocket-switched networks [12] [22] work has been done to analyze Bluetooth traces in order to understand people's mobility patterns, the distributions of the rendezvous times between mobile nodes, and the inter-contact time (i.e., the time interval between two consecutive rendezvous). Our work provides similar results associated with contact times but for 802.15.4, and includes a broader study of the mobile-to-mobile and mobile-to-static nodes rendezvous showing detailed RSSI, LQI, and throughput maps as a function of nodes distance for different experimental scenarios, as discussed in Section 3. We also record the contact time and effective contact time measurements during the mobile-to-mobile and mobile-to-static interactions, and consider the body factor and the position of sensors on the body.

3 Experiments: Methodology and Results

In this section, we discuss the methodology we follow for experimentation and the results derived from the measurements. For all experiments we use two Tmote Invents operating in the 2.4 GHz band, one acting as a transmitter and the other as a receiver. A different two are chosen for each experiment from a large pool of Invents to avoid biases specific to a particular Invent's hardware. The transmitter is programmed to send packets at the maximum transmission power (0 dBm) and transmission rate. We investigate the same metrics, (viz. RSSI, LQI, and throughput) as previous work targeting studies to characterize the radio environment in wireless sensor networks [2] [3] [19] [21] [26] [20]. We also measure the effective contact time, i.e., the time window during which nodes are in radio contact with each other and have enough available bandwidth between them to support data transfer (this is somewhat application specific and it will be defined in Section 3.2). Here we extend the results discussed in [12] [22] where contact time is simply defined as the time interval in which nodes are in radio contact, saying nothing about communication potential between nodes. The contact time is an important parameter to consider in mobile sensor networks because it is the time interval when nodes can exchange data. The contact time is obviously a function of the speed the nodes are moving at, i.e., it decreases as the speed increases and viceversa. Throughout our evaluation, however, we notice that when nodes move at walking speed (i.e., relatively low speeds of 1.5-2 meters/sec) the 802.15.4 radio and link performance in terms of signal quality and throughput is similar to static nodes communicating. This is because of the relatively low speed people move at. So, in our evaluation speed is not considered as a factor that impacts the RSSI, LQI, and throughput.

We carry out our experiments according to three benchmarks: *i)* outdoor experiments in a soccer field away from obstacles and radio interference in the 802.15.4 radio band, *ii)* outdoor experiments along a sidewalk which is an example of urban environment, and, *iii)* indoors experiments in a 55 meter hallway in an office building. In all the cases people were moving at walking speed. We repeat the experiments positioning the transmitter and receiver nodes at different places on the body, (i.e., on the chest front hanging on from a necklace, inside a pocket). This choice is motivated by the fact that we are also interested in quantifying the impact of the position on the body where the nodes are more likely to be carried. A third position, i.e., where the node is clipped onto a belt on the side of the body, is evaluated. Given the similarity of the results with the node carried in the pocket (due to the side position on the body in both cases), we omit results of the belt experiment due to space limitations. We run each experiment five times and calculate the 95% confidence interval (represented by the error bars in the plots presented in this paper). In what follows, we describe the experimental setup for each of the scenarios discussed above.

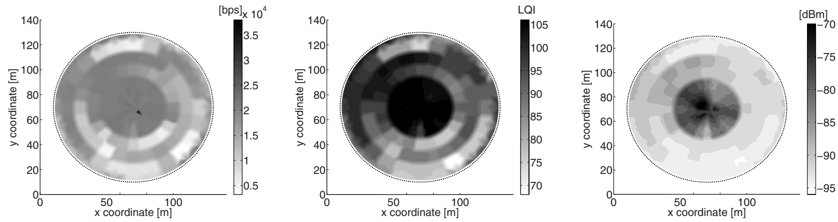
Outdoor open space benchmark. We perform this benchmark experiment in a soccer field out of town in a rural setting away from obstacles and radio activity to minimize any external source of interference and perturbation on the measurements. We implement a TinyOS [13] application to make the transmitter send 18 byte long packets (note, this size is selected for experimental reasons) as fast as possible and the receiver retrieve and store the RSSI and LQI from each packet received from the sender. We also record the throughput of the sender measured at the receiver. We draw concentric circles with different radii on the ground, the center being the position of the sender node during the measurements. The radii are: {5, 10, 20, 30, 40, 50, 60} meters. Along the circumference of each circle we place equally spaced markers that identify the distance walked along the circles. The experiment consists of a stationary person standing in the center of the circles wearing a necklace mote (transmitter) and facing a fixed direction while the other person walks along each circle wearing a necklace mote (receiver). Each time the person carrying the receiver passes a marker the user button on the receiver mote is clicked and a counter, which represents an abstraction of the distance walked along the circle, is incremented. Every RSSI and LQI sample is stamped with the latest marker value which means that the RSSI, LQI, and throughput values are stored in bin structures identified by the number of markers minus one. The RSSI, LQI, and throughput values for a position denoted by i in the circle are an average of the RSSI, LQI, and throughput values between position i and $i+1$ (assuming the receiver moves according to the i to $i+1$ direction). This way we are able to produce 360 degree RSSI, LQI, and throughput maps around the transmitter. To have a set of comparison points we also perform LoS measurements between the transmitter and the receiver where the transmitter is placed in the center of the circles in such a way so there are no obstacles in the proximity, and the transmitter and receiver are lifted 1.5 meters above the ground. The receiver is slowly moved along the concentric circles keeping the LoS condition with the transmitter. This way we obtain 360 degree LoS maps around the transmitter for throughput, LQI, and RSSI measured at the receiver.

Outdoor urban environment benchmark. The second benchmark experiment aims to show the radio behaviour during a mobile-to-mobile communication rendezvous in the common case of people carrying short-range radio nodes and passing each other in a typical urban environment: a sidewalk. In this case, we record RSSI, LQI, and throughput values measured at the receiver as a function of the transmitter and receiver distance. The experiments consists of having two people respectively carrying a transmitting and a receiving mote walking toward each other from a long distance and eventually passing each other. The sidewalk runs along a street which is about 15 meters away from buildings on both sides making this environment distinct from the open soccer field experiments. Since the measurements are reported as a function of the distance between the sender and the receiver we mark a 160 meter portion of the sidewalk. Each marker is 2 meters apart and every measurement starts with the two people located at a distance of 160 meters (in order to start the experiment by having them out of radio contact). Every time each person encounters a marker, the user button of the mote is clicked and a counter, which again represents an abstraction of the distance walked, is incremented. Every RSSI and LQI sample is stamped with the latest marker value which means that the RSSI and LQI values fall into bins identified by the number of markers minus one. The RSSI, LQI, and throughput values at the receiver at position i with the transmitter at position j are calculated as the average of the RSSI, LQI, and throughput values collected by the receiver between position i and $i+1$ (assuming the receiver moves according to the i to $i+1$ direction). By knowing the starting location of the nodes it is possible to determine the relative sender-receiver distance and an RSSI, LQI, and throughput map for each distance.

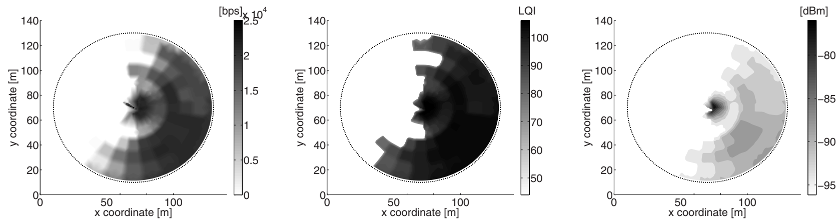
Indoor long hallway benchmark. We carry out this benchmark experiment in a building hallway of an office building. The hallway represents one of the common indoor scenarios where people approach each other from a long distance, get in radio contact and pass each other. Because we are interested in evaluating scenarios when nodes rendezvous, the hallway allows us to repeatably control and record this situation. Even in this case we take RSSI, LQI, and throughput measurements at the receiver as a function of the transmitter-receiver distance. To investigate the mobile-to-mobile interaction in this environment the experiment setup is the same manner as the sidewalk setup, with the 55 meter hallway marked by equally spaced markers and starting the experiments with the people at the far edges of the hallway. Furthermore, we perform some experiments having a static transmitter hanging from the ceiling while the receiver is mobile and carried by a person. The aim of these experiments is to analyze the mobile-to-static interaction in the case where a short-range mobile node performs rendezvous with a static gateway placed in an indoor environment for either data upload or tasking purposes [4] [8]. Before we start each experiment we measure the noise floor in the 2.4 GHz band. In order to do this we modify the TinyOS source code (CC2420ControlM.nc and CC2420RadioC.nc files).We observe the noise floor values oscillating between -98.79 dBm and -100.28 dBm.

3.1 Body Factor and Zero Bandwidth Crossing

In Figure 1, the results of the measurements for the soccer field LoS experiment and nodes carried by people experiment are shown. In both cases the transmitter is located at (x,y) = (70 meters, 70 meters). Given the limited size of the soccer field we do not



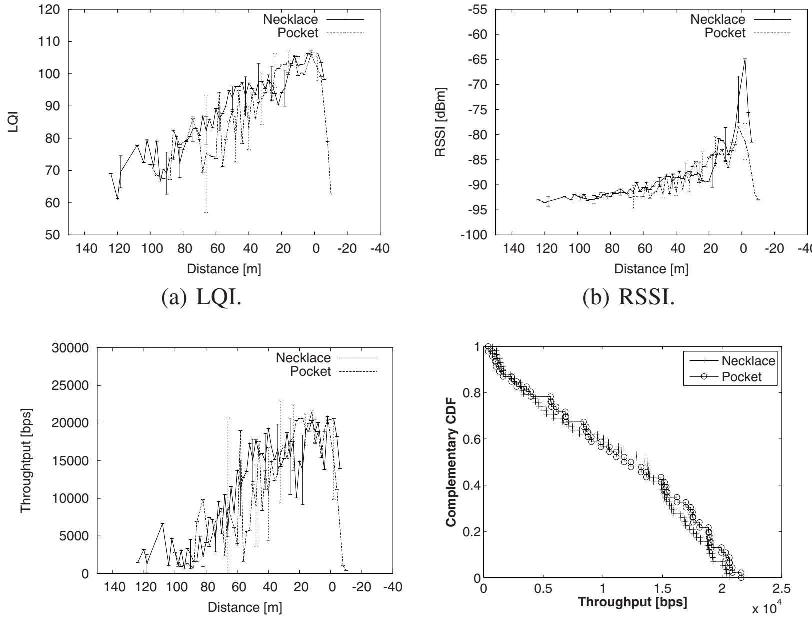
(a) LoS throughput. (b) LoS LQI. (c) LoS RSSI.



(d) People presence throughput. (e) People presence LQI. (f) People presence RSSI.

Fig. 1. 360 degree LQI, RSSI, and throughput maps for the soccer field benchmark in the LoS and people presence cases

show the maximum outdoor transmission coverage, which is almost 70 meters for a Telos platform with a transmission power of 0 dBm [21]. Instead, we are interested in the RSSI, LQI, and throughput map around the transmitter given the impact of the body factor. For this reason a maximum radius of 60 meters around the transmitter fulfills our needs. Thus, the plots in Figure 1 do not show the boundary of the radio cell of the transmitter, but just a portion of it, namely within a 60 meter radius. Figures 1(a), 1(b), and 1(c) confirm the non-uniform nature of radio signal LoS propagation and symmetric regions around the transmitter present very different radio patters, as also discussed in [3] [23]. It is of more interest when we compare these data to the case when the transmitter and the receiver are worn by people as a mote necklace. The person wearing the transmitter is standing at (x,y) = (70, 70) facing the right hand side of the circle (e.g., watching the point of coordinates (x,y) = (130,70)). The person wearing the receiver node moves along each circle in a counter-clock wise fashion. The dotted boundary circle delimits the area where the measurements are taken. The results are shown in Figures 1(d), 1(e), and 1(f). From the plots the impact of the body factor on the radio signal is evident. The white color in almost the entire left hand side of each map of Figures 1(d), 1(e), and 1(f) indicates no data reception in that area. This is due to the fact that the transmitting node's signal is blocked by the person wearing the node so that when the receiver is carried to the back of the transmitter (i.e., from the upper left side to the lower left side of the circle) no radio signal is actually received. This phenomenon occurs independent of the distance between the transmitter and the receiver. The interesting result is that the body factor, that is mainly caused by the fact that radio frequencies in the 2.4 GHz band are strongly attenuated by water which is the main constituent of the human body, significantly limits the radio performance when



(a) LQI. (b) RSSI.

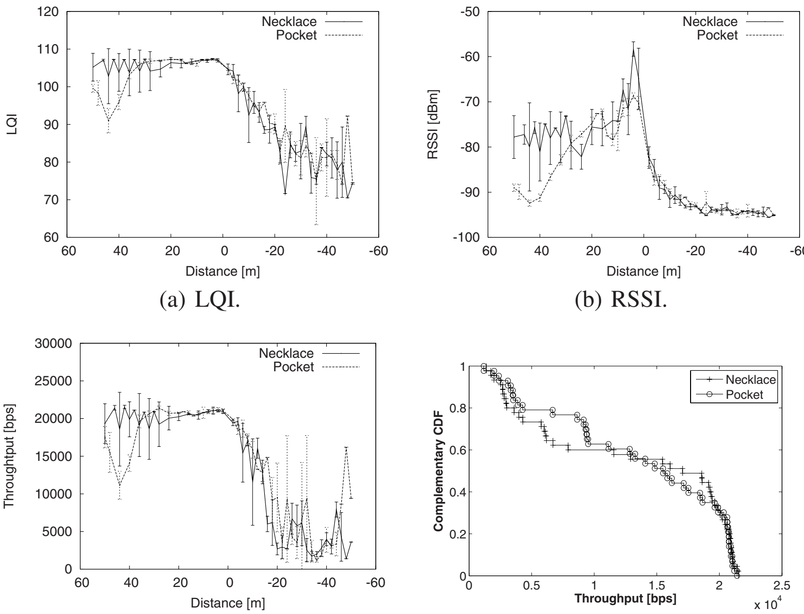
(c) throughput. (d) throughput CCDF.

Fig. 2. Sidewalk urban environment: LQI, RSSI, throughput, and throughput Complementary CDF measured at the receiver as a function of the transmitter-receiver distance

the nodes are carried by people. In fact, the radio contact opportunity is significantly reduced given the radio coverage asymmetry shown in Figures 1(d), 1(e), and 1(f). We define the *zero bandwidth crossing* point as the relative position(s) between a transmitter and a receiver beyond which the throughput drops to zero because of the body factor. In Figure 1(d) the zero bandwidth crossing points for the receiver moving counter-clock wise are encountered on average along the radius of coordinates (x_1, y_1)=(70,70) and (x_2, y_2)=(80,130).

The implications of the zero bandwidth crossing point are more evident when analyzing the case of nodes performing a rendezvous along a straight path. This is the case where people are walking along a sidewalk according to the experimental setup described earlier. The LQI, RSSI, and throughput measurements as a function of the transmitter-receiver distance are shown in Figure 2. The coordinate x=0 on the x-axis in Figures 2(a), 2(b), and 2(c) denotes the point where the two people cross along the sidewalk.

If we first analyze the mote necklace case we can see from Figures 2(a), 2(b), and 2(c) that the RSSI, LQI, and throughput increase as the transmitter and receiver move to the crossing point at x=0. Right after the crossing point the receiver stops receiving data (note the absence of data for the mote necklace case on the right of x=0). The x=0 coordinate represents the zero bandwidth crossing point for the sidewalk experiment. This result confirms the trend shown in the soccer field (Figure 1) where no signal is



(a) LQI. (b) RSSI.

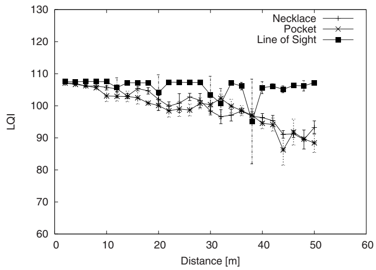
(c) throughput. (d) throughput CCDF.

Fig. 3. Indoor (hallway): LQI, RSSI, throughput, and throughput Complementary CDF measured at the receiver as a function of the transmitter-receiver distance

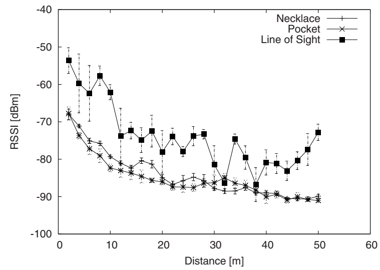
received by the receiver node when the body of the person carrying the transmitter is between the transmitter and the receiver.

When the nodes are carried in the pant/trouser pocket (akin to a sensor-enabled cellphone) the results are different. Being in a pocket, which implies a node position slightly to the side of the person's body, the performance degradation particularly at large transmitter-receiver distances is larger. In Figures 2(a), 2(b), and 2(c) it is shown that when the nodes are in the pocket the LQI and throughput increase slower than the necklace case when the distance decreases reducing the time window in which nodes experience high throughput. The complementary CDF of the throughput is also shown in Figure 2(d). Having the node more towards the side of the body translates into a positive effect as well, i.e., the nodes have the opportunity to remain in radio contact beyond the crossing point at x=0. This occurs because the position of the nodes, which now experience some degree of LoS contact being on the side of the body, allows some radio signal to be received even when the nodes pass each other extending the zero bandwidth crossing point by 10 meters beyond x=0 (this can be seen in Figures 2(a), 2(b), and 2(c) for the pocket related curves).

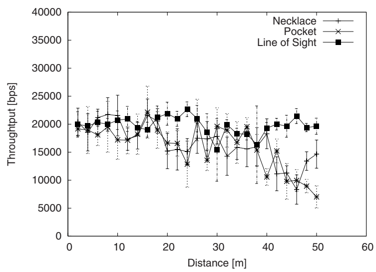
The zero bandwidth crossing point is pushed even further in indoor scenarios. This is shown in Figures 3(a), 3(b), and 3(c) where the x-coordinate x=0 represents the point where the people carrying the nodes cross in the hallway. Note the asymmetry in Figures 3(a), 3(b), and 3(c) for LQI, RSSI, and throughput signatures respectively as the mobile nodes pass each other at x=0. This is again due to the bodies of the two



(a) LQI.



(b) RSSI.



(c) throughput.

Fig. 4. Indoor (hallway): LQI, RSSI, and throughput measured at the receiver as a function of the transmitter-receiver distance. The transmitter is static and positioned at one edge of the hallway.

people between the transmitter and the receiver. The interesting aspect is that the zero bandwidth crossing point is extended for more that 50 meters (up to the end of the hallway) beyond the physical crossing point. Even when the people's bodies attenuate the LoS component of the signal propagation, we believe that radio signal reflections off walls and other obstacles provide a non-LoS propagation path to the receiver. For this scenario, again the necklace case produces LQI, RSSI, and throughput patterns slightly better than the pocket case when the people approach each other from a long distance.

Modeling the Body Factor. In order to quantify the impact of the body of the person carrying the node we perform the following experiment: we position the transmitter node at one edge of the hallway, hanging from the ceiling and in LoS contact with the rest of the hallway. The receiver node is carried starting under the transmitter to the other end of the hallway as a mote necklace at first and then as a pocket mote. As a term of comparison, we also carry out LoS measurements along the whole hallway having the receiver lifted 50 cm above the ground. The LQI, RSSI, and throughput measurements for the LoS and body factor experiments are reported in Figures 4(a), 4(b), and 4(c) respectively.

We can see that the LQI degrades almost linearly with the distance for both the mote necklace and pocket mote cases. The throughput, which in general mirrors the LQI pattern [21], also degrades with the transmitter-receiver distance and in the necklace case it almost follows a linear decay. The RSSI for both the necklace and pocket cases

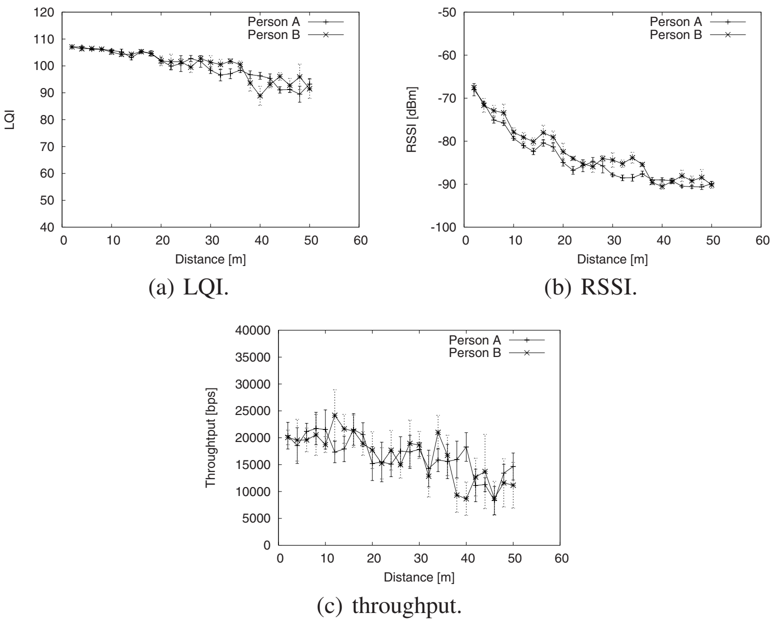


Fig. 5. Indoor (hallway): LQI, RSSI, and throughput measured at the receiver when the receiver is carried by two different people as a function of the transmitter-receiver distance. The transmitter is static and positioned at one edge of the hallway.

remains on average 15 dBm below the nominal value measured in the LoS case and presents an exponential decay [21]. Given these findings we believe that it is possible to model the impact of the body factor over distance. The results suggest that probably linear interpolation for LQI and throughput and exponential interpolation with a known offset for the RSSI might be used in order to design models that consider the impact of the body factor for indoor scenarios. At the moment this is out of the scope of this work but we are planning to continue our research to consolidate our findings and present radio models that take such insights into account.

Body factor for different people. We conduct experiments to quantify the body factor caused by different people with different body sizes. We design an experiment where the transmitter is positioned at one edge of the hallway, hanging from the ceiling in LoS contact with the rest of the hallway. The receiver node is carried, starting under the transmitter node, to the other end of the hallway by two people with different body sizes. Person *A*'s weight and height are 55 kg and 1.65 meters respectively, whereas Person *B*'s weight and height are 78 kg and 1.79 meters, respectively. We measured LQI, RSSI, and throughput on the receiver node carried as a mote necklace and the results are reported in Figures 5(a), 5(b), and 5(c). From the plots no substantial difference exists between Person A and Person B in terms of LQI, RSSI, and throughput patterns. As for this result, we conjecture that for a broad class of people's figure, at least falling in the same category as the people we have experimented with, the body factor does not vary significantly with individuals. Clearly, a more comprehensive set of experiments might highlight such differences. We leave this for future work.

3.2 Mobility Issues: Contact Time and Effective Contact Time

An important parameter to take into consideration in mobile sensor networks is the time interval nodes are in radio contact with each other. It is during this time that the rendezvous takes place and data exchange can occur. For the sidewalk and hallway experiments, which again are representative of the class of scenarios where short-range radio devices carried people could operate a rendezvous, we also measure the contact time (CT) which is the time between the first and last packet received. Average contact times distribution is presented in [12] for several nodes being carried in a conference setting for few days. In our study we take a different approach, i.e., we want to investigate the detailed performance of atomic rendezvous between nodes to provide deeper insights for protocol and applications designers. For this reason we also define the effective contact time (ECT) as the time interval within which nodes experience a throughput larger than the median between the lowest and largest throughput across the experiment. We introduce the ECT to be able to compute normalized time interval measurements particularly useful indoors where the nodes' contact time mainly depends on the building's floorplan. Knowing the CT and ECT is helpful to determine the amount of bytes of data that can actually be exchanged when mobile nodes start a rendezvous during common walking patterns, like in a sidewalk or hallway. The average CT and ECT values measured in the sidewalk along with their confidence intervals are reported in Table 1.

Table 1. Contact Time and Effective Contact Time measured on the sidewalk

Scenario	CT (sec)	ECT (sec)	CT Conf. Interv. (sec)	ECT Conf. Interv. (sec)
Necklace	59.42	33.64	10.65	8.08
Pocket	31.14	17.21	10.29	2.73

What is interesting about this result is that the amount of time during which two mobile nodes performing a rendezvous can exchange data is limited to few tens of seconds consequently limiting the overall amount of data that can be exchanged. This has to be taken into consideration when designing applications that require peering interaction and data exchange between mobile nodes with short-range radios, as can be found in delay tolerant networks [12] for example. The short contact time also impacts the performance of the mobile-to-static node rendezvous that occurs when mobile nodes interact with static gateways to upload data or receive tasks [8] [4]. The average CT and ECT values along with their confidence intervals for the mobile-to-mobile rendezvous in the hallway are reported in Table 2.

Although the CT becomes less important in an indoor scenario because it depends on the topology of the environment which impacts the maximum physical distance the nodes can be placed at, the ECT is still meaningful. In fact, no matter how big the indoor space is, when two mobile nodes approach each other we would always observe

Table 2. Contact Time and Effective Contact Time measured in the straight part of the hallway

Scenario	CT (sec)	ECT (sec)	CT Conf. Interv. (sec)	ECT Conf. Interv. (sec)
Necklace	39.14	27.21	2.63	2.09
Pocket	37.24	27.64	1.46	1.67

the following performance: the throughput, first increasing and then decreasing. By applying the median throughput thresholding technique as part of the ECT definition, the ECT provides a normalized measure of the time interval when the throughput is above a certain threshold (in our case the median value between the highest and lowest throughput during the measurement). In Table 2 it is shown that even for the indoor case the ECT is in the order of less than 30 seconds. Clearly, different definitions of ECT could be determined. We plan to study this issue as part of future work.

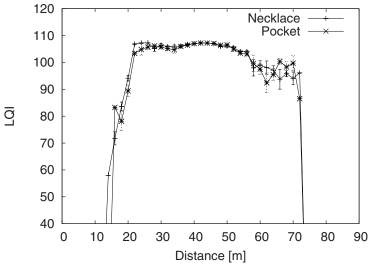
Impact of obstacles on the contact time. So far results are related to the case when the nodes are moving along a straight path from one end to the other end of the hallway. We conduct an experiment to analyze the effect of obstructions, in particular the L-shape corners at each end of the hallway when a person turns them. The transmitter node is positioned in the middle of the hallway hanging from the ceiling and the receiver is carried as a mote necklace and pocket mote. The results are shown in Figures 6(a), 6(b), and 6(c) for LQI, RSSI, and throughput, respectively. The corners are turned at coordinates x=20 meters and x=70 meters.

Table 3. Contact Time and Effective Contact Time measured in the hallway turning corners

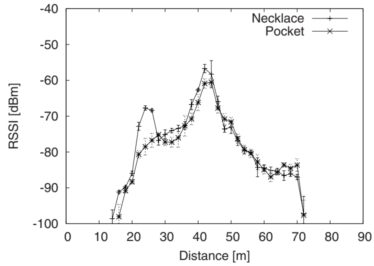
Scenario	CT (sec)	ECT (sec)	CT Conf. Interv. (sec)	ECT Conf. Interv. (sec)
Necklace	43.66	36.59	0.82	1.86
Pocket	42.55	35.40	0.73	1.87

It is shown that the receiver stops receiving the transmitter's packets almost immediately as the corners are turned. If we look at Table 3 the CT and ECT are below 45 seconds and 37 seconds, respectively. Given the short amount of time nodes are in contact with each other, data exchange or task download could be challenging. Even in this case the CT depends on the length of the hallway whereas the ECT assumes a more general validity.

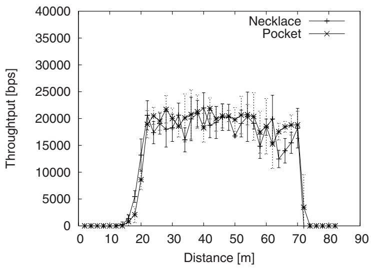
As shown in Figure 6(b), the RSSI measured at the receiver approaching the transmitter increases (from 15 to 42 meters), whereas it decreases when the receiver moves away from the transmitter (from 42 to 72 meters). Although the RSSI signature might not present a monotonic pattern (note the necklace case RSSI at 25 meters) when either approaching or moving away from a node, it might still be used as an input to ranging algorithms to coarsely determine the distance between two nodes or at least their relative position variation. In fact, it may be possible to filter the local maximum at 25 meters in Figure 6(b) by applying an exponentially weighted moving average over the



(a) LQI.



(b) RSSI.



(c) throughput.

Fig. 6. Indoor (hallway): LQI, RSSI, and throughput measured at the receiver as a function of the transmitter-receiver distance turning around corners. The transmitter is static, hanging from the ceiling in the middle of the hallway.

RSSI samples. Then, by looking at the increasing RSSI gradient the receiver could infer that it is approaching the transmitter. At the same time, as the receiver moves away from the transmitter at its back, the decreasing RSSI gradient could make the receiver infer that it is leaving the radio coverage of the transmitter. From our experiments the RSSI and LQI signatures have similar patterns if the receiver is static (in the middle of the hallway) and the transmitter mobile (i.e., the RSSI measured at the static receiver increases as the transmitter approaches the receiver while it decreases as the transmitter moves away from the receiver). For this reason we do not show the results for the latter scenario but we can draw the same conclusion as the static transmitter and mobile receiver case.

4 Architectural Considerations

All the experiments discussed so far lead us to assert that characterizing short-range low power radio performance in mobile sensor networking scenarios is complicated. This is particularly true when considering arbitrary static and mobile node positions across the experimental field because of the dependence on the surrounding environment, the background noise in the same radio band, neighboring obstacles, etc. However, we take a systematic approach to experimentally investigate and quantify the effect of a person's body and mobility on short-range radio transmissions by designing a number of simple benchmark tests.

We believe that the findings of this work could be considered as an important step towards understanding the complex radio behaviour of mobile 802.15.4 devices carried by people. In particular, the results discussed in Section 3 could drive application and protocol design for mobile people-centric sensor networks [4] and delay tolerant networks [12]. In what follows, we discuss some of the implications of our results on the communication protocol stack for short-range radio mobile node architectures.

Application layer. The data exchanged between nodes is limited by the short mobile-to-mobile and mobile-to-static rendezvous times, i.e., the CT and ECT metrics discussed in Section 3. The former includes scenarios such as a peering application or the result of delay-tolerant data exchange [12]. The latter includes the case when mobile nodes engage in a rendezvous with static nodes for uploading data to the Internet or receiving tasks [8] [4].

In our experiments, at most 96 kBytes and 73 kBytes can be exchanged in the sidewalk and hallway scenarios, respectively, given the average throughput achieved during the nodes interaction and the measured contact time at normal walking speed. For this reason, an application should minimize the number of data bytes to be exchanged. This could be achieved by implementing fusion and filtering algorithms directly on the nodes to minimize the amount of data produced (and/or locally stored) by the on-board sensors.

Transport layer. Any communication protocol should minimize the signaling overhead to maximize the data transmission opportunities during the rendezvous time. A transport protocol must act quickly and a NACK-ing or cumulative acknowledgment solution would be preferred over a per-packet ACK-ing scheme. The transport protocol should be opportunistic in the sense that it should be able to rely, for example in the mobile-to-static case, on multiple static nodes to accomplish the job. The mobile-to-static interaction in fact is most likely associated with data upload or task download sessions [8] [4], where the static node acts as a gateway between the static and mobile infrastructure.

If the mobile node goes out of the radio range of a static node, then the data upload or tasking session must be able to recover/complete when the next static node in the neighborhood is encountered. For example, this could be done by having a static node involved in a mobile uploading or tasking session propagate the state of the ongoing session to its neighboring nodes (e.g., to the static nodes in the same building or on the same street). As the mobile node enters the radio cell of one of the notified static nodes the uploading/tasking session would eventually complete.

Network layer. Any routing protocol must be reactive enough to the strong asymmetry on the radio signature caused by the body factor (Section 3). In particular, given this asymmetry, maintaining multi-hop paths between nodes is challenging. This is because when a link is established between two mobile nodes approaching each other, this link could suddenly disappear as the nodes pass each other (as we have seen in Section 3) causing a sudden disruption of the path. There is a need then for proactive routing protocols that, by monitoring the radio channel conditions (for example the RSSI gradient as the nodes approach each other) and maintaining alternative paths if possible, can quickly recover from any sudden links loss due to the body factor.

MAC layer. The body factor could make the hidden terminal problem more severe in mobile people-centric sensor networks than in the static LoS grid topology. Imagine node A approaching node B (having the two nodes facing each other), and imagine node A passing node B and eventually stopping behind B. Assume that B is static and it is willing to start communicating with a node C approaching node B from the front. As we have seen in Section 3, given this configuration node A will not be able to overhear B's transmission to C. Assuming a CSMA access scheme, A hears a clear channel and assumes it can start transmitting packets to a node D in the neighborhood. This means that even if nodes A and B are physically close to each other, by not being able to sense the respective radio activity their radio transmissions will possibly interfere with each other. We plan to experimentally investigate the impact of the body factor on the MAC layer design in future work.

Physical layer. Our findings can be leveraged to develop more accurate radio models for the short-range, low power 802.15.4 radio networks when the nodes are carried by people. These models could have applications in: *i)* improving network simulators widely used in the research community (e.g., NS-2 [31], Omnet++ [32], and Tossim [33]) to include radio models that take into account the body factor and the zero bandwidth crossing point; *ii)* in the domain of opportunistic communications; there have been studies to characterize mobility and radio contact patterns between people [34] [35] where nodes are assumed to be in radio contact if they are in the same venue at the same time [34]; delay tolerant routing protocols using routing functions based on nodes distance have been proposed [35]. However, we show that given the body factor nodes that are almost co-located and near each other are not guaranteed to have radio contact. Our work could be used to enhance the radio models for opportunistic communication networks.

5 Conclusion

In this paper, we have studied the impact of the human body on 802.15.4 radio communication under a variety of experimental conditions (mounting positions, indoor/outdoor environments, body size, etc.). We show how the body factor, and particularly the zero bandwidth crossing point phenomenon, combined with mobility, makes people-centric sensor networking based on low-power 802.15.4 radios challenging. Our work underscores the importance of taking the body factor into consideration when designing applications, networking protocols, and radio models in the people-centric sensing domain [4]. Our experimental data are publicly available in the CRAWDAD repository [36].

As part of future work we plan to investigate the body factor in the context of more sophisticated scenarios, for example, in multihop, multi-node environment with simultaneous transmissions. Additionally, we hope to demonstrate the extent of the body factor in other short- to mid-range radio networks (e.g., Bluetooth and 802.11abg).

Acknowledgments

This work is supported in part by Intel Corp., NSF NCS-0631289, ARO W911NF-04-1-0311, and the Institute for Security Technology Studies (ISTS) at Dartmouth College. Kristóf Fodor is supported as a Fulbright Scholar. ISTS support is provided by the U.S. Department of Commerce under Grant Award Number 60NANB6D6130. The views and conclusions contained in this document are those of the authors and should not be interpreted as necessarily representing the official policies, either expressed or implied, of the U.S. Department of Commerce, NIST, NSF, ARO, and Intel.

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