

Research Article

Link Characteristics Measuring in 2.4 GHz Body Area Sensor Networks

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Received 16 July 2012; Accepted 26 September 2012

Academic Editor: Yingshu Li

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With the increasing demands on the remote healthcare and the rich human-machine interacting, body area sensor network (BASN) has been attracting more and more attention. In practice, understanding the link performance and its dynamics in the emerging BASN applications is very important to design reliable, real-time, and energy-efficient protocols. In this paper we study the link characteristics of body area sensor network (BASN) through extensive experiments with very realistic configurations. We evaluate the packet reception ratio, RSSI, LQI, and movement intensity of body under indoor and outdoor environments, all of which can provide direct insights to practical account.

1. Introduction

Recently, the emerging body area sensor network (BASN) [1–3] has established itself into an important branch of pervasive computing and personal communications, and more and more BASN-based applications are employed in remote healthcare monitoring as well as wearable medical systems [4–10] and human-centric context recognition [11–15]. In a typical BASN, multiple sensors are attached on or implanted in the human body, and they sample physiological data, such as acceleration, heart rate, SpO₂, and breath apnea interval, and transmit these data through wireless channel to a gateway (e.g., mobile phone), which is often carried by users. The gateway performs further computation and communication tasks—diverse interactions with users or services. By far, the operation frequency likely used in BASN ranges from the low-frequency band such as 10 MHz, the industrial-scientific-medical (ISM) band from 2.4 to 2.8 GHz, and to the ultra-wideband (UWB) standard. Bluetooth and IEEE 802.15.4 are two commonly-used 2.4 GHz communication standard. However, Bluetooth has a complicated protocol stack and runs with more energy than 802.15.4, so most literatures and applications use 802.15.4 as their communication protocols, and, in practice, the number

of applications using IEEE 802.15.4-based 2.4 GHz devices has been increasing, which is the main motivation of carrying out our work at 2.4 GHz.

To design reliable, robust, energy-efficient communication protocol, BASN designers must know how links vary with time and what factors affect the link dynamics. Understanding and profiling the BASN links are very important and very challenging in implementing BASN applications of high efficiency. We argue that the existing investigations of BASN link dynamics, either under a few well-controlled movements or a completely real-world movements, cannot provision a continuous, accurate snapshot for the link characteristics and then are not more insightful for practical designing.

In this paper we attempt to investigate, via extensive experiments, the link layer characteristics of BASN using commercial wireless sensor motes and working in realistic environments. The resulted analysis will provide valuable insights for engineers to design efficient communication protocols, like MAC and routing. In summary the main contributions of our work are as follows. First, our studies are carried out with more realistic configurations in which subjects do as they usually do; and specifically, the on-body mote placement as well as the many-to-one communication

pattern used in experiments reflect the practical scenario of BASN. Second, we deeply inspect the asymmetric property of BASN link and the feasibility of RSSI and LQI as link quality predictors. Third, we analyze the effect of node's placement as well as possible radio reflection on link performance. Finally, through comparing the link throughputs under indoor and outdoor environments, we analyze the possible dominance on link performance for different environments.

In the rest of this paper, Section 2 briefly introduces some works related to ours. Section 3 describes the platform and methodology used in our experiment. Section 4 shows the overall link performance both for indoor and outdoor cases. Sections 5 and 6 inspect the effects of mote placement and body position on the link behavior. Sections 7 and 8 discuss the link asymmetry and dynamics in detail. Section 9 evaluates whether and when RSSI and LQI are good link quality predictors. Finally, Section 10 concludes this paper and present our future work.

2. Related Work

Recently there has been more and more attention about BASN. In the literature of BASN communication, two sorts of researches can be roughly categorized. The first one focuses on the wireless propagation patterns of BASN, that is, on modeling the path loss. Instead, the second one is for the link layer—the link throughput and dynamics are followed with great interests. In general, these two sorts of studies work for different goals: the former is often directed towards physical layer designs while the latter aims at preparing for designing efficient schedules for link and MAC layers. Our work is close to the latter one.

The physical layer studies like [16–19] model the radio propagation in BASN scenario, examining the impact of body and antenna on the path loss of channel. In fact, modeling the path loss for the physical layer often needs strict assumptions about the environment and then it is not enough to provide insights directly to the engineers implementing BASN applications. So, in the past a few years, some preliminary efforts [20–24] have been put on measuring the link layer of BASN. But most of these previous works have not thoroughly investigated the link behavior of BASN with realistic configurations; for instance, the degree of link asymmetry, the performance of RSSI and LQI metrics, the effect of reflections, and so forth have not yet been investigated; particularly, these works often depend on well-controlled environments and contexts for studying link characteristics. Actually, a large amount of activities and movements cannot be simply categorized into some specified sort.

The works more closely related to ours are [22, 23]. The authors in [22] compare the performance of Bluetooth and 802.15.4 in the context of BASN with well-specified configurations. Rather, the authors in [23] investigate the link behaviors under more generally daily configurations, but their experiments are based on any-to-any communication with antennas exposed outside, which is not a very typical scenario for BASN and especially, their link asymmetry

evaluation as well as RSSI and LQI examination is not too sufficient to provide insights for engineers to design efficient schemes.

3. Experimental Methodology

In our experiments we conduct real test-bed experiments using MicaZ motes which are equipped with CC2420 radio chip working at 2.4 GHz and then are compatible with IEEE 802.15.4. The 2.4 GHz 802.15.4 radio interface and protocol (especially at channels 25 and 26) are generally robust against interferences from other 2.4 GHz systems such as Bluetooth and WiFi. And more and more BASN applications adopt 2.4 GHz 802.15.4 radio as the communication interface—that is the reason we focus on it in this study. Next we give details about the hardware as well as software configurations and the experimental methodology in this paper.

3.1. Hardware and Software Configuration. Produced by Crossbow, MicaZ mote is based on the Atmel ATmega128L, which is a low-power microcontroller running programs from its internal flash memory. The 51-pin expansion connector of MicaZ supports analog inputs, digital I/O, I2C, SP, and UART interface. So, these interfaces make it very easy to connect to a wide variety of external sensors or other peripherals. The MicaZ mote is fitted with IEEE 802.15.4-compatible radio chip, CC2420. MicaZ consumes energy of 8 mA in active mode and less than 15 μ A in sleep mode; it uses 29.7 mA, 17.4 mA, and 20 μ A energy in receiving, transmitting, and idle states, respectively. The radio chip CC2420 runs in 2.4 GHz ISM band. Using 16 channels (from 11 to 26), CC2420 operates with a maximum data rate of 250kbps, while achieving a very low energy cost. In this paper the MicaZ motes all run at channel 26. In summary CC2420 is very suitable for embedded, low-power, and low-rate wireless applications, such as sensor network and body area network. The feasibility and availability of MicaZ in BASN scenarios let us choose it to build our test-bed for investigating the BASN links at 2.4 GHz. In addition, we use MTS310 sensor-board—one for each MicaZ—to capture the movement of motes.

3.2. Experiment Descriptions. In our experiments, six MicaZ motes are attached on the body, five working as body sensors and one as the gateway (GW). The GW mote is placed on the right side of waist (tightly above the right-side hip), the way a lot of people often carry or place their mobile-phone, and other five motes are attached on the torso or limbs. Figure 1 shows the specific deployment of six motes. Particularly, in our experiments all motes as well as their short antenna are attached directly to skins and covered by volunteer's clothes; we believe that such placement without exposing mote's antenna is much closer to practice. In fact, we consider a reasonable deployment of sensors and GW for mobile healthcare or human activity analysis. As shown in Figure 1, mote 1 is attached on the left chest, working as a ECG sensor; mote 3 as well as mote 4 on the wrist, as pulse or SpO₂ sensor; motes 4 and 5 (on the left-side waist and the

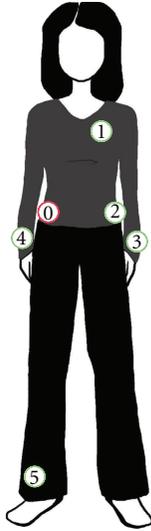


FIGURE 1: The deployment of body sensor network in experiment. The red circle with label 0 represents the GW mote, and the green ones represent the sensor motes with labels from 1 to 5. The sensor 2 and the GW locate on the two sides of the waist, respectively, that is, they are of not line-of-sight in reality.

right ankle, resp.) function in activity analysis. Particularly our experiments focus on data-gathering communication pattern—all five motes send packets to the GW rather than on any-to-any pattern as done in [23].

We program our test-bed using TinyOS [25], an open source operating system for embedded sensor networking, and we use the default channel and CSMA configurations of MicaZ in experiment. In our experiments, the operation of BASN is divided into successive rounds; each round lasts one second within which the GW broadcasts five messages over all motes with the time interval of 200 ms, and once a mote receives the message from the GW it immediately samples its two-axis accelerometer using the `ReadStream` interface provided by TinyOS for 40 ms and then sends these sampling results to the GW. In this paper we consider the quality of two directions of a link, as we know the radio channels are often of asymmetry in real world. Therefore, the delivery over a link is successful only if the packet and its acknowledgement are both received successfully. Understanding the link asymmetry is more important in BASN than in traditional wireless sensor network; for example, healthcare BASN applications often need to timely issue feedbacks (not just ACKs) to configure body sensors or even invoke actuations on body. So both the message from the GW and the packet from the sensor are set to be 40 Byte in our evaluation. It is worth noticing that the contention-based MAC scheme, rather than the TDMA-like schemes [22, 23], is used in our experiments. We argue that the time synchronization among all motes is very resource-consuming and cannot even be achieved when the links keep varying for a long term. We believe CSMA-like MAC is a more desirable choice in human body context.

Three subjects (volunteers) with different sizes and forms attend the experiments for two sorts of environments: indoor (an office of size $4 \times 6 \times 3.5 \text{ m}^3$ with desks, chairs, and bookcases) and outdoor (a middle-size square in our campus with very sparse population). The subjects can work as well as move in the office as they do usually, and when they are in the outdoor square, they can arbitrarily walk at a common speed or sit for rest. The experiment of each subject for an environment lasts 30 minutes. In average, for indoor case, subjects consume about 75% of their time in working at their desk, often with two arms on desk, 10% in moving within around the office, and the remaining time in sitting to talk; for outdoor case, nearly equal period of time is used in walking and sitting. Obviously, the movement configurations, either in office or outdoor square, tightly follow what subjects usually do in their working or daily time. In each experiment, communications are carried out with three transmit incremental powers: -15 dBm , -5 dBm , and 0 dBm , but, at a time, all the motes use the same transmit power. Note here that 0 dBm is the maximum transmit power MicaZ mote can achieve.

In this paper we mainly use four measurements to evaluate the link throughput and inspect the possible impact factors; they are PRR (packet reception ratio), RSSI (received signal strength indicator), LQI (link quality indicator), and two-axis acceleration data. The PRR for a link is the fraction of packets sent in a period of time that are correctly delivered over this link. The RSSI and LQI are provided by CC2420 chip [26], both of which are used to estimate the link quality at packet level. The two-axis accelerometer of MTS310 sensor-board, though unable to provide absolutely accurate movement profiles of human body as the three-axis accelerometer does, should be helpful to roughly reflect the movement intensity of the corresponding part of body.

3.3. Considerations in Experiment Setup. For deeply investigating the link characteristics appearing in BASN real-world applications, we design extensive and dedicated experiments described in previous section. Next we explain the choices considered in our experiment design.

- (i) *Daily-life environments*: BASN is often used in monitoring human body as well as its surroundings, and then, in daily life, office (or home) and open space are the two most likely environments BASN works in.
- (ii) *Bi-directional links*: we investigate the link asymmetry of BASN with extensive experiments, for, unlike traditional sensor networks, the feedback controls are often very critical for BASN applications, especially for real-time ones. Therefore we inspect the asymmetric property of BASN link in a time scale of millisecond.
- (iii) *CSMA-based communications*: all the motes contend channel, that is, work with CSMA scheme, which is easier to be implemented and maintained than the TDMA scheme and consequently is widely used in the literature or practice.

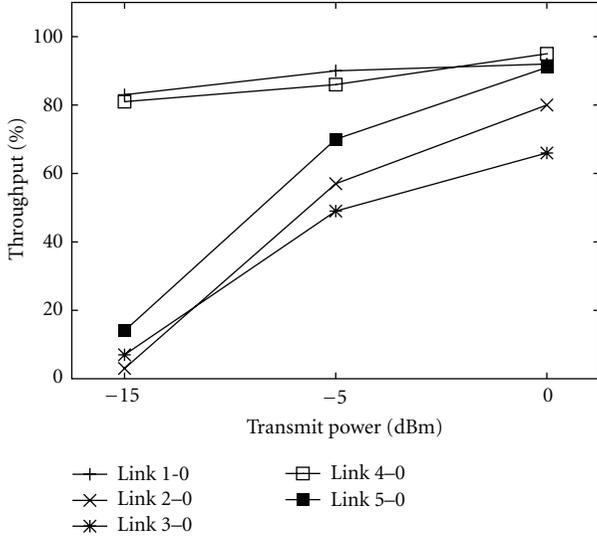


FIGURE 2: The average throughput over all subjects in indoor environment.

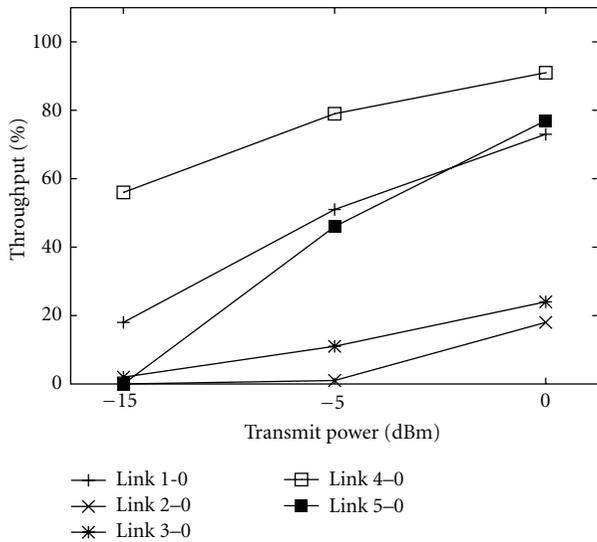


FIGURE 3: The average throughput over all subjects in outdoor environment.

- (iv) *Uncontrolled human movements*: most of existing studies have focused on the impact of postures on the link throughput of BASN. But they all require well-controlled postures or movements and consider less about the obstacles from the body part or surroundings. In this paper, subjects do what they usually do; this way makes our results be of more practical account.

4. Overall Performance

This section introduces the overall performance of BASN links for all subjects and all environments. Figures 2 and 3 show the PRR of each link at different transmit powers.

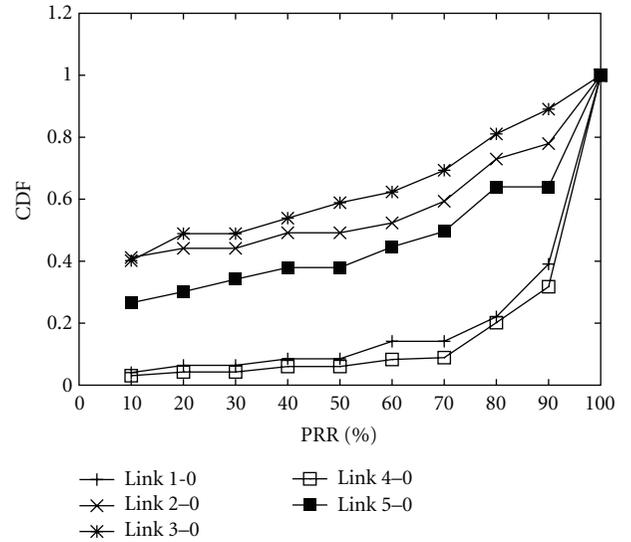


FIGURE 4: CDF of PRR over all subjects in indoor environment.

From Figure 2 we can see that, in office environment, all links perform better as the transmit power increases, and under three transmit powers, the link 1-0 performs best while the link 3-0 performs worst. In particular, increasing transmit power leads to large gain for links 2-0, 3-0, and 5-0, but small gain for links 1-0 and 4-0. According to Figure 1, it is easy to find that motes 1 and 4 are closer to the GW than motes 2, 3, and 5 are. In particular, both motes of 1 and 4 can keep line-of-sights to the GW almost all the time, but it is not the case for motes 2, 3, and 5 because the links from them to the GW are easy to be obstructed by body movement or special activity and thereby become weak, especially when the transmit power is low. Similar to the results for indoor environment, the performances of all links for outdoor environment acquire gains, and still, links 1-0 and 4-0 are stronger than other three links. We find, however, that each of the five links performs worse in the outdoor than it does in the indoor. The link 2-0 achieves the PRR up-bounded by 20% in outdoor scenario while its PRR can go up to 80% in indoor scenario. Moreover, it can be seen that increasing transmit power cannot result in significant throughput increases for all links in outdoor environment. Noticeably, link 4-0 is fairly better in PRR than link 1-0 for outdoor case, while both are almost identical for indoor case. In Figures 4 and 5, the CDFs of link PRR are presented. These observations reveal the impacts of environment and node placement on the link throughput, which will be investigated in detail in later sections.

5. Effect of Mote Placement

From Figures 2 and 3, we can see that links obviously perform differently from placement to placement; which part the mote is placed on will affect the link throughput because the distance of two motes communicating with each other and the line-of-sight between them are both of spatial-temporal variation caused by body's movement and possible

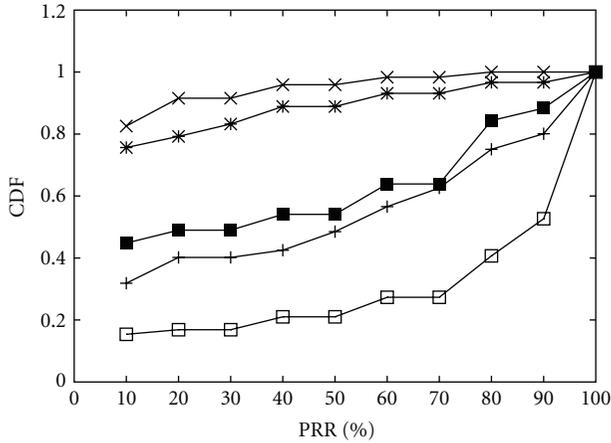


FIGURE 5: CDF of PRR over all subjects in outdoor environment. Here the data curves are distinguishably marked as done in Figure 4.

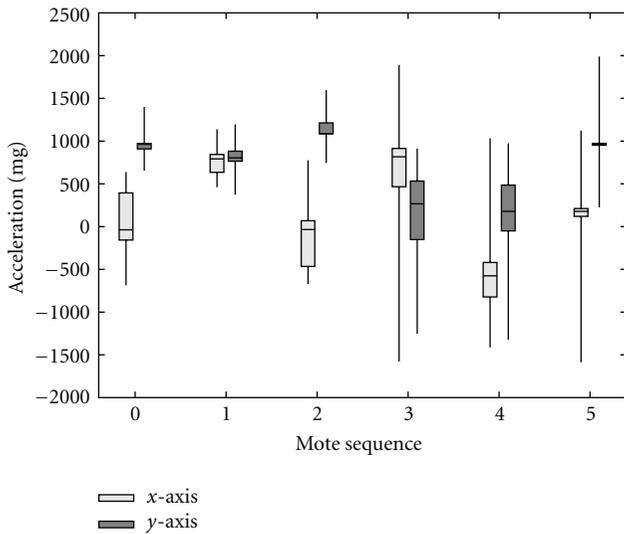


FIGURE 6: The distribution of two-axis acceleration of all motes for indoor environment.

obstacles. For instance, by Figure 1, the link 1-0, whose two end-motes are amounted on the torso (up half of body), can almost always keep unchanged in link distance as well as line-of-sight and thereby can deliver much more packets than other links except link 4-0. On the other hand, the motes 3 and 4, though having similar movement pattern in office environment, lead to different link performances—the average PRR of link 4-0 is significantly greater than that of link 3-0, either in indoor or outdoor case. In practice, the mote placement is generally determined by the application; for example, the wireless ECG sensor is often attached on the chest, the application concerned with gait analysis needs to mount at least one accelerometer on ankles. Therefore, it is very important to investigate the effect of node placement on link throughput before building BASN applications.

The intensity of body movement is described through analyzing the acceleration data sampled by all motes; the

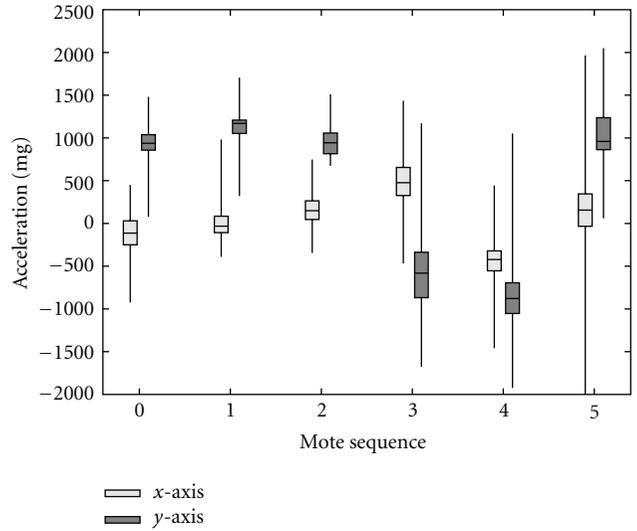


FIGURE 7: The distribution of two-axis acceleration of all motes for outdoor environment.

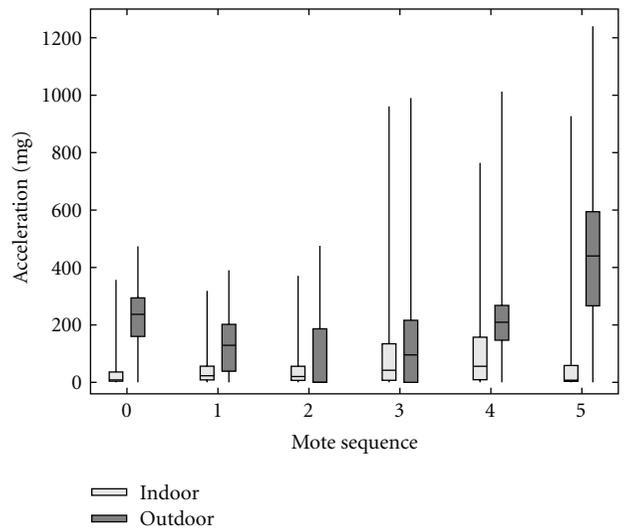


FIGURE 8: The distribution of the vector distance between the standard variances of two-axis acceleration for all experiments.

results are shown in three box-plots: Figures 6, 7, and 8. In the two environments, motes 3, 4, and 5 vary in a larger range. On the contrary, motes 0 (the GW), 1, and 2 are relatively indifferent in terms of the acceleration and deceleration caused by body movement, both for indoor and outdoor environments. However, we do not find out confident relation between the acceleration of motes and their throughput—it appears at least that the movement of body does not dominate the link performance, for example, link 2-0 whose two end-motes both have the lowest movement intensity performs better only than link 3-0 for indoor case and performs the worst for outdoor case. Another counterexample goes to link 4-0, which is almost the best in terms of PRR in two environments; but its acceleration samples distribute within a large range more

TABLE 1: The correlation between PRR and acceleration over all links.

Env.	Tx (dBm)	CORR1	CORR2
Indoor	-15	0.42	0.24
	-5	0.10	-0.03
	0	-0.12	-0.18
Outdoor	-15	0.06	-0.2
	-5	0.55	0.29
	0	0.69	0.46

extensively than most of other links. With comparing link 2-0 with link 4-0, it can be reasonably concluded that the body tissues between mote 2 (on the left side of waist) and the GW (on the right side of waist) play a decisive role in link throughput, even at 0dBm transmit power, the maximum one MicaZ mote can support.

For inspecting the relation of PRR and movement intensity, we first estimate the movement intensity by measuring the standard variances of two-axis readings from the whole experiments, respectively, and then for each link, we consider the vector distance of both standard variances as the indicator of movement intensity for this link. Table 1 gives the two sorts of correlations between PRR and acceleration over all experiments, in which CORR1 is the correlation coefficient between the PRR and the median of the movement intensity and CORR2 the correlation coefficient between the PRR and the Q3 of the movement intensity (according to statistics, Q3 is the top of the box in the box-plot). According to Table 1, we find that for two environments, neither CORR1 nor CORR2 is always negative as we expected, in other words, more intensive movements sometimes result in no degradation of link throughput. In particular, for outdoor case, almost all correlation coefficients are positive. Also, even for negative correlations for indoor case, their coefficient is very low (e.g., -0.03 or -0.12) such that no model can be confidently constructed for understanding the impact of body movements on link quality. Although being hard to be modeled, the observations on the link quality dynamics under body movements is still insightful to engineers. For instance, the link scheduling police for BASN application would perform well in terms of energy by switching off activity-monitoring modules, if it can adapt to the environments (indoor or outdoor) in which it works. In other words, the engineers could reasonably focus only on investigating other factors that affect the link quality dynamics.

6. Effect of Body's Position in Environment

The previous observations give rise to a question: why the overall throughput of link for indoor case is higher than that for outdoor case? One possible answer may be that there are much more reflective surfaces in indoor environment and reflections from those surfaces can do a good for receiver to successfully receive packet. To validate the existence of helpful reflections, we conduct a specific experiment which only involves link 4-0.

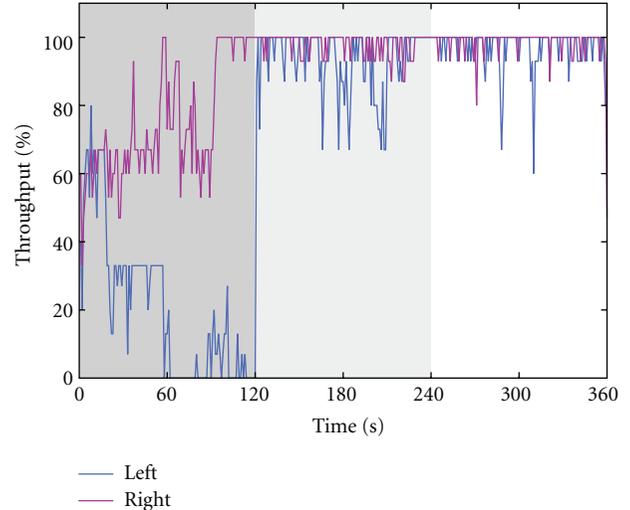


FIGURE 9: The link throughput of mote 4 attached to the right wrist for three incremental transmit powers. Left: the left-side of body is close to the corner; Right: the right-side of body is close to the corner. In experiment the transmit power is changed from -15 to -5 dBm at time 120, and from -5 dBm to 0 dBm at time 240; in this figure, the transmit powers are water-marked by distinct gray scales.

In the office room, two desks locate at two corners, respectively. The subjects work at each desk for six minutes without leaving. Figure 9 differentiates the impact of two different positions of subject on the link performance. When the subject sits by one corner such that his right wrist (wearing mote 4) is close to this corner, the link 4-0 achieves higher PRR at all three transmit powers than it does at the other corner. Particularly when the transmit power is -15 dBm, a relatively low level, the link throughput improvement in the Right scenario is very significant (about three times the Left one) because in general, the closer a link is to the office corner, the more surface can be possibly employed by the link. It is now easy to understand why links tend to perform better in indoor environment than in outdoor environment, especially when the transmit power is low. In the indoor there are often desks, chairs, and cabinets as well as walls and floor, all with smooth surfaces which can lead to more intensive reflections; in contrast, the outdoor environment has less reflective surface and thereby goes against packet reception. Our results suggest that the environments play a critical role in link performance of BASN system.

7. Link Asymmetry

For wireless communication, the upstream and the downstream of a given link are often different in link quality, even within a large time-scale. Link asymmetry, as a common behavior of radio link, affects not only the delivery performance but also the control efficiency. First, in the case in which acknowledgement scheme is used, both successful receptions of packet and ACK message are critical for implementing reliable delivery. Second, for

applications that use feedback controls to achieve adaption or actuation, the control or instruction message should be reliably disseminated from the GW to body motes.

This section examines the asymmetry property of BASN links. Different than the method of evaluating link asymmetry proposed by the authors [23], which first sends a batch of packets lasting eight seconds and then replies over the reverse link a packet batch with the same amount as well as rate. In our experiment, the GW broadcasts a packet to all motes, and each mote immediately replies a size-identical packet to the GW if it receives packet successfully. Such back-and-forth and packet-by-packet pattern can accurately profile the upstream (from mote to GW) and the downstream (from GW to mote) of a link in a time-scale of milliseconds, which makes our results more effective and reliable in link asymmetry evaluation. In our evaluation, we present only three typical links, 1-0, 2-0, and 3-0, as mentioned in a previous section, and consider the PRR, RSSI, and LQI measured from the two directions of link under two environments; these three metrics are calculated every one second.

Figures 10, 11, and 12 plot the link symmetry for indoor case, from which we observe that link 1-0 is better than link 2-0 which is, though, better than link 3-0. However, within these scatter plots, the three links have good symmetry when their PRR values for two directions are both greater than 90%. In addition, for links 2-0 and 3-0, both are of high symmetry when they have every low PRR for two directions, for example, 10% or less. Different from links for the indoor, outdoor links do not possess any symmetry, especially the links 2-0 and 3-0, as shown in Figures 13, 14, and 15. Such high asymmetry, in some degree, reflects the weak and dynamical link throughput for outdoor scenario as Figure 3 demonstrates.

Besides using the PRR in evaluating the link symmetry, we use the RSSI and LQI metrics calculated by the CC2420 radio-chip to estimate the link quality. The indoor results are presented in Figures 16, 17, 18, 19, 20, and 21. We observe that the distributions of RSSI of two directional links hold high symmetry, either for link 1-0, link 2-0, or link 3-0. However, the LQI values for each two-way link are not as good as RSSI in symmetry. Considering the scatter plots of PRR shown in previous figures, we find that evaluating RSSI indicates that the RSSI measurement for each packet cannot reasonably serve as an effective metric for link quality. On the other hand, the LQI distribution shown from Figure 19 to Figure 21, cannot still weigh the PRR correctly.

In later sections we will, in detail, discuss in which case RSSI and LQI might be feasible indicators for link throughput. Here we do not present the RSSI and LQI distributions with regards to link symmetry for outdoor case; their distributions are very similar to those results from indoor experiments and then cannot effectively estimate the link throughput neither. The results about the link asymmetry suggest that, most of time, a BASN mote cannot confidently use the RSSI, LQI, or PRR information (calculated by its receptions) to evaluate the corresponding metric for its reverse link.

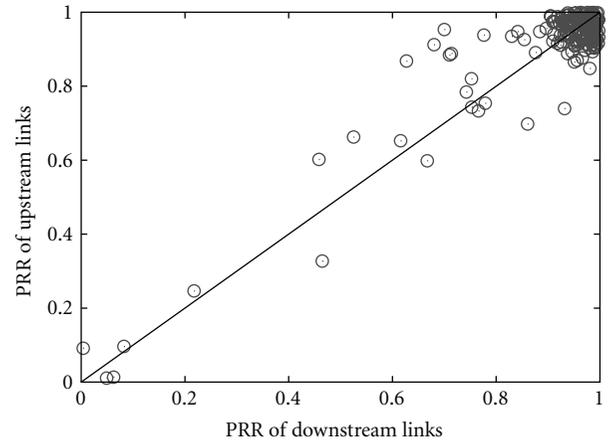


FIGURE 10: Downstream PRR versus upstream PRR for link 1-0 in indoor environment.

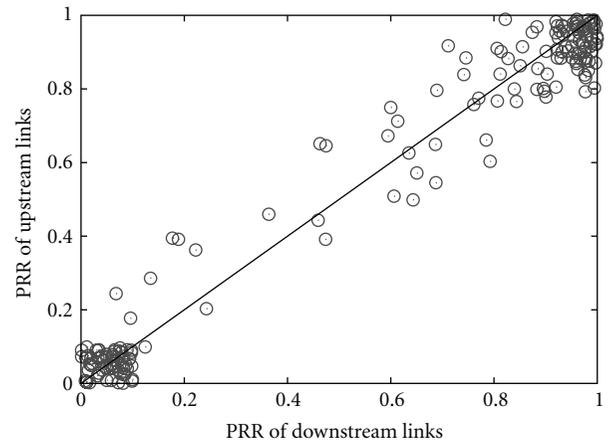


FIGURE 11: Downstream PRR versus upstream PRR for link 2-0 in indoor environment.

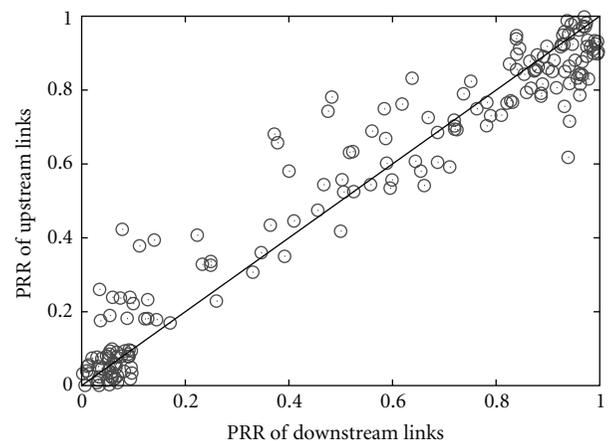


FIGURE 12: Downstream PRR versus upstream PRR for link 3-0 in indoor environment.

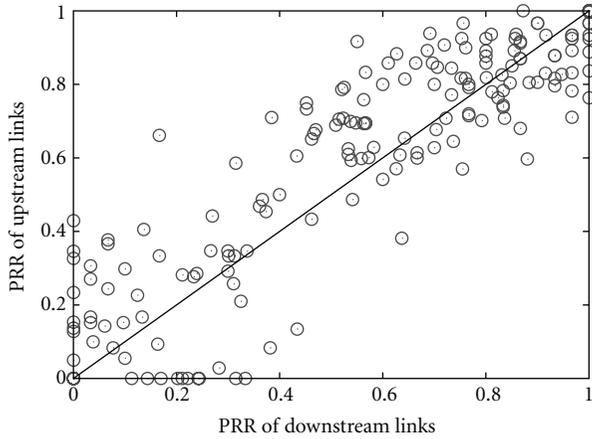


FIGURE 13: Downstream PRR versus upstream PRR for link 1-0 in outdoor environment.

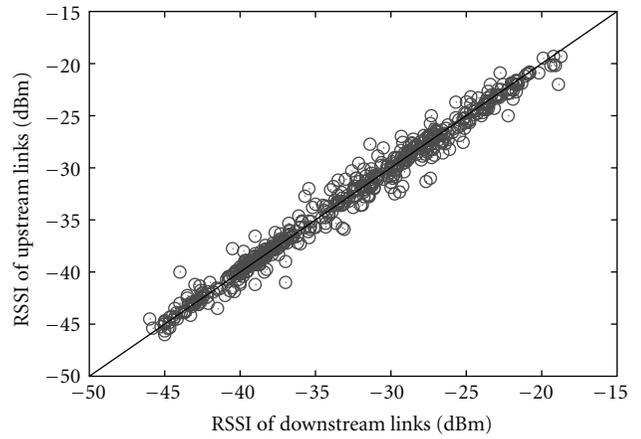


FIGURE 16: Downstream-link versus upstream-link RSSI for link 1-0 in indoor environment.

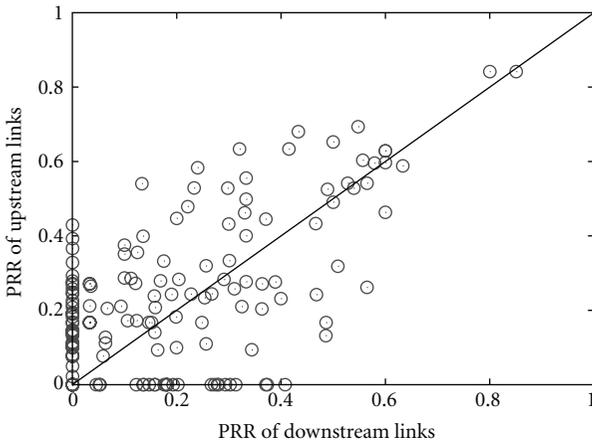


FIGURE 14: Downstream PRR versus upstream PRR for link 2-0 in outdoor environment.

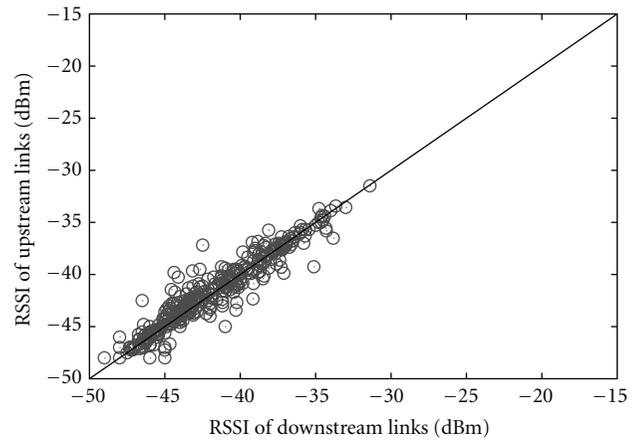


FIGURE 17: Downstream-link versus upstream-link RSSI for link 2-0 in indoor environment.

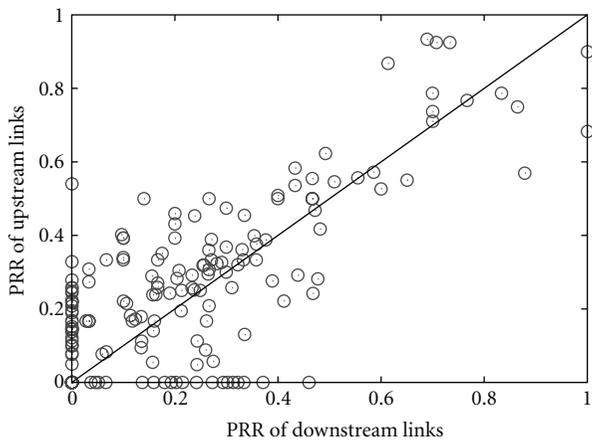


FIGURE 15: Downstream PRR versus upstream PRR for link 3-0 in outdoor environment.

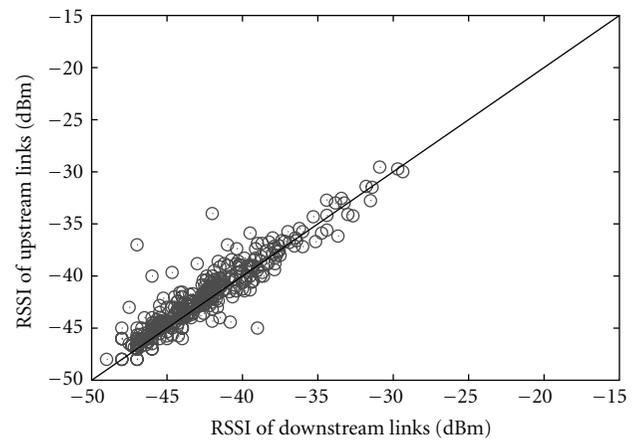


FIGURE 18: Downstream-link versus upstream-link RSSI for link 3-0 in indoor environment.

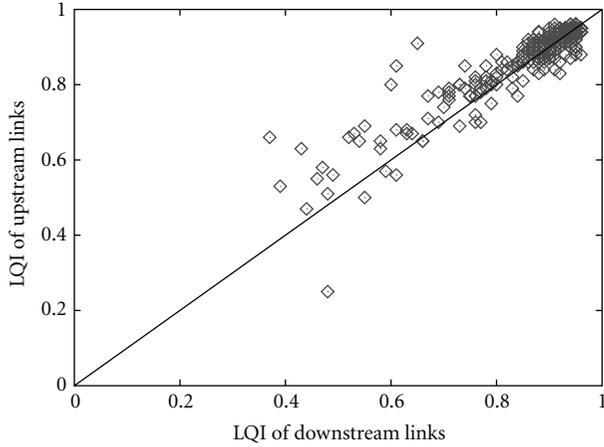


FIGURE 19: Downstream-link versus upstream-link LQI for link 3-0 in indoor environment.

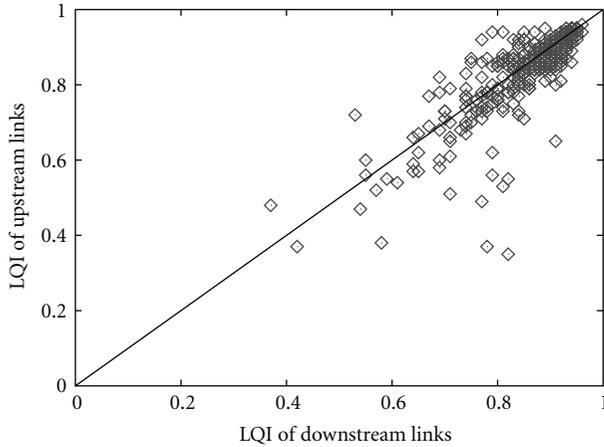


FIGURE 20: Downstream-link versus upstream-link LQI for link 3-0 in indoor environment.

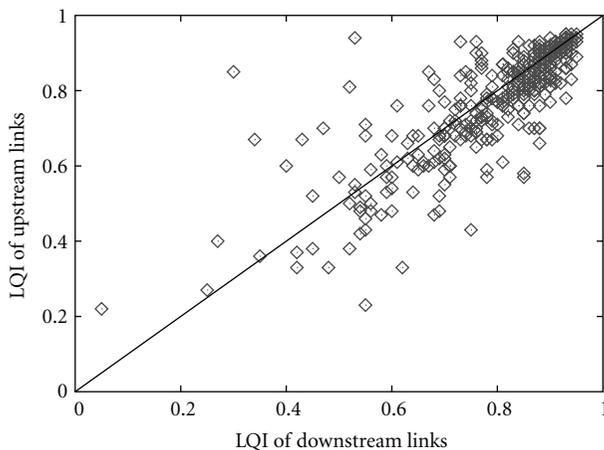


FIGURE 21: Downstream-link versus upstream-link LQI for link 3-0 in indoor environment.

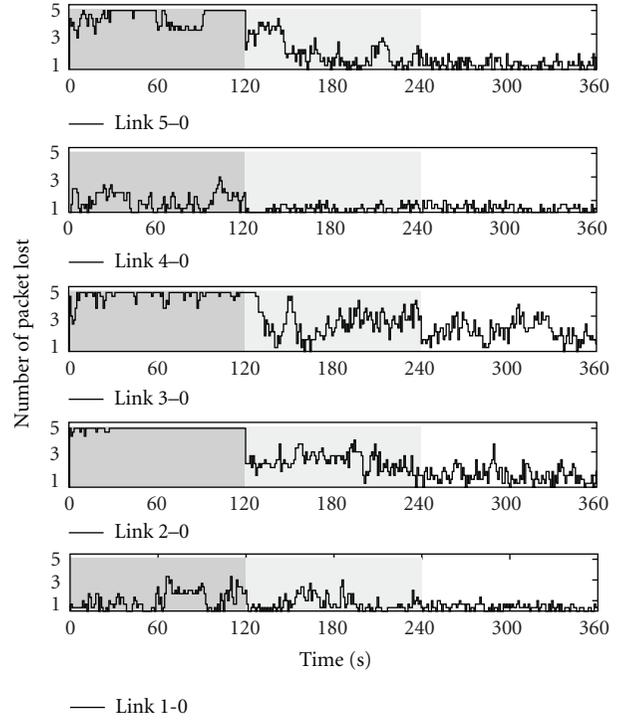


FIGURE 22: Loss of consecutive packets in indoor environment. Here, the packet loss is examined over deliveries within one second and as water-marked with distinct gray scales, each curve (link) experiences three incremental transmit powers (-15 dBm, -5 dBm, and 0 dBm from left to right) with time increasing.

8. Link Dynamics

The previous discussions in this paper focus on the average performance of PRR and other metrics. As we know the wireless link is highly time-varying, especially in BASN scenario where the body diffracts and absorbs the energy of radio wave, the movement and activity of body frequently lead to obstacles between two communicating nodes. Therefore, it is necessary to investigate the link throughput variation within a small time-scale, that is, understanding such dynamics of BASN links is very important to design protocols adaptive to highly link dynamics for real-time applications. This section attempts to present the time-varying link performance by examining the consecutive loss of packet over each link under two environments.

We consider only the loss event involving as least five consecutive packets. Note that our link is defined with two directions, and so the packet is treated to be lost (failed) if either its reception (over upstream link) or acknowledgement (over downstream link) cannot be performed correctly. Figure 22 compares the packet loss of five links for office environment. Links 2-0 and 5-0 lose more packets in a successive fashion than other links; links 1-0 and 4-0 are still better in reliability than other three links. In particular, link 2-0 nearly fails continuously in packet delivery with the transmit power less than -5 dBm, mainly because the radio signals are too weak to penetrate the body tissues with energy

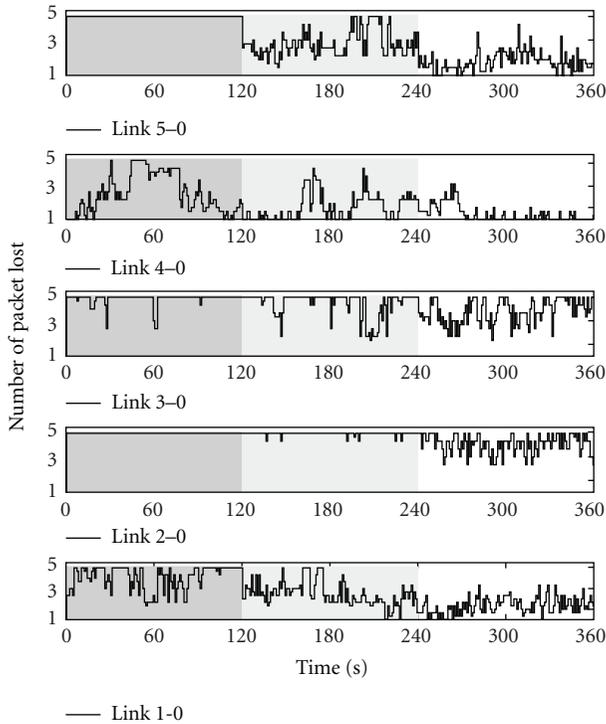


FIGURE 23: Loss of consecutive packets in outdoor environment. Here, the packet loss is examined over deliveries within one second and as water-marked with distinct gray scales, each curve (link) experiences three incremental transmit powers (-15 dBm, -5 dBm, and 0 dBm from left to right) with time increasing.

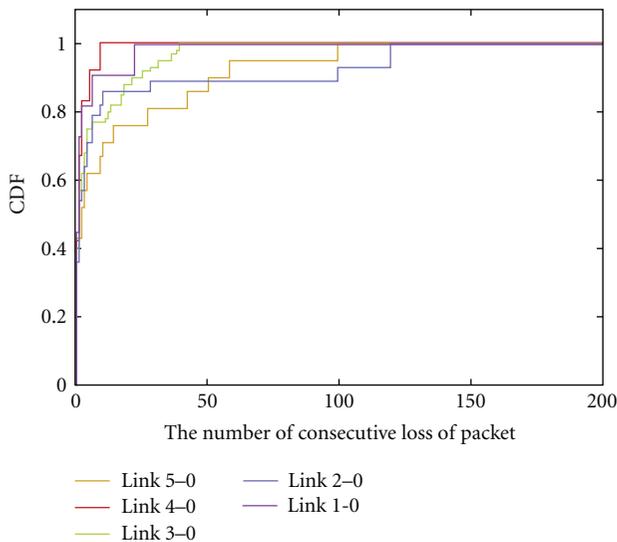


FIGURE 24: The CDF of the number of consecutive loss of five packets under indoor environment.

enough to be detected by receiver. From Figure 22 we can see that the links in BASN scenario vary significantly, even within a short period of time, say five seconds or less. On the other hand, it is still difficult, even for only one link, in modeling its dynamics under a given environment. We also observe that for -5 dBm case, all five links perform

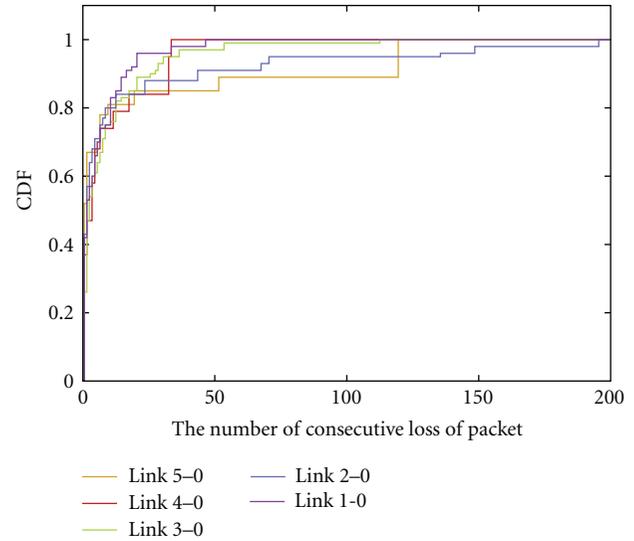


FIGURE 25: The CDF of the number of consecutive loss of five packets under outdoor environment.

differently with regards to packet delivery. So, in BASN application, it is necessary to take different actions (policies) from link to link if the throughput is what designers care about.

Figure 23 plots the packet loss of each link for outdoor case. Compared with the results in Figure 22, the packets over all links are harder to be delivered correctly when the subjects are outside of building. The outdoor environment is, in general, unable to provide much more reflective surfaces as the office environment does. By comparing Figure 2 and Figure 3 as well as comparing Figures 22 and 23, we find that with -5 dBm transmit power, link 2-0 can achieve a throughput of 60% for indoor case while it loses nearly all packets for outdoor case. Figures 24 and 25 show the CDF (\leq) of consecutive packet loss for two environments. This observation indicates the impact of surroundings and body tissues on the link throughput of BASN.

9. Performances of RSSI and LQI

Using a low-cost and easily calculating way to predict the link quality is one of the most important considerations for wireless application; estimating the link quality has become an enable function provided by radio chip. Two commonly used metrics for link quality are RSSI and LQI, both of which are of packet level and can be returned directly by the radio chip (e.g., CC2420)—what the application needs to acquire the two measurements is just reading the analog or digital channel. These two metrics are often used in low-power low-rate wireless sensor networks. In this section we evaluate both metrics to determine whether they are able to serve as desirable predictor for BASN link quality and which case they will work well in. And the results presented here are for links 1-0 and 3-0 in indoor environment.

We examine the correlation between the RSSI and the PRR over a period of time. Within the data-set, both are

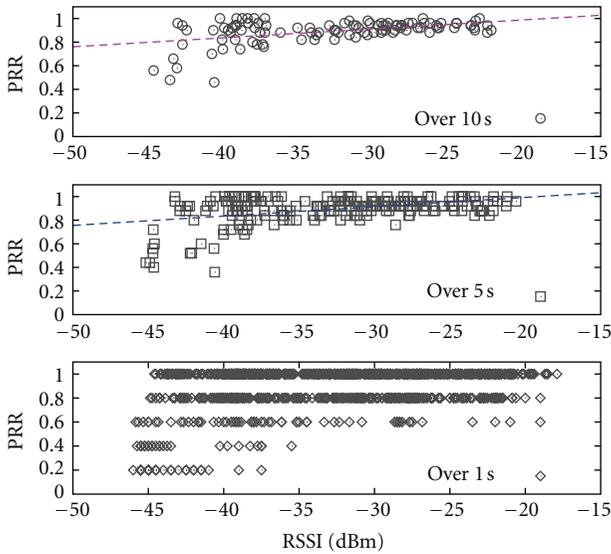


FIGURE 26: PRR versus RSSI over three time windows for link 1-0 in indoor environment.

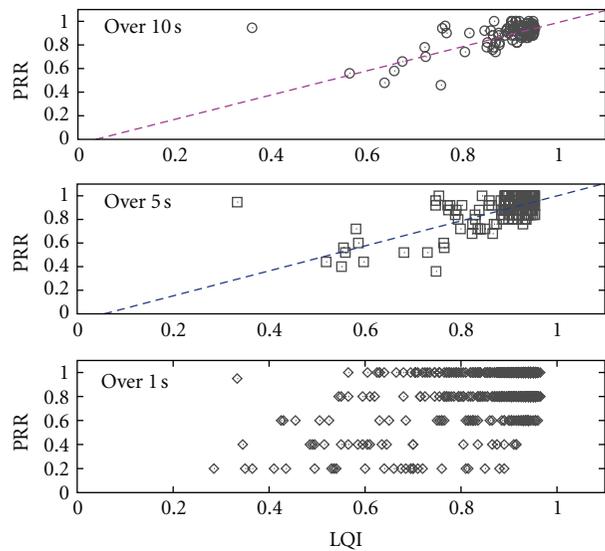


FIGURE 27: PRR versus LQI over three time windows for link 1-0 in indoor environment.

calculated over three time windows, respectively, one second, five seconds, and ten seconds. Figures 26 and 27 show the scatters of PRR of link 1-0 against its RSSI and LQI, respectively. It is clear that when examining the relation between the PRR and the RSSI (or LQI) using one-second time window, the scattering points diverge. When using ten-second time window, the PRR-RSSI relation can be well fitted with the least-square method provided the RSSI values are greater than -42 dBm; however, the PRR-LQI relation can be roughly modeled only when the LQI readings are greater than 0.87 (as shown in Figure 27). For link 1-0 whose two ends are mote 1 and the GW, the relative movement between both can be kept stably, but link 3-0 is shaped by diverse factors because the left wrist which mote 3 is attached to

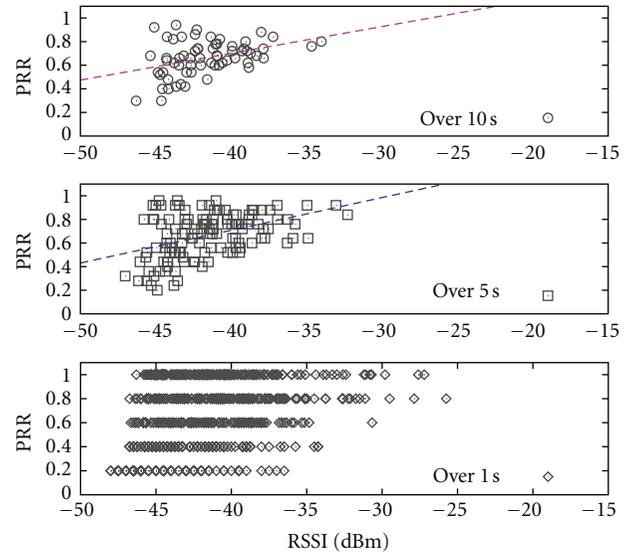


FIGURE 28: PRR versus RSSI over three time windows for link 3-0 in indoor environment.

is the most often used part of body in daily life. As can be seen from Figures 28 and 29, for link 3-0, its RSSI and LQI readings cannot reasonably predict the link quality within each of three time windows. Also, for other three links, the qualifications of their RSSI and LQI are not very useful also in predicting the link quality even based on the ten-second time window.

When our BASN runs outdoor, it is hard to find out any correlation between PRR and RSSI (as well as LQI). And the observations tell that for motes with more frequent movement, like motes 3 and 4, their RSSI and LQI measurements, even accumulated within ten seconds, are nearly useless for predicting future link quality because the body movement significantly impacts the path loss of channel and then on the RSSI measurement. In addition, the PRR measurements, though valuable with large time window, should be carefully considered in design because the long-term calculating PRR with intensive probe messages will waste bandwidth and energy significantly.

10. Conclusions and Future Work

We have investigated the characteristics of BASN links via extensive and realistic test-bed experiments and achieved a set of results insightful to BASN engineers. First, different mote placements lead to different link throughputs. Particularly, the link penetrating the body tissues might not to produce desirable PRR even with high transmit power. Second, the movement intensity of mote has not significant correlation with PRR and slightly impacts on PRR, and instead, the obstacles (nonline-of-sight), either from torso as well as limbs or from surroundings, play a critical role in link throughput. Third, the environment the BASN works in will largely affect the PRR, and, generally, the more reflective surfaces the BASN experiences, the more possibly the link throughput can be improved. Fourth, the BASN link is highly

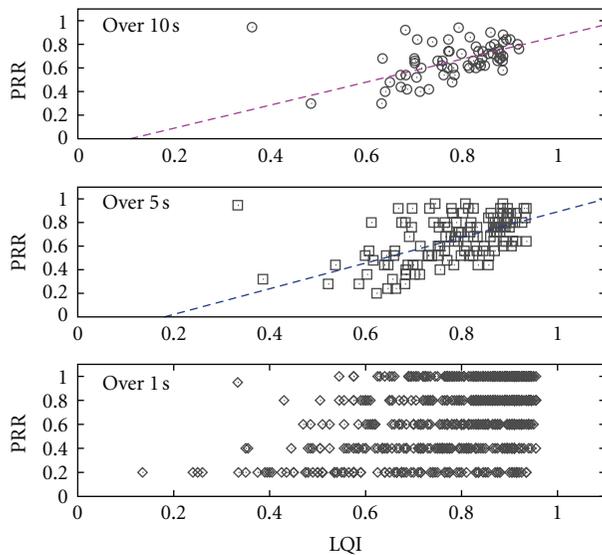


FIGURE 29: PRR versus LQI over three time windows for link 3–0 in indoor environment.

asymmetric in most of time, except the case in which the PRR for each direction is very high, say more than 90%. Fifth, the RSSI and the LQI both cannot serve as the desirable link predictor, especially when they are sampled in the outdoor. We believe that those observations and analyses would be helpful for designing practical BASN systems.

In the future we will further investigate the behaviors of BASN link with more environments and subjects. And we will focus on seeking for effective and efficient link metrics to realize more reliable delivery for BASN applications.

Acknowledgments

This work was supported, in part, by two NSFs of China with Grants no. 20111300702 and no. 51008098 and by the Fundamental Research Funds for the Central Universities of China with Grant no. BLX2012048.

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