Providing Reliable and Real-Time Delivery in the Presence of Body Shadowing in Breadcrumb Systems

HENGCHANG LIU, University of Science and Technology of China
PAN HUI, HKUST, Telekom Innovation Laboratories and Aalto University
ZHIHENG XIE and JINGYUAN LI, University of Virginia
DAVID SIU, OCEANIT Inc.
GANG ZHOU, College of William and Mary
LIUSHENG HUANG, University of Science and Technology of China
JOHN A. STANKOVIC, University of Virginia

The primary goal of breadcrumb trail sensor networks is to transmit in real-time users' physiological parameters that measure life-critical functions to an incident commander through reliable multihop communication. In applications using breadcrumb solutions, there are often many users working together, and this creates a well-known body shadowing effect (BSE). In this article, we first measure the characteristics of body shadowing for 2.4GHz sensor nodes. Our empirical results show that the body shadowing effect leads to severe packet loss and consequently very poor real-time performance. Then we develop a novel *Intentional Forwarding* solution. This solution accurately detects the shadowing mode and enables selected neighbors to forward data packets. Experimental results from a fully implemented testbed demonstrate that Intentional Forwarding is able to improve the end-to-end average packet delivery ratio (PDR) from 58% to 93% and worst-case PDR from 45% to 85%, and is able to meet soft real-time requirements even under severe body shadowing problems.

Categories and Subject Descriptors: C.2.2 [**Computer-Communication Networks**]: Network Protocols

General Terms: Design, Algorithms, Performance

Additional Key Words and Phrases: Breadcrumb systems, body shadowing effects, packet delivery ratio, real-time performance

ACM Reference Format:
Hengchang Liu, Pan Hui, Zhiheng Xie, Jingyuan Li, David Siu, Gang Zhou, Liusheng Huang, and John A. Stankovic. 2014. Providing reliable and real-time delivery in the presence of body shadowing in breadcrumb systems. ACM Trans. Embedd. Comput. Syst. 13, 4, Article 94 (February 2014), 24 pages.
DOI: http://dx.doi.org/10.1145/2557633

1. INTRODUCTION

Breadcrumb sensor networks, or breadcrumb systems, have been emerging in mission-critical application domains, such as firefighting [Souryal et al. 2007; Refaei et al.

This work was performed on a Phase II SBIR on Wireless Body Area Networks funded by the Science and Technology Directorate of the Department of Homeland Security. This work was also supported, in part, by NSF grants NSFC-U1301256, EECS-0901686, and CSR-0720640.
Authors' addresses: H. Liu (corresponding author) and L. Huang, Computer Science Department, University of Science and Technology of China; P. Hui, Hong Kong University of Science and Technology, Telekom Innovation Laboratories, and Aalto University; Z. Xie, J. Li, and J. A. Stankovic, Computer Science Department, University of Virginia; G. Zhou, Computer Science Department, College of William and Mary; D. Siu, OCEANIT Inc.; corresponding author's email: liu.heng.chang@gmail.com.

DOI: http://dx.doi.org/10.1145/2557633

2008; Liu et al. 2010, 2011, 2010b]. The primary goal of such sensor systems is to transmit users' physiological parameters that measure life-critical functions to an incident commander reliably and in real time. Challenges to achieving this goal include dealing with complicated indoor environments (e.g., stairways, consecutive corners, basements, and metal walls); users must completely focus on their rescue or search work, implying that alternative solutions such as manual deployments [Souryal et al. 2007] are not desirable; data must be received at command stations in a reasonable real-time manner; and when there are multiple users near each other, this creates body shadowing.

Nowadays, breadcrumb sensor network hardware is equipped with either 2.4GHz [Liu et al. 2010a, 2011] or 916MHz [Souryal et al. 2007] transceivers. Recent works [Oliveira et al. 2008; Krishnamurthy et al. 2005; Miluzzo et al. 2008; Quwaider et al. 2010; Silva et al. 2009] have shown that body shadowing causes significant problems with these frequencies, that is, both packet delivery ratio (PDR) and received signal strength (RSSI) are significantly affected. However, these studies mainly focus on single-body sensor networks in which the transmitter and the receiver are placed on the same human body. There is a lack of quantified measurements when the transmitter and receiver are further from each other, for example, on a firefighter and the ground or on different bodies. In addition, solutions proposed by the state of the art, such as retransmissions and delay-tolerant networking, do not meet the soft real-time requirements [Sha et al. 2006] of emergency response applications. Manual deployment by attaching new breadcrumbs on walls can lower the problem of body shadowing but not eliminate it, but this is not practical for mission-critical tasks, such as firefighting.

In this article, we first measure the characteristics of body shadowing on exfiltrating physiological data in breadcrumb sensor networks with various distances, number of users, and indoor environments. Our empirical results reveal that both PDR and RSSI are severely affected in all cases, and the communication quality becomes worse as the user density increases. Severe packet losses have been observed, that is, PDR at a 50-feet distance drops to as low as 14% in hallways and 12% in stairways when two users are blocking the line of sight transmission. Such performance fails to meet the reliability and real-time requirements of a breadcrumb sensor network.

We also evaluate the body shadowing effect on the deployed breadcrumb-to-breadcrumb communication, and the experimental results show the same trends. More concretely, the PDR at a 50-feet distance decreases from 94% to 69% and 8% when one and two users are standing between breadcrumbs, respectively. This result indicates that continuously deploying new breadcrumbs is not helpful when body shadowing is present, resulting in a waste of system resources.

Based on the empirical evaluation, we propose *Intentional Forwarding*, a novel solution for overcoming body shadowing. The benefits of Intentional Forwarding include improving the packet delivery ratio while maintaining real-time data delivery. The solution also maintains the completely automatic nature of the system. Note that the design philosophy of Intentional Forwarding is general enough to be applied to any safety-critical sensor network applications that function on multiple users, such as remote monitoring on patients in medical applications, but this is not addressed in this article.

The key technical ideas are to accurately detect that the system is experiencing a body shadowing effect and then temporally allow neighbors to help forward data packets. Simple but effective rules are adopted to make decisions on whether a body transmitter (called a dispenser) is shadowed or not. When a dispenser enters a shadowed state, data packets are temporally forwarded by a carefully selected neighbor. To avoid lost connections, we also propose a novel technique called *double assurance* to enable a deployment of a new breadcrumb, if necessary.

We fully implemented the Intentional Forwarding solution and evaluated it using a testbed including four dispensers and twenty breadcrumbs. Our experimental results with a 66-meter-long indoor trace demonstrate that (1) when four users walk together and close to each other, severe packet losses are experienced, the average PDR is 58%, and the worst-case PDR is only 45%. In addition, the range extension decreases nearly 40%. (2) Intentional Forwarding is able to improve the end-to-end data packet delivery ratio to 93%, and the worst-case PDR to 85%. It also increases the overall range extension by 10%. (3) The average data packet delivery time using Intentional Forwarding is 714 milliseconds for five hops, which indicates that it meets soft real-time data delivery requirements. Moreover, it maintains the completely automatic nature of the system, leaving users to focus on their important missions. For comparison purposes, we also evaluate a manually placed wall-based solution and a delay-tolerant networking (DTN) solution.

The remainder of this article is organized as follows. We compare our work with the state of the art in Section 2 and present the measurement of the body shadowing effect in Section 3. The Intentional Forwarding solution is explained in detail in Section 4 and evaluated in Section 5. Finally, we conclude in Section 6.

2. STATE OF THE ART

Breadcrumb sensor networks were proposed mainly due to the limited transmission range of one-hop communication used by first responders. One example system of this kind is the P25 system.[1] The drawbacks of this approach are mainly twofold. First, the P25 radio has a limited transmission range. Second, indoor environments often contain substantial amounts of metal and other reflective materials that affect the propagation of radio frequency signals in nontrivial ways, causing severe multipath effects, dead spots, noise, and interference [Halder and Kim 2011]. Therefore, users inevitably lose their connection to the remotely located base station as they climb up to top floors or enter the basement of buildings. Thus, they are likely to miss important commands from the base station, like retreat orders, and could possibly result in first-responder fatalities.

Souryal et al. first investigated the feasibility of dynamic breadcrumb deployment to extend the range of wireless communications based on stable PDR-RSSI mapping they observed in indoor environments and evaluated by experiments with Mica2 motes and a PDA [2007]. However, their work requires a first responder to manually place the node on the ground, which is impractical in real applications.

The first automatic systematic design was presented in Liu et al. [2010a] in which the solution includes a breadcrumb dispenser with an optimized link estimator to decide when to deploy breadcrumbs to maintain reliable wireless connectivity. In the breadcrumb system design we proposed in Liu et al. [2010a], each first responder carries m breadcrumbs in his breadcrumb dispenser and deploys one whenever connection to the breadcrumb chain is getting weak. As they run into the building, breadcrumbs are deployed automatically on the ground. Due to the harsh environment in which breadcrumbs may break or burn up, our deployment policy requires that each breadcrumb keeps "good communication" with at least two breadcrumbs at any time in order to have redundancies to tolerate physical failures. As the first responder moves on for rescue work, the link quality between the dispenser on the user and the breadcrumbs becomes weaker (red dashed lines in Figure 1 indicate those affected by body shadowing). The *link monitoring algorithm* is used to monitor the link quality and make decisions on when to deploy a new breadcrumb. After the new breadcrumb is deployed and joins the crumb chain, the link quality between this new crumb and its n neighbors may vary

[1] P25 projects. `http://www.project25.org/`.

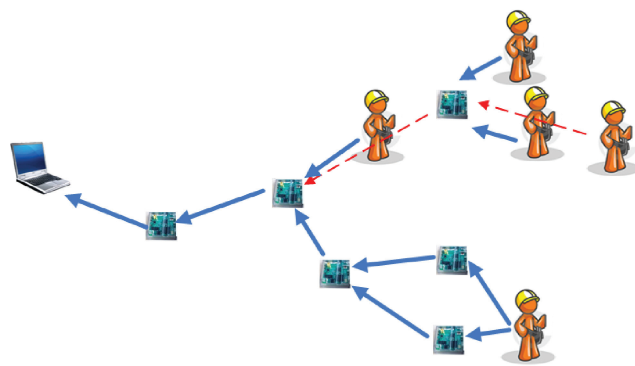

Fig. 1. Breadcrumb system illustration.

due to the dynamic impact from the environment. *Adaptive power control* enables it to adaptively adjust its transmission power according to real-time link quality estimation. The limitation of Liu et al. [2010a] mainly lies in that it only considered the scenario of a single first responder; therefore, opportunities and challenges brought by multiple users, including the body shadowing problem that we deal with in this article, was not addressed.

Other related work in breadcrumb sensor networks include dealing with WiFi external interference [Refaei et al. 2008], wireless link measurements [Wapf and Souryal 2009], group management [Liu et al. 2011a], and using delay-tolerant networking techniques when the users are disconnected [Liu et al. 2010b]. To the best of our knowledge, the important body shadowing problem in breadcrumb sensor networks has not been effectively addressed.

Existing work on body shadowing effects (BSE), in general, have focused on theoretical modeling and validation in ultra-wideband (UWB) networks [Ghaddar et al. 2007; Zhang et al. 2009; Zhang and Cai 2009]. Ghaddar et al. measured the BSE on the signal propagation of a fixed UWB link and revealed that the obstruction of a human body can introduce severe attenuation to the total received power by up to 8dB, which may interrupt the data transfer completely. Zhang and Cai proposed a packet-level UWB channel model for BSE using a Markov Chain Model [2009], and Zhang et al. [2009a] further extended it by considering more general cases where the distance between the transceivers can be arbitrary. However, all these works assume that both transceivers are static, which is not valid in breadcrumb sensor networks. In addition, the different physical-layer characteristics between UWB networks and platforms using 916MHz or 2.4GHz means that separate performance evaluation of the BSE should be conducted, as we do in this article.

There are also previous works on the single-body-based shadowing problems in ZigBee (2.4GHz) or 916MHz-based body sensor networks. In 2.4GHz-based systems, experimental results [Oliveira et al. 2008; Miluzzo et al. 2008; Quwaider et al. 2010] show that the body factor, which comprises the human body and where sensors are located on the body, has a significant effect on the performance of the communication systems. The human body can introduce attenuations of up to 26dBm. Sensor placement, body posture, and activities are all factors that matter. In 916MHz-based systems, Quwaider et al. presented extensive experimental results on how body postures, sensor orientations, and on-body obstructions affect RF link qualities using Mica2Dot motes[2] with

[2]http://webs.cs.berkeley.edu/tos/mica2.html.

a Chipcon SmartRF CC1000 radio chip[3] and the TinyOS platform [Levis et al. 2004]. Their results showed a peak-to-peak swing of 16dBm, and even within a given posture, there are some intraposture body movements that affect the on-body RF link qualities. Silva et al. show that interuser interference, including body shadowing and wireless interferences, reduces the packet delivery ratio by almost 35% in cases of eight or more high-rate networks operating in the same location [2009]. Different from these works, our article targets the scenario where the transmitter and receiver are far away from each other, ranging from 20 centimeters to more than 15 meters. Also, we measure how BSE changes with blocker positions, blocker density, and environmental factors.

Since wireless sensor networks sometimes require information processing in intermittently-connected networks, DTNs [Ho and Fall 2004] have been considered as an important overlapping field of research to breadcrumb systems. Selavo et al. built a sensor system to monitor the shrubs on Hog Island in the Atlantic Ocean, and data packets were temporally stored in a local buffer when the antenna connecting the mainland to the island was affected by the windy weather [2007]. In general, it is possible to use a similar approach by allowing users to store data packets when the communication link is weakened by body shadowing. However, such solutions do not meet real-time constraints. Other related works include those targeting cross-system interferences [Refaei et al. 2008; Liang et al. 2010], which may exist in breadcrumb systems when WiFi base stations are located near the on-fire building. Potential solutions for this problem include multichannel [Zhou et al. 2006; Liang and Terzis 2010] and cognitive radios [Yang et al. 2010]. However, these solutions cannot address the problem of physical interferences, since they rely on detection of wireless signal frequencies.

The main differentiators of our proposed system with all related work are in measuring and overcoming the BSE in the special breadcrumb sensor network settings. This work is of particular importance for the performance evaluation of ZigBee-based body sensor networks and the design of breadcrumb sensor networks.

3. CHARACTERIZING THE BSE

In this section, we present a series of experiments to quantify the impact of BSE on breadcrumb system deployment. The knowledge of when and how real-time system performance is affected is used to develop a set of compensation techniques that overcome body shadowing and improve the breadcrumb sensor network performance.

3.1. Methodology

Most previous work that has examined BSEs in wireless sensor networks has focused on a single-body characteristic, that is, the transmitter and the receiver are on different places on the same body. In contrast, we investigate a scenario in which the transmitter and the receiver are far away from each other and are blocked by one or more human beings.

Before presenting our new solution, we first examine how the packet delivery ratio and received signal strength are affected by blocker(s) standing in between a dispenser and breadcrumbs. Different distances between dispenser and breadcrumbs are tested in the hallways of a building. Second, we proceed to check whether BSE becomes more serious when more blockers present. Both stationary and mobile cases are considered. Third, we repeat the experiments in stairways to examine various indoor environments. Finally, we evaluate the BSE on breadcrumb-to-breadcrumb communication to see whether dropping new relay nodes helps or not in shadowed situations.

[3] `http://www.chipcon.com/files/CC1000Datasheet21.pdf`.

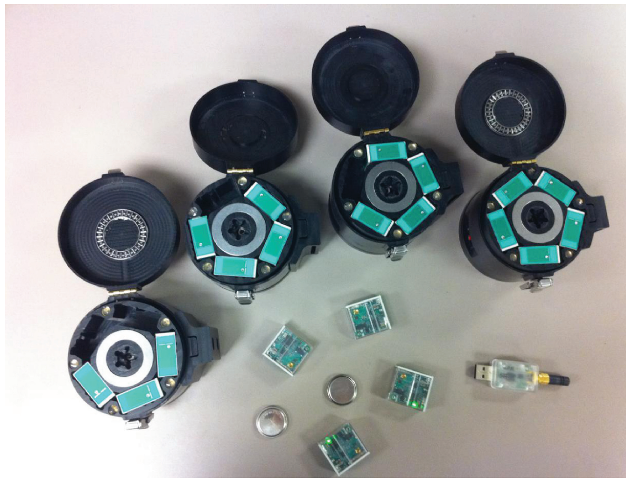

Fig. 2. Prototype including four dispensers, one base station, and twenty breadcrumbs.

3.2. Hardware

We use a 2.4GHz-based customized automatic deployment prototype (as shown in Figure 2) for our experiments. An automated dispenser (displayed at the top) can contain five quarter-size breadcrumbs. The reason breadcrumbs are designed to be square-shaped is that round nodes are more prone to roll around when dropped and lead to an unreliable breadcrumb chain. When the automatic decision support system determines it is time to deploy a new breadcrumb, the turntable rotates until one breadcrumb is dropped out from a hole at the bottom of the dispenser, which allows for fast and automated deployment in real time. The dispenser is powered by two AA-size batteries, and breadcrumbs are powered with a standard 3-volt, 560mAh lithium battery cell from Panasonic. The battery is capable of running each breadcrumb at full power for three hours. The dispenser and breadcrumbs can communicate with each other via their CC2430 series radio chip. Finally, data packets are sent back to the incident commander (an IBM T61 laptop) via a USB-ported base station (displayed at the bottom right).

3.3. Distance Factor

In the first group of experiments, we placed a breadcrumb in the hallway on the floor, and one user walked away slowly from the breadcrumb. Another user (without a dispenser) kept walking three feet behind him as a blocker of data packets at the dispenser side. A third user (also without a dispenser) stood three feet from the breadcrumb as a blocker at the breadcrumb site, acting as a second blocker. Ten data packets were sent from the dispenser to the breadcrumb per second, and an ACK packet was sent back for each packet. We recorded the PDR and RSSI for two-way directions between dispenser and breadcrumb, and the results are shown in Figure 3 to Figure 6.

First, we observe that there was always RSSI degradation for both-way communications, surprisingly as high as 20dBm at the point of 30 feet in Figure 3 and Figure 5, when both blockers were present. This result indicates that BSE introduces a large reduction in communication quality that thus may lead to an overbuilt breadcrumb chain with greater wireless interference and increased cost. In addition, the sharp decrease of RSSI implies that the threshold in the link monitoring algorithm may be affected, resulting in earlier deployments than expected and decreased overall range extension.

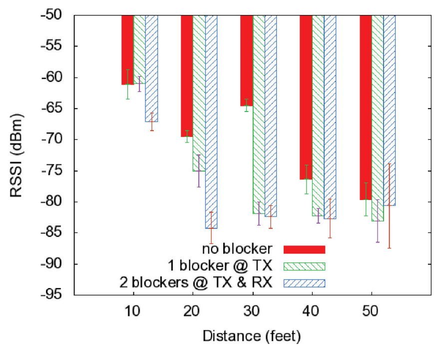

Fig. 3. RSSI (dispenser moving): from dispenser to breadcrumb.

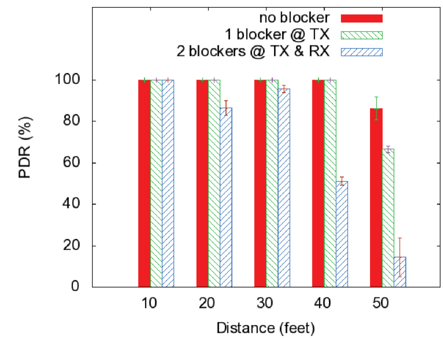

Fig. 4. PDR (dispenser moving): from dispenser to breadcrumb.

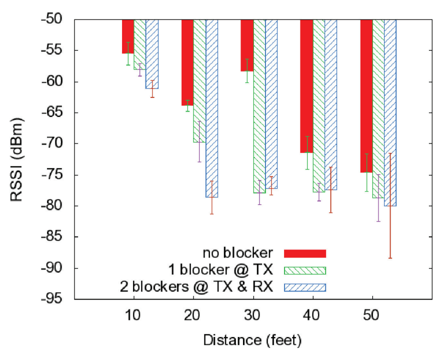

Fig. 5. RSSI (dispenser moving): from breadcrumb to dispenser.

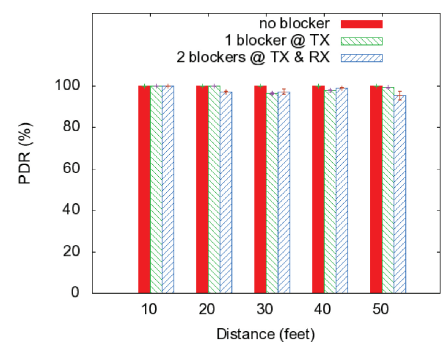

Fig. 6. PDR (dispenser moving): from breadcrumb to dispenser.

Second, we can see clearly from Figure 4 that packet loss becomes more severe as the number of blockers increases. When there are even only two blockers near the transmitter and receiver, there was only 14% PDR at the point of 50 feet, which is totally undesirable for this type of mission-critical system. Therefore, we must take steps to deliver packets in the presence of body shadowing.

Finally, we notice the asymmetry of wireless communications between the dispenser and breadcrumb. We can see from Figure 3 and Figure 5 that the RSSI from dispenser to breadcrumb is always 5dBm worse than in the opposite direction. Similarly, the PDR from dispenser to breadcrumb is much worse than the other direction, especially when they are far apart. This is mainly because the dispenser is more powerful in circuit design and power supply than the breadcrumbs. This must be taken into consideration for breadcrumb sensor network design for better reliability and efficiency.

3.4. Density Factor

In the second group of experiments, we fixed the user with the dispenser 30 feet from the breadcrumb (point with the largest link quality gap in the first experiment), and let at most four blockers move slowly between them for 60 seconds. The RSSI and PDR for both directions were recorded, and results are shown in Figure 7 and Figure 8, respectively.

We can observe from Figure 7 that as the number of blockers increases, the RSSI values for both directions decrease. For instance, the RSSI from dispenser to breadcrumb drops from -64 to -80 dBm when four blockers walked in between. This implies that

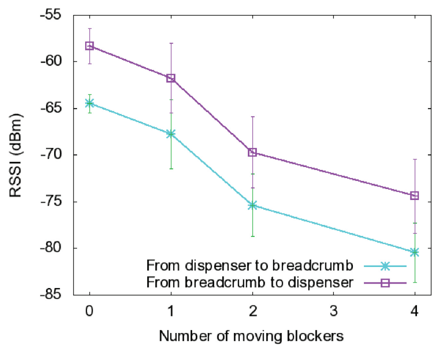

Fig. 7. RSSI (dispenser fixed and blockers moving).

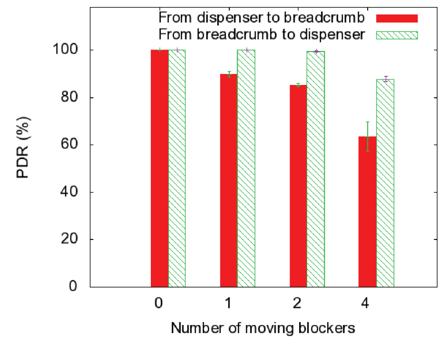

Fig. 8. PDR (dispenser fixed and blockers moving).

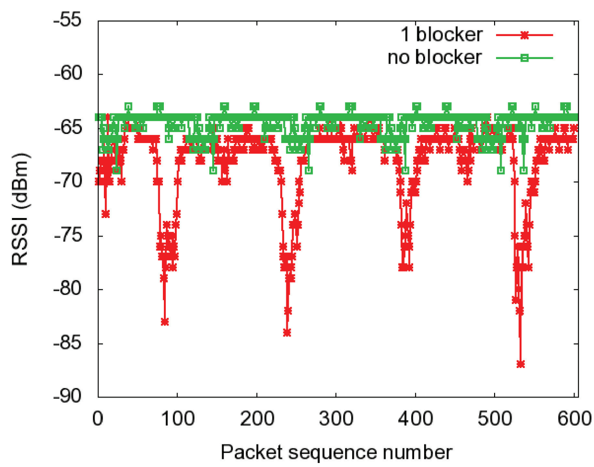

Fig. 9. Pattern of BSE for one blocker.

user density is an important factor for breadcrumb system design. Figure 8 shows a similar trend. For example, the packet reception ratios from dispenser to breadcrumb are 100%, 89%, 85%, and 63% when there are 0, 1, 2, and 4 blockers. Also packet loss becomes a big issue as more blockers show up, for example, the packet reception ratios for both ways are 63% and 87% for four blockers. These results indicate that the body shadowing effect does have a bigger impact on the communication quality in breadcrumb sensor networks as the number of user increases.

Finally, in Figure 9, we show the pattern of RSSI values from dispenser to breadcrumb when there is one blocker moving in between. We can clearly see the periodic RSSI drop when the blocker is close to either the transmitter or the receiver. Also note that the link is affected more when the blocker is near the receiver. This is mainly because he blocks most of the signal paths to the receiver. The difference is around 5dBm when the blocker is near the transmitter and 15dBm when the blocker is near the receiver.

3.5. Environment Factor

We next proceed to examine the body shadowing effect in different indoor environments. We repeated the first group of experiments in stairways. A breadcrumb was placed at the top of the stairs to an upper floor, and the user with dispenser and at most two

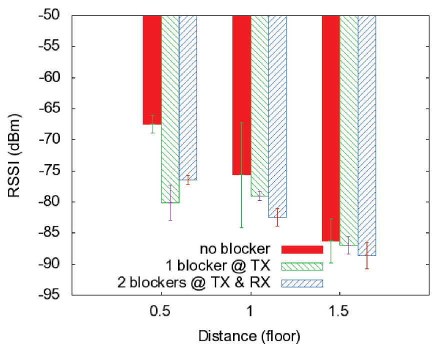

Fig. 10. RSSI (at stairway): From dispenser to breadcrumb.

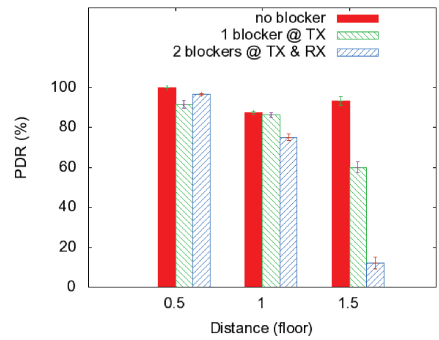

Fig. 11. PDR (at stairway): From dispenser to breadcrumb.

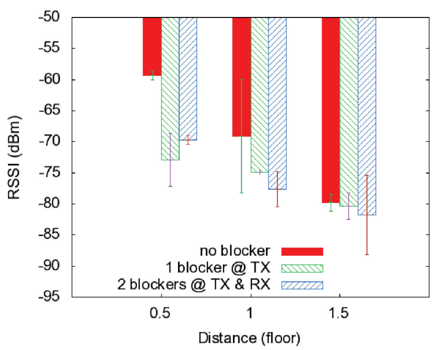

Fig. 12. RSSI (at stairway): From breadcrumb to dispenser.

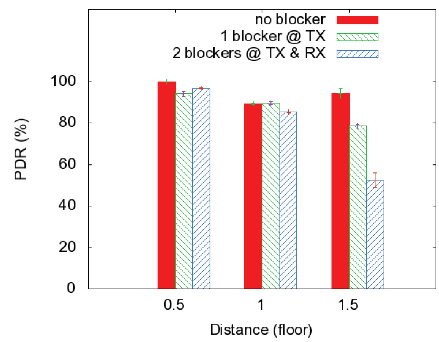

Fig. 13. PDR (at stairway): From breadcrumb to dispenser.

blockers stood downstairs. Link quality at the distance of half, one, and one and a half floors was measured. The relative positions of blockers are the same as in the previous experiments. Each experiment was repeated and 100 data packets were sent in each case. The results of PDR and RSSI are shown in Figure 10 to Figure 13.

We can see from the figures the same trends as in the experiments in the hallways. First, there was always RSSI degradation for both-way communications, which results in earlier deployments than expected and decreased overall range extension. Second, the communication link suffers from large packet losses with two blockers. The average packet delivery ratio at 1.5 floors is as low as 12% from dispenser to breadcrumb, and 53% in the other direction, while above 90% with no blockers. This result indicates that the BSE can result in total breadcrumb system failure when users are in the stairways.

The same results obtained from both hallways and stairways show that BSE can cause significant problems in indoor environments in terms of system reliability and efficiency. Even worse, our experiments in the next section show that body shadowing also significantly affects the breadcrumb-to-breadcrumb communication, which implies that even if a shadowed dispenser deploys a new relay node immediately, the generated data packets still cannot get through the breadcrumb chain.

3.6. Breadcrumb-to-Breadcrumb Communication

To evaluate the BSE on breadcrumb-to-breadcrumb communications, we deployed a breadcrumb chain with two breadcrumbs. One dispenser kept sending data packets

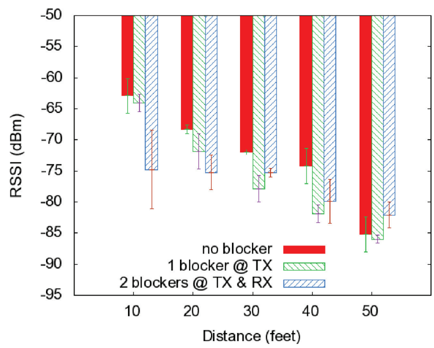

Fig. 14. RSSI: from breadcrumb to breadcrumb.

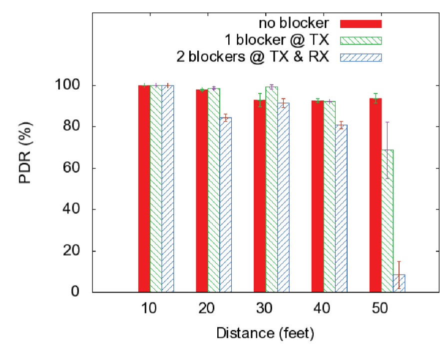

Fig. 15. PDR: from breadcrumb to breadcrumb.

to one breadcrumb, and the other breadcrumb forwarded these packets to the base station. At most two blockers stood in between these two breadcrumbs, and the RSSI and PDR were recorded with various distances between the breadcrumbs. The results are shown in Figure 14 and Figure 15.

We observe from Figure 14 that the RSSI is slightly affected with blockers, especially when the two breadcrumbs are close to each other. The result at 50 feet is interesting because the RSSI with two blockers is even better than those with zero and one blocker. This is mainly because only a few packets that have stronger link quality were received by the base station, and the signals of most packets were too weak to get through. From Figure 15, we can see that only 8% of the packets are received by the base station when two blockers stand there and 69% received with one blocker, while 94% of packets can be delivered to the base station with no blockers.

3.7. Summary

Our experimental results have shown that body shadowing indeed has a big impact on breadcrumb sensor networks in terms of packet delivery ratio and received signal strength. Severe packet losses have been observed in both hallways and stairways, and packet delivery ratio is as low as 14% in hallways and 12% in stairways while it is above 90% without body shadowing. The strength of received signals also decreases as much as 20dBm in hallways and 15dBm in stairways, resulting in earlier deployments determined by link monitoring algorithms. Even worse, newly deployed breadcrumbs are also shadowed, meaning links are still poor. Our results also show that body shadowing effects become more serious as the number of users increases. Therefore, breadcrumb sensor networks are problematic under multiple user situations, and some solution must be proposed to overcome the body shadowing effects. In the next section, we explain our Intentional Forwarding solution in detail.

4. INTENTIONAL FORWARDING

To overcome the body shadowing effects and based on the experimental results in Section 3, we designed and fully implemented a detection and recovery framework, called *Intentional Forwarding*. This solution consists of two individual components: *Detection* and *Reaction*. These components run on each dispenser to help monitor whether it is in the shadowing mode and to provide guidance on drop decisions and data transmission policies. To deal with the highly dynamic environment, we design the framework in a simple but effective fashion in order to avoid late decisions caused by sophisticated algorithms.

Type	*Shadowed*	*Fwding #*	*Id 1*	*Lq 1*	… … … … … …	*Id k*	*Lq k*

Fig. 16. Probing packet format.

4.1. Solution Overview

The *Detection* component detects that the system is experiencing a body shadowing effect. Real-time broadcasting for information sharing among dispensers is not desirable because the communication overhead is too large and may block normal data transmission. Based on this motivation, we propose a novel approach that leverages periodic probing packets as "information carriers". More concretely, we inject link quality information between dispensers and on-ground breadcrumbs into probing packets. By doing this, each dispenser periodically hears the messages sent from his neighbor dispensers and keeps a local table for updated information. Then simple but effective rules are adopted to determine whether this dispenser is in the shadowing mode at the current moment.

When the Detection component makes a decision that this dispenser is shadowed, the Reaction component is triggered. When the shadowed dispenser requires a new breadcrumb, the Reaction component carefully selects a blocker to temporally help forward data packets. The selection of neighbors takes relative position, shadowing information, and load balancing into account. To avoid lost connections, we propose a new technique called *double assurance* to enable deployment of a new breadcrumb, if necessary.

4.2. Detection Component

The Detection component running on each dispenser requires additional information from its neighbor dispensers, such as their current link quality, which breadcrumb(s) they are talking to, and whether they are shadowed or not. Therefore, communications among dispensers are indispensable to obtain sufficient information. However, broadcasting this information periodically brings extra burden to the network traffic which is already responsible for link monitoring, group management, and data transfer. In future applications for breadcrumb sensor networks, such as video/voice transmissions, the data rate is even higher, and only limited bandwidth is available. Based on this motivation, we propose an alternative solution that does not introduce additional traffic to the network. Instead, we leverage the probing packets that each dispenser sends out periodically in order to measure its current link quality to on-ground breadcrumb(s) and inject required information into them so that all neighbor dispensers can overhear and record locally.

Figure 16 shows the structure of modified probing packets. *Type* indicates that this packet is used as a probing packet. *Shadowed* is a binary number representing whether this dispenser is shadowed at this moment or not, and *Fwding #* indicates how many dispensers are now shadowed and using this dispenser as a relay. These two segments will be used in the Reaction component, as explained later. Finally, the (Id, Lq) pairs represent the identities and link qualities of breadcrumbs that this dispenser is now communicating with.

In addition, each dispenser keeps a local table, referred to as the *shadowing lookup table*, to store the information received from its neighbors. Each entry maintains a list of neighbor dispensers (together with the dispenser-breadcrumb link quality, *Shadowed*, and *Fwding #*) that share the same breadcrumb with this dispenser, and the link quality among them. If one dispenser in the list does not update its information for a while, it will be removed from the list. An example of this table is shown in Figure 17. Four users, $D1$, $D4$, $D5$, and $D7$, walk right, and three breadcrumbs, $B1$, $B6$, and $B9$, have been

ID	*LQ*	*List of Nbrs*	*B-D LQ*	*Shadowed*	*Fwding #*	*D-D LQ*
B1	-72	D7	-57	0	0	-74
B6	-81	D4	-82	1	0	-78
		D5	-66	0	1	-88
B9	-66	D4	-72	0	1	-78
		D5	-87	1	0	-88
		D7	-81	1	0	-74

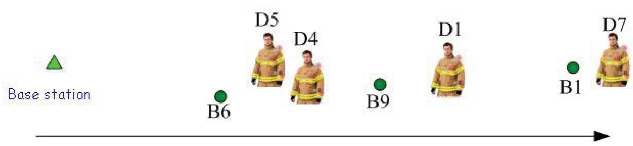

Fig. 17. Shadowing lookup table (for dispenser D_1).

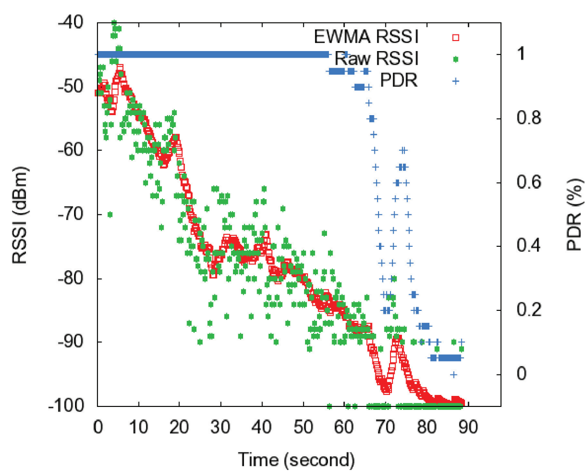

Fig. 18. *PDR* and filtered *RSSI* as time changes in an example trace.

deployed. At some point, user $D1$ collects information from the other three neighbors and stores it in his local shadowing lookup table. The first two columns in the table show that $D1$ can communicate to breadcrumbs $B1$, $B6$, and $B9$, and the link qualities are -72, -81, and -66 dBm, respectively. For each breadcrumb, a list of dispenser IDs is kept, indicating that they are currently communicating to this breadcrumb as well. The Shadowed and *Fwding #* columns are used later in the Reaction component.

We choose the exponentially-weighted moving average (EWMA) RSSI as the filtered link quality indicator. The reason being that it can provide approximately linear correlation between the link quality and the breadcrumb-dispenser distance. In an example trace shown in Figure 18, we placed a breadcrumb on the ground, and one user with a dispenser walked away from it until the link was disconnected. The real-time raw RSSI and PDR were recorded, and the EWMA RSSI was calculated. We observed a clear trend of an approximately linear EWMA curve as time goes on, thus it can provide estimations for relative positions that are required for body shadowing detection. The EWMA filter associates two parameters: current weighted value for RSSI Exp and weight coefficient β. Exp is updated when new data packets with RSSI value R arrive

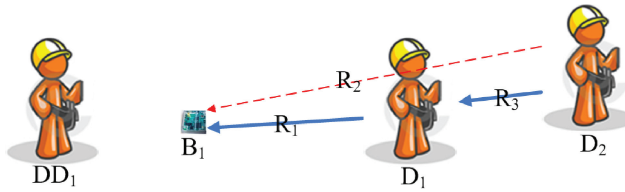

Fig. 19. Illustration of the detection algorithm.

using the following formula.

$$Exp = (1 - \beta) \cdot Exp + \beta \cdot R. \tag{1}$$

With the set of shadowing lookup tables and appropriate indicators of link quality, we proceed to design the detection approach. As shown in Figure 19, assuming that two firefighters wearing dispensers D_1 and D_2 walk together near a breadcrumb B_1, since the filtered link quality R_1 (between B_1 and D_1), R_2 (between B_1 and D_2), and R_3 (between D_1 and D_2) are available in the shadowing lookup table of dispensers, we can infer their relative positions using this information. For instance, a formula $R_2 < R_1$ indicates two possible positions of D_1: standing between B_1 and D_2, or at the other side of B_1, but with less distance than that between B_1 and D_2 (the position of DD_1). Then, a second formula $R_2 < R_3$ can eliminate the second possibility, and results in the case that D_1 stands between D_2 and B_1 as a blocker. Based on this analysis, the detection method we propose for body shadowing is set to the combination of the two formulas. Due to the fluctuation of wireless signals, we add a pair of thresholds, T_1 and T_2, to further compare the link qualities. The modified formulas are shown here:

$$R_1 - R_2 > T_1, \tag{2}$$

$$R_3 - R_2 > T_2. \tag{3}$$

T_1 can be measured by the fluctuation of the gap of filtered received signal strength. Figure 18 shows that the maximum difference of filtered received signal strength before PDR starts to drop is around 5dBm, at the point of 30 seconds. Thus, T_1 is set to 5dBm in later experiments. T_2 is mainly used to reflect the different receiving capabilities between dispenser and breadcrumb, and the signal gap introduced by different heights. We conducted a group of experiments to obtain this parameter. One user with a dispenser on his waist stood at the same place with a breadcrumb on the ground, and a second user moved at normal walking speed away from them until the links were disconnected. Data packets were sent periodically among them, and the received signal strengths were recorded. Figure 20 shows the results of the filtered RSSI in real time for three trials each in the hallway, corner, and stairway, respectively. We observe that the RSSI gap between the two curves in each trial is very consistent. Taking the average value in the region from the starting point to the −85 dBm threshold point, the RSSI gap is approximately 13dBm in the hallway, 8dBm in the corner, and 14dBm in the stairway. Thus we pick the highest value and set T_2 to 14dBm. For more details on the system parameters and their impact on the system performance, please refer to Liu [2011].

4.3. Reaction Component

When the Detection component determines that the dispenser is in shadowing mode, the Reaction component is triggered. It takes the body shadowing effect into account and maintains high packet reception ratio in the network. It enables a shadowed dispenser to temporally send its data packets to one of its blockers, acting as a forwarder,

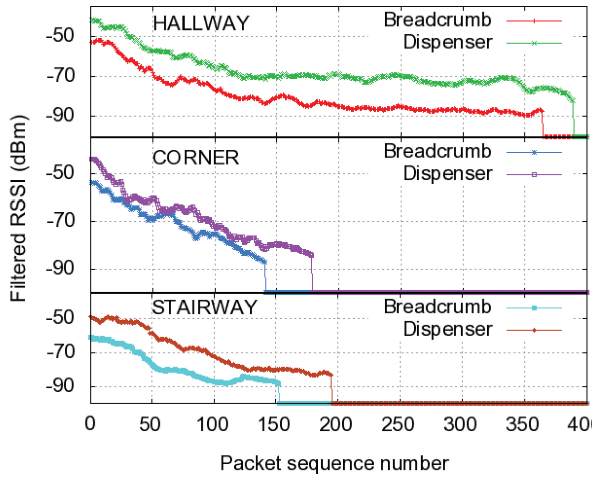

Fig. 20. Filtered RSSI values from a moving dispenser to an on-ground breadcrumb and hooked dispenser in an example trace (−100 dBm indicates disconnected links).

when this dispenser indicates a new deployment. Therefore, the communication stays reliable by splitting one weak link into two stronger ones.

The main reason we forward data packets instead of deploying new breadcrumbs is that our empirical results in Section 3.6 show the fact that new deployments are still shadowed and thus not helpful in surviving more data packets. Also, there is a chance the link quality may return to normal if the blocker walks away to another route or drops a new breadcrumb. Thus, by carefully setting up a timer, breadcrumbs are saved and better range extension is achieved. If the link quality increases above the threshold before the timer expires, the timer is canceled. Otherwise, a breadcrumb is dropped after the timer expires.

The length parameter of the timer is critical to the system performance. On the one hand, we want to maximize the period for better range extension. On the other hand, setting the time too long increases the risk of disconnection between the shadowed dispenser and the breadcrumb chain if users diverge at some point. Details of timer length selection are described later in this section.

The selection of the forwarder considers the following factors: whether the forwarder is shadowed itself, load balancing among blockers, and signal strength of communication links. First, if the forwarder is shadowed itself, then reliable communication cannot be guaranteed. Since multihop forwarding creates extra traffic overhead, delay time, and a need for sophisticated protocol design, we decided to let the system directly drop a new breadcrumb if all blockers are in the shadowing mode. The *Shadowed* column in the shadowing lookup table indicates whether each blocker is in the shadowing mode or not. Second, load balancing among blockers can decrease the risk of single-point failure and a communication bottleneck, thus increasing the system robustness. The *Fwding #* column in the shadowing lookup table shows the number of dispensers each blocker is now forwarding packets for. We always choose the one with the fewest numbers. Finally, if there are multiple blockers that satisfy the first two requirements, we pick the one with the best communication link quality for reliability considerations. The *Max-Min* approach is applied to the *B-D LQ* and *D-D LQ* columns in the shadowing lookup table, and the entry with the maximum minimal value will be selected.

Note that the Intentional Forwarding approach gets in trouble when the blocker follows the shadowed dispenser for a while (i.e., no breadcrumbs are deployed during this

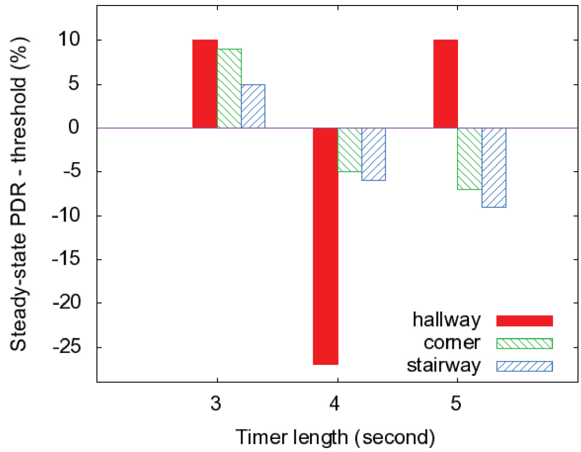

Fig. 21. Post-deployment PDR under varying timer lengths.

period), then changes to another route before the timer expires, leaving the dispenser with an unreliable or even disconnected link. This could happen because the timer is a static setting and cannot handle certain dynamic situations. To overcome this problem, we use an extra threshold, denoted by the double assurance threshold, to bind the breadcrumb, the blocker, and the shadowed dispenser. Whenever both the *B-D LQ* and *D-D LQ* values exceed the threshold, a new breadcrumb is deployed regardless of the timer.

Implementation of the Reaction component requires selecting values for the following parameters: the timer length (t) and the double assurance threshold (S_0). Now we present how these parameters were selected and the reasons behind the selections.

The value for the timer length t was selected after studying the performance of post-deployment wireless link reliability with the Intentional Forwarding algorithm for different timer lengths. For each trial, the shadowed dispenser was carried away from a fixed on-ground breadcrumb in a building environment at walking speed. When the dispenser gave the indication to deploy, the timer was triggered, and a new breadcrumb was deployed after the timer expired. A long sequence of packet transmissions was then initiated over the breadcrumb-to-breadcrumb link (with no blockers present) to measure the steady-state packet delivery ratio.

Figure 21 depicts the results of three separate trials for each of three timer length candidates, that is, three, four, and five seconds. Each trial has a different starting point and path in the hallway, corner, and stairway. Results are given in terms of the difference between the steady-state PDR and a predefined reliability threshold, chosen here to be $R_{th} = 90\%$. We observe that the packet delivery ratio is above the threshold in all trials when the timer is set to three seconds, and generally below the threshold in the other two cases. We also notice that the link was very unreliable (around 63% PDR) when the timer length was four seconds. This is mainly because the place of the new deployment was close to a drinking fountain, and the communication link was largely affected by the metal materials. Note that our system still works in a reliable way in these complex environments and only range extension is affected. The results indicate that we should choose three seconds as the timer length in later experiments.

We then examine the selection of the double assurance threshold S_0 value. The primary goal of S_0 is to provide dynamic support in real time for link reliability and to force a new deployment if the link becomes weak before the timer expires. Therefore, it is natural to select S_0 as the RSSI value in the situation that *B-D LQ* is equal to *D-D*

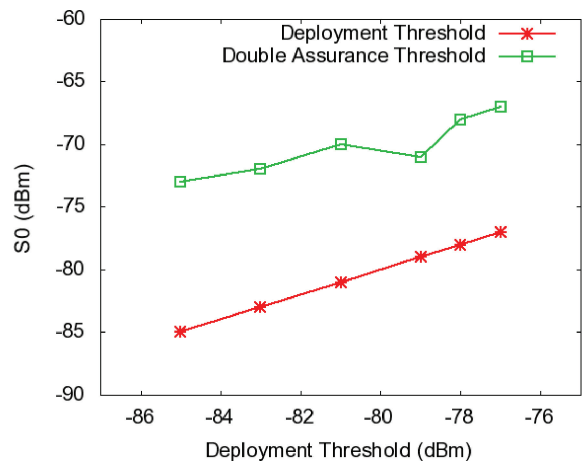

Fig. 22. Double assurance threshold under varying deployment thresholds.

LQ and the deployment threshold is exactly achieved. We fixed a breadcrumb (on the ground) and dispenser (carried by a user) and then move a second dispenser in between them to find the balance point. We measured the S_0 value under different deployment thresholds, ranging from -85dBm to -77dBm. For each threshold, five separate trials were conducted, each with a different starting point and path.

Figure 22 presents the results of the S_0 value for varying deployment thresholds. We select this range because it is the reasonable region for practical deployment threshold to establish reliable breadcrumb trails. We can see from the figure that, in most cases, S_0 increases uniformly as the deployment threshold grows, and the gap between them is around 10dBm. The clear correlation between them implies that the selection of S_0 can be based on the value of the deployment threshold. In later experiments, S_0 is chosen using this approach.

5. EVALUATION

In this section, we present extensive evaluation results on (1) how system reliability and efficiency are affected by body shadowing; (2) improvements made by Intentional Forwarding and compared to two alternative solutions: manual deployments by attaching breadcrumbs on the wall and delay tolerant networking; and (3) how Intentional Forwarding meets real-time requirements. For convenience, we use IF, MANUAL, and DTN for these three solutions, respectively. Before presenting the evaluation results in detail, we summarize them. Note that they are achieved using a testbed with four dispensers and twenty breadcrumbs. They are the following.

—While severe packet losses in multiple-user scenarios have been observed in the state of the art [Souryal et al. 2007; Liu et al. 2010a] that did not systematically address body shadowing, we specifically measure the shadowing effect and show that when four users walk together, IF is able to improve the end-to-end data packet delivery ratio from 58% to 93% and the worst-case PDR from 45% to 85%.

—MANUAL only improves the average and worst-case PDR to 78% and 65%, which implies that IF outperforms MANUAL in terms of system reliability. Moreover, IF maintains the completely automatic nature of the system, while MANUAL requires users involved in system establishment, which is not practical in mission-critical applications.

(a) Hallway. (b) Corner. (c) Stairway.

Fig. 23. Various indoor experimental environments.

—Although DTN achieves a comparable PDR to IF, it suffers from long delay for packets generated when the dispenser is shadowed and new breadcrumbs have not been deployed yet, and this delay time can be arbitrarily long due to indeterministic position and moving patterns of non-shadowed users. The average data packet delivery time using IF is 714 milliseconds for five hops, which indicates that it meets the real-time data delivery requirements.

5.1. Experimental Setup

We conducted all experiments in a university building using the customized prototype as described in Section 3.2. As shown in Figure 23, various indoor environments such as hallways, corners, and stairways are included in our experimental trace. The trace simulates a rescue path, starts in an entrance of the building on the second floor, and the rescue point is somewhere in the hallway of the basement. The total length of this trace is 65.89 meters. The experiments involve four users in total, denoted by A, B, C, and D. Each user has an automated dispenser hooked on his waist, and five breadcrumbs are contained in each dispenser. Users walk at normal walking speed and keep close to each other (within one meter) during each trial. We set the threshold for average PDR to 90% and end-to-end delivery time to 2 seconds.

As users walk along the predefined trace, breadcrumb trials are established and generated data packets are transmitted to the base station (placed at the entrance) through multihop communication. Each dispenser talks to at least two breadcrumbs at any time for redundancy purposes. Exponentially weighted moving average filter is adopted to guide when a new breadcrumb is needed, and the parameters are set to the optimal value that results in the least probability of dropping late while maintaining a low least squares value [Liu et al. 2010a]: the weight β is 0.0313 and the dropping threshold is -81.8dBm. For simplicity, the height effect is solved by a fixed offset of 10dBm, and the user with the most amount of remaining breadcrumbs deploys upon request for fairness purposes. Ties are broken by selecting the one with the smaller ID.

Breadcrumbs are attached with stickers in the MANUAL solution. Whenever a dispenser starts to vibrate and the inside turntable begins to rotate, the corresponding user puts his hand under the hole of the dispenser to hold the dropped breadcrumb and then quickly sticks it on the nearest wall, approximately at the same height as his waist. In the settings of the DTN solution, we use the same Detection component as used in the IF solution, but the Reaction component is not triggered. Instead, when a shadowed dispenser requires a new deployment, it temporarily stores the generated data packets in a local buffer until the body shadowing goes away or the communication link quality comes back to normal. In the DTN settings, only users that are not shadowed can deploy new breadcrumbs.

Along the trace, each dispenser sends out request messages periodically at the rate of ten packets per second in order to get responses from active breadcrumbs. Link quality information is then recorded according to the identity of breadcrumbs. Physiological data are sent from the dispensers to active breadcrumbs at the rate of two packets per second to mimic the results of processing. For performance analysis purposes, in each data packet, we include information such as time stamp and source node ID. Upon receiving the data packet, the intermediate breadcrumbs record this information in their own flash memory. ZigBee techniques[4] are used for the networking-layer protocol during the experiments. To eliminate the effect of random noise, experiments were repeated three times when evaluating the reliability, efficiency, and delivery time of candidate solutions. Unless stated otherwise, we used the previous default values in all the experiments.

5.2. PDR

The most important metric for measuring design in a breadcrumb sensor network is system reliability. In our work, this metric is characterized by observing the packet delivery ratio sent by users when they walk through the predefined trace described in Section 5.1. When there are multiple users, packer delivery ratios are recorded separately to obtain the average, best-case, and worst-case values.

To investigate how system reliability is affected by body shadowing and the performance of candidate solutions, two groups of indoor experiments were conducted. First, various numbers of users walked through the predefined indoor experimental trace, ranging from one to four. Experiments in each case were repeated three times, and the end-to-end PDR for each user in the whole period was recorded by attaching sequence numbers to data packets. Second, four users walk through the trace with candidate solutions. Three solutions, MANUAL, IF, and DTN, were applied separately in different experimental trials under the same settings.

Figure 24 and Figure 25 depict the PDR values with varying numbers of users in each of the three trials. We can observe that the average PDR decreases from 97% to 58% as the number of users increases from one to four. This severe packet loss indicates that systems designed for one user, as in the state of the art [Souryal et al. 2007; Liu et al. 2010a], do not work for multiple-user scenarios. We also notice that the average worst-case PDR for four users is only 45%, which results in total system reliability failure. We can clearly see from Figure 25, the effect of body shadowing. The best-case PDR stays high as the number of users increases, that is, 97%, 91%, 90%, and 88%, respectively, but the average and worst-case values decrease a lot. These results imply that systems without considering solutions for body shadowing will meet serious trouble in practice.

Figure 26 and Figure 27 show the average and worst-case PDR using various candidate solutions. For comparison, we added the cases of one user and four users in the previous experiment, denoted by "Single" and "Baseline", respectively. We can see that the MANUAL, IF, and DTN solutions increase the average and worst-case PDR to 78% and 65%, 93% and 85%, 92% and 84%, respectively. The reasons IF and DTN outperform MANUAL are that sticking relay nodes on walls can enlarge the angle of line-in-the-sight regions but cannot completely remove the possibility of body shadowing. Therefore, MANUAL improves the system reliability a bit but still not good

[4]`http://www.zigbee.org`.

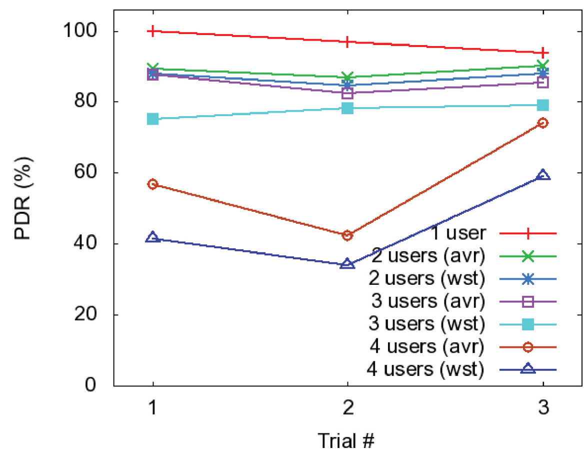

Fig. 24. PDR with varying numbers of users.

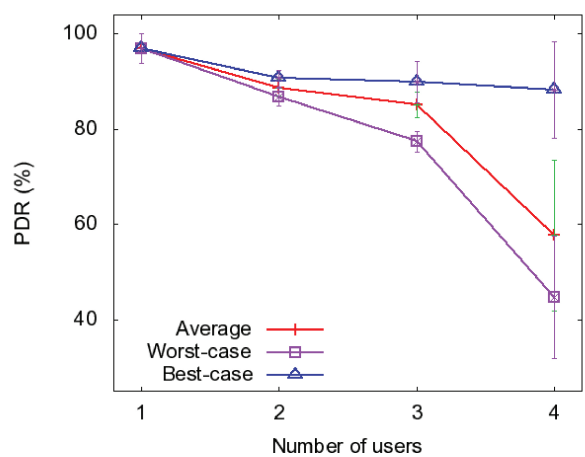

Fig. 25. Average, best-case, and worst-case PDR with varying number of users.

enough. In contrast, IF and DTN rely on accurate detection of body shadowing and then either forward packets to another user with better link quality or save them until the good link returns. So their overall reliability performance is better than MANUAL. Especially, IF improves the average PDR by 62% and worst-case PDR by 90%. Moreover, IF outperforms DTN by resulting in less standard deviations than DTN for both average and worst-case scenarios.

5.3. Providing Real-Time Delivery

We next compare the performance of IF and DTN in terms of meeting soft real-time delivery requirements. As described in Section 5.1, the real-time metric is represented by the end-to-end delivery time of data packets. Two users walked through the trace, and ten data packets were sent per second. We recorded the time stamps when each packet was generated and when it arrived at the base station. In addition, we synchronized the base station with each dispenser when the system was initiated by calculating the offset of system clocks. Since each dispenser talks to two breadcrumbs at any time, the maximum number of hops is five. IF and DTN were evaluated separately, and the

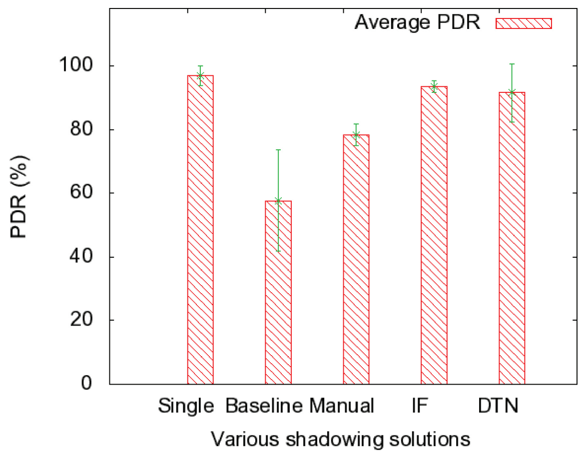

Fig. 26. Comparison of various body shadowing solutions: average PDR.

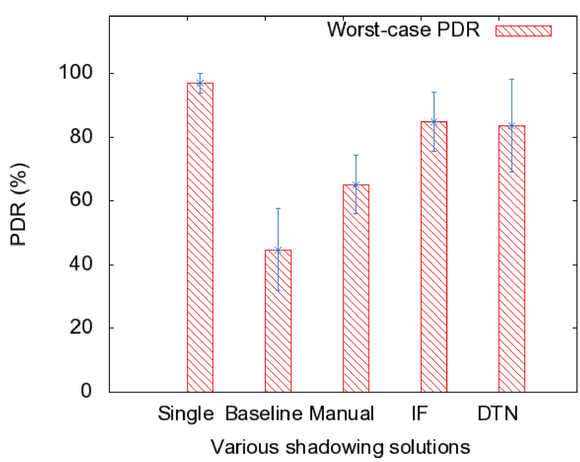

Fig. 27. Comparison of various body shadowing solutions: worst-case PDR.

results are shown in units of milliseconds. When using DTN, a shadowed dispenser starts to store data packets locally when its link monitoring algorithm decides for a new deployment, and offloads them when its link quality goes back to normal or a new breadcrumb requested by a non-shadowed user is deployed. The offloading rate is set to the same as packet transmission rate in order to avoid packet loss caused by bursty traffic, while still reflecting the delay for end-to-end delivery time.

Figure 28 shows the results of a user's end-to-end packet delivery time for the first twenty seconds in one trial. We can see that IF results in a low packet delivery time; less than 300 milliseconds for all two hundred packets. On the other hand, DTN suffers from long delay for packets generated when the dispenser is shadowed and new breadcrumbs have not been deployed yet, and this delay time can be arbitrarily long due to indeterministic position and moving patterns of non-shadowed users. This result indicates that DTN cannot meet real-time requirements. Also, note that the delivery time increases slightly even for the same hop number; this is caused by the extra time at the receiver side dealing with other network traffic, such as the probing and group management packets.

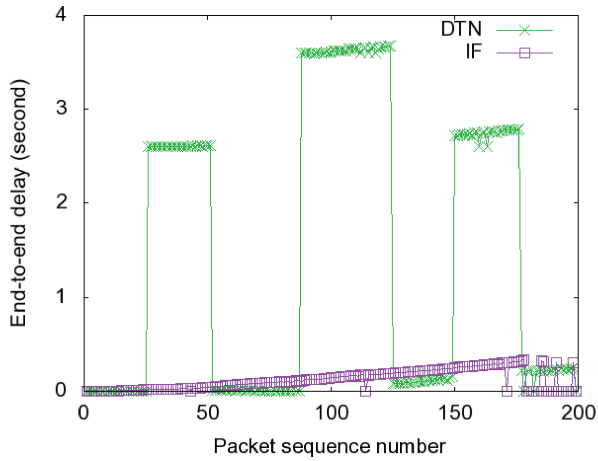

Fig. 28. End-to-end delivery time using IF and DTN in an example trial.

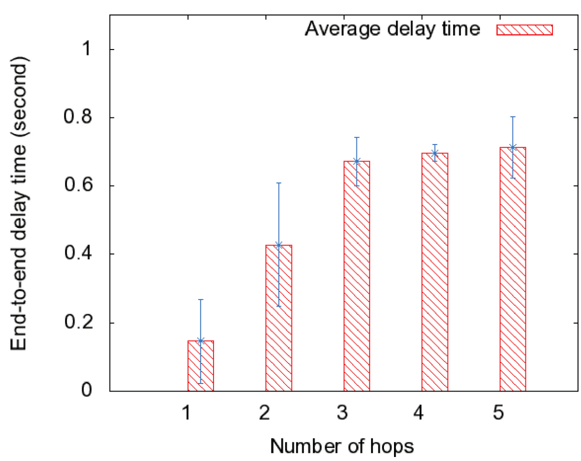

Fig. 29. End-to-end delivery time with varying number of hops.

Figure 29 presents the average delivery time with standard deviation using IF for a varying number of hops. We observe that the average delivery time increases as the hop number goes up, from 146 milliseconds with one hop to 714 milliseconds with five hops. In addition, the rate increases more slowly with more hops. Based on the result, we can infer that when there are ten users and in total 50 breadcrumbs, the worst case for end-to-end delivery time through 25 hops is still within four seconds.

5.4. Range Extension

We also observed in the preceding experiments that IF was able to increase the overall range-extension distance. Although system efficiency is not as important as other metrics like reliability and real-time delivery in such safety-critical applications, we argue that it is still worthwhile to evaluate the system efficiency, especially given that hardware design is far from perfect (i.e., cheap, tiny, and solid) nowadays. In this section, we first examine how body shadowing affects the range extension, and then compare IF to MANUAL and DTN in terms of improving the system efficiency while body shadowing exists in the network.

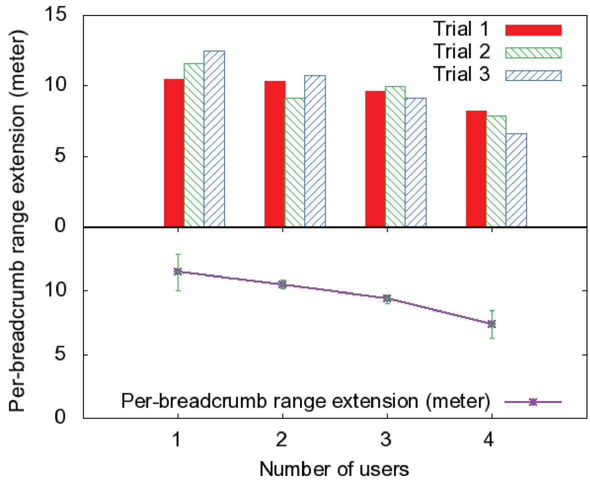

Fig. 30. Per-breadcrumb range extension with varying number of users.

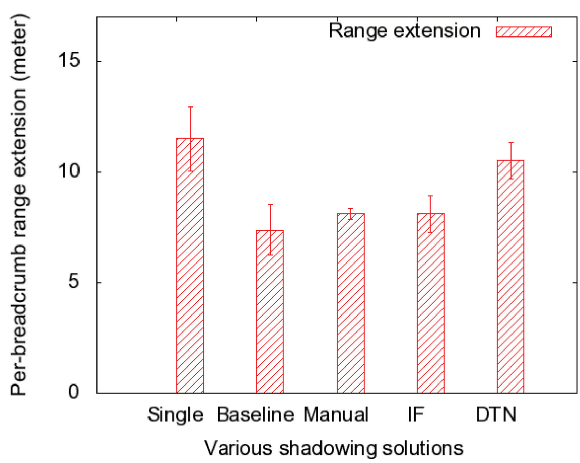

Fig. 31. Comparison of various body shadowing solutions: range extension.

Figure 30 presents the per-breadcrumb range-extension distance with varying numbers of users, ranging from one to four. Users walked through the trace defined in Section 5.1, and the positions of deployments were recorded. Each case was repeated three times, and the results are displayed using bargraphs as well as the average values with the standard deviation.

We can clearly observe that body shadowing without any solutions indeed affects the system efficiency. More concretely, the average range extension drops from 11.49 to 10.52, 9.38, and 7.38 meters, when there are one, two, three, and four users, respectively. This results in a nearly 40% decrease of system efficiency, which implies that 1.67x breadcrumbs are needed to cover the same trace.

Figure 31 shows the per-breadcrumb range-extension distance with various shadowing solutions. We observe that solutions MANUAL, IF, and DTN increase the range extension to 8.11, 8.11, and 10.51 meters on average. The reason that DTN perform better than MANUAL and IF is as follows. As mentioned in Section 5.2, sticking relay nodes on walls cannot completely eliminate body shadowing, thus the RSSI values are still affected, and deployments are earlier than expected. IF results in 10% better than the baseline case in terms of range extension, which is impressive for use in practice. The reason IF does not achieve the range extension in the single-user case is that we set the double assurance thresholds to force new deployments in dynamic environments. This trade-off is necessary because reliability is a much more important goal than efficiency in such applications.

6. CONCLUSIONS

Breadcrumb sensor networks have been emerging in mission-critical application domains, such as firefighting. In this article, we have measured the serious body shadowing problem through extensive empirical results for 2.4GHz sensor nodes and have introduced a novel Intentional Forwarding approach. Its benefits include improving the packet delivery ratio while maintaining real-time data delivery. The solution also maintains the completely automatic nature of the system. Evaluation results indicate that our proposed solution is able to improve the end-to-end data packet delivery ratio from 58% to 93% and the worst-case PDR from 45% to 85%, and can meet real-time requirements even under severe body shadowing problems. Additionally, it extends the overall coverage distance by 10%.

REFERENCES

K. Fall. 2003. A delay-tolerant network architecture for challenged internets. In *Proceedings of the ACM Conference on Applications, Architectures, and Protocols for Computer Communication (SIGCOMM)*.

M. Ghaddar, L. Talbi, and T. Denidni. 2007. A conducting cylinder for modeling human body presence in indoor propagation channel. *IEEE Trans. Antennas Propagation* 55, 11.

S. Halder and W. Kim. 2011. Adaptive filtering for indoor localization using Zigbee RSSI and LQI measurement. *IEEE Trans. Syst. Man Cybernet.*

M. Ho and K. Fall. 2004. Poster: Delay tolerant networking for sensor networks. In *Proceedings of the IEEE Conference on Sensor and Ad Hoc Communications and Networks (SECON)*.

L. Krishnamurthy, R. Adler, P. Buonadonna, J. Chhabra, M. Flanigan, N. Kushalnagar, L. Nachman, and M. Yarvis. 2005. Design and deployment of industrial sensor networks: Experiences from a semiconductor plant and the North Sea. In *Proceedings of the ACM SenSys.*

P. Levis, S. Madden, D. Gay, J. Polastre, R. Szewczyk, A. Woo, E. Brewer, and D. Culler. 2004. The emergence of networking abstractions and techniques in TinyOS. In *Proceedings of the 1st USENIX/ACM Symposium on Networked Systems Design and Implementation (NSDI)*.

C. Liang, N. Priyantha, J. Liu, and A. Terzis. 2010. Surviving Wi-Fi interference in low power ZigBee networks. In *Proceedings of the 8th ACM Conference on Embedded Networked Sensor Systems (SenSys)*.

C. M. Liang and A. Terzis. 2010. Rethinking multi-channel protocols in wireless sensor networks. In *Proceedings of the 6th Workshop on Hot Topics in Embedded Networked Sensors (HotEmNets)*.

H. Liu, J. Li, Z. Xie, S. Lin, K. Whitehouse, D. Siu, and J. A. Stankovic. 2010a. Automatic and robust breadcrumb system deployment for indoor firefighter applications. In *MobiSys*.

H. Liu, Z. Xie, J. Li, S. Lin, K. Whitehouse, D. Siu, and J. A. Stankovic. 2011. Efficient and reliable breadcrumb systems via coordination among multiple first responders. In *Proceedings of IEEE PIMRC*.

H. Liu, A. Srinivasan, Y. Chen, K. Whitehouse, and J. A. Stankovic. 2010b. Melange: Supporting heterogeneous QoS requirements in delay tolerant sensor networks. In *Proceedings of IEEE INSS*.

H. Liu. 2011. Design and implementation of an automatic, reliable, and efficient breadcrumb sensor network. Ph.D. Dissertation, University of Virginia.

E. Miluzzo, X. Zheng, K. Fodor, and A. T. Campbell. 2008. Radio characterization of 15.4 and its impact on the design of mobile sensor networks. In *Proceedings of EWSN*.

C. Oliveira, L. Pedrosa, and R. Rocha. 2008. Characterizing on-body wireless sensor networks. In *Proceedings of IEEE NTMS*.

M. Quwaider, J. Rao, and S. Biswas. 2010. Transmission power assignment with postural position inference for on-body wireless communication links. *ACM Trans. Embed. Comput. Syst.*

M. Refaei, N. Moayeri, and M. Souryal. 2008. Interference avoidance in rapidly deployed wireless ad hoc incident area networks. In *Proceedings of IEEE MCN*.

L. Selavo, A. Wood, Q. Cao, T. Sookoor, H. Liu, A. Srinivasan, Y. Wu, W. Kang, J. Stankovic, D. Young, and J. Porter. 2007. LUSTER: Wireless sensor network for environmental research. In *Proceedings of the 5th ACM Conference on Embedded Networked Sensor Systems (SenSys)*.

K. Sha, W. Shi, and O. Watkins. 2006. Using wireless sensor networks for fire rescue applications: Requirements and challenges. In *Proceedings of the IEEE Conference on Electro/Information Technology*.

B. Silva, A. Natarajan, and M. Motani. 2009. Inter-user interference in body sensor networks: Preliminary investigation and an infrastructure-based solution. In *Proceedings of the 6th International Workshop on Wearable Sensor Networks*.

M. R. Souryal, J. Geissbuehler, L. E. Miller, and N. Moazeri. 2007. Real-time deployment of multihop relays for range extension. In *Proceedings of ACM MobiSys*.

A. Wapf and M. R. Souryal. 2009. Measuring indoor mobile wireless link quality. In *Proceedings of ICC*.

Z. Xie, M. Hong, H. Liu, J. Li, K. Zhu, K. Whitehouse, and J. Stankovic. 2011. Quantitative uncertainty-based incremental localization and anchor selection in wireless sensor networks. In *Proceedings of MSWiM*.

L. Yang, B. Y. Zhao, and H. Zheng. 2010. The spaces between us: Setting and maintaining boundaries in wireless spectrum access. In *Proceedings of the ACM 16th Annual International Conference on Mobile Computing and Networking (MobiCom)*.

R. Zhang, L. Cai, S. He, X. Dong, and J. Pan. 2009. Modeling, validation, and evaluation of body shadowing effect in UWB networks. *Phy. Commun.* 2, 4, 237–247.

R. Zhang and L. Cai. 2009. A packet-level model for UWB channel with people shadowing process based on angular spectrum analysis. *IEEE Trans. Wirel. Commun*.

G. Zhou, C. Huang, T. Yan, T. He, J. A. Stankovic, and T. F. Abdelzaher. 2006. MMSN: Multi-frequency media access control for wireless sensor networks. In *Proceedings of the 25th IEEE Conference on Computer Communications (INFOCOM)*.

Received December 2012; revised July 2013; accepted November 2013