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

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***Abstract*—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 paper, we first measure the characteristics of body shadowing for 2.4 GHz 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 meet soft real-time requirements even under severe body shadowing problems.**

***Keywords*-breadcrumb systems; body shadowing effects; packet delivery ratio; real-time performance.**

I. Introduction

Breadcrumb sensor networks, or breadcrumb systems, have been emerging in mission critical application domains such as firefighting [17], [14], [7], [8], [9]. 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 [17] are not desirable; data must be received at command stations in 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 2.4 GHz [7], [8] or 916 MHz [17] transceivers. Recent works [12], [6], [11], [13], [16] have shown that body shadowing causes significant problems with these frequencies, i.e., 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 lack of quantified measurements when the transmitter and receiver are further from each other, e.g., 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 [15] of emergency response applications. Manual deployment by attaching new breadcrumbs on walls can lower the problem of body shadowing but not eliminate it, and this is not practical for mission-critical tasks such as firefighting.

In this paper, we present the first sophisticated solution to overcome the body shadowing problem. The main contributions of this work are:

- We investigate the characteristics of body shadowing on exfiltrating physiological data in breadcrumb sensor networks. Our empirical results reveal that both PDR and RSSI are severely affected, and the communication quality becomes worse as the user density increases. We also evaluate the body shadowing effect on the deployed breadcrumb to breadcrumb communication, and the experimental results show the same trends. Therefore, continuously deploying new breadcrumbs is not helpful when body shadowing is present, resulting in a waste of system resources.
- We propose *Intentional Forwarding*, a novel solution to overcome body shadowing among first responders that are equipped with breadcrumb system devices. It consists of a new approach for detecting body shadowing and a new reacting algorithm to save the system from body shadowing.
- We fully implemented the *Intentional Forwarding* solution, and evaluated it using a testbed including four dispensers and twenty breadcrumbs (as shown in Fig-

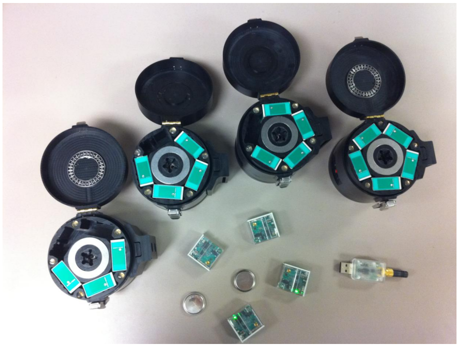


Figure 1. Our breadcrumb system Prototype.

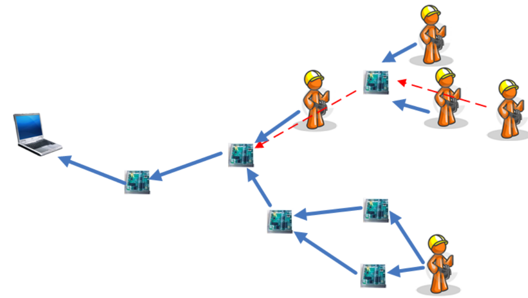


Figure 2. Breadcrumb system illustration.

ure 1). Our experimental results demonstrate that: 1) *Intentional Forwarding* is able to improve the end-to-end data packet delivery ratio to 93%, and the worst-case PDR to 85%; and 2) the average data packet delivery time using *Intentional Forwarding* is 714 milliseconds for five hops, which indicates that it meets the soft real-time data delivery requirements. Moreover, it maintains the completely automatic nature of the system, leaving users to focus on their important missions.

The remainder of this paper is organized as follows. We compare our work with state of the art in Section II-A and present the measurement of the body shadowing effect in Section III. The *Intentional Forwarding* solution is explained in detail in Section IV and evaluated in Section V. Finally, we conclude our paper in Section VI.

II. Background

A. State of the Art

Breadcrumb sensor networks were proposed mainly due to the limited transmission range of one-hop communication like the $P25$ system [1]. The drawbacks of this approach are mainly two-fold. 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 non-trivial ways, causing severe multi-path effects, dead-spots, noise and interference [5]. 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.

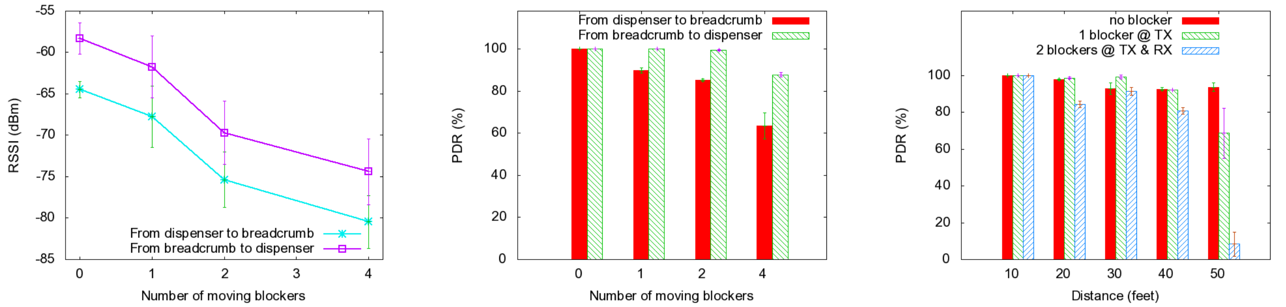
Souryal et al. first investigated the feasibility of dynamic breadcrumb deployment to extend the range of wireless communications [17]. However, their work requires a first responder to manually place the node on the ground, which is impractical in real applications. The first automatic systematic design was presented in [7], in which the solution includes a breadcrumb dispenser with an optimized link estimator to decide when to deploy breadcrumbs to maintain reliable wireless connectivity. Other related work in breadcrumb sensor networks include dealing with WiFi external interference [14], wireless link measurements [18], group management [8], localization [19], and using delay tolerant networking techniques when the users are disconnected [9]. To the best of our knowledge, the important body shadowing problem in breadcrumb sensor networks has not been effectively addressed.

There are also previous works on the single-body based shadowing problems in 2.4 GHz or 916 MHz based body sensor networks. In 2.4 GHz based systems, experimental results in [12], [11], [13] show that the body factor, which means 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 26 dBm. In 916 MHz 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 [3] with a Chipcon CC1000 radio chip [4]. Their results showed a peak-to-peak swing of 16 dBm, and even within a given posture, there are some intra-posture body movements that affect the on-body RF link qualities. Different from these works, our paper targets the scenario where the transmitter and receiver are far away from each other, ranging from 20 centimeters to more than 15 meters.

The main differentiators of our proposed system over all the related work are in the sense of measuring and overcoming the BSE in the special breadcrumb sensor network settings. This work is of particular importance for the design of breadcrumb sensor networks.

B. Breadcrumb System Overview

In the breadcrumb system design we proposed in [7], 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



(a) RSSI. (b) PDR. (c) BSE on breadcrumb-to-breadcrumb communication.

Figure 3. Results of BSE Characteristics experiments.

for rescue work, the link quality between the dispenser on the user and the breadcrumbs becomes weaker (Red Dashed lines in Figure 2 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 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.

III. Characterizing the BSE

In this section, we present a series of experiments to quantify the impact of BSE on breadcrumb system deployment. We first examine whether BSE becomes more serious when more blockers are present. Then we evaluate the BSE on breadcrumb-to-breadcrumb communication to see whether dropping new relay nodes helps or not in shadowed situations. In our work we define blockers as users of breadcrumb systems and carry dispensers. if there are other obstacles blocking the breadcrumb link, there is no way other than deploying a new breadcrumb immediately to improve the link quality. Due to page limit, we skipped some experimental results on how the RSSI and PDR are affected by body shadowing in stationary situations. Please refer to [10] for more details.

A. Breadcrumb-to-Dispenser Communication

First, we fixed a user with dispenser 30 feet from a breadcrumb on the ground, 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 3(a) and Figure 3(b), respectively.

We can observe from Figure 3(a) 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 user density is an important factor for breadcrumb system design. Figure 3(b) 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. 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, we clearly notice the asymmetry of wireless communications between the dispenser and breadcrumb. This is mainly because the dispenser is more powerful in circuit design and power supply than breadcrumbs. Similarly, the PDR from dispenser to breadcrumb is much worse than the other direction especially when they are far apart. This is due to the fact that the dispenser has better receiving capabilities. This must be taken into consideration for breadcrumb sensor network design for better reliability and efficiency.

B. 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 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 PDR were recorded with various distances between the breadcrumbs.

We observe from Figure 3(c) 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. Therefore, breadcrumb sensor networks are problematic under multiple user situations and some solution must be proposed to overcome the body shadowing effects.

IV. Intentional Forwarding

To overcome the body shadowing effects and based on the experimental results in Section III, we designed and fully implemented a detection and recovery framework, called *Intentional Forwarding*. This solution consists of two individual components: *Detection* and *Reaction*. These

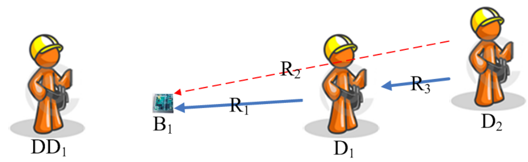


Figure 4. Illustration of the detection algorithm.

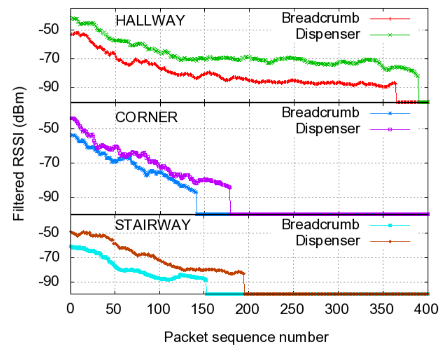


Figure 5. Filtered RSSI values from a moving dispenser to an on-ground breadcrumb and hooked dispenser in an example trace (-100 dBm indicates disconnected links).

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.

A. Detection *Component*

The *Detection* component detects that the system is experiencing a body shadowing effect. The main challenges in this part include how to quickly and accurately determine the presence of blockers, and to keep the communication overhead as low as possible.

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 (each together with the dispenser-breadcrumb link quality, whether it is shadowed, and how many dispensers it is forwarding packets for.) 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 (ten seconds in our implementation), it will be removed from the list.

We proceed to design the detection approach. As shown in Figure 4, assuming that two 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 the above 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 below:

$$R_1 - R_2 > T_1 \tag{1}$$

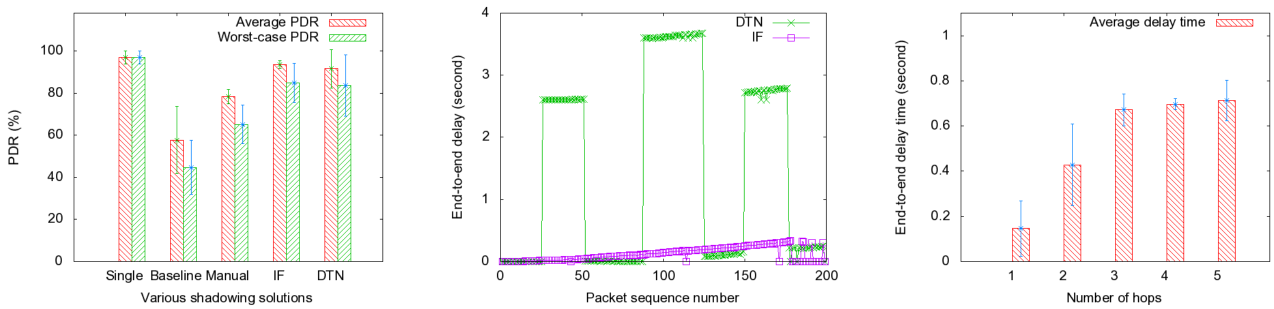
$$R_3 - R_2 > T_2 \tag{2}$$

T_1 can be measured by the fluctuation of the gap of filtered received signal strength. According to our previous results in [8], T_1 is set to 5 dBm 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 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 5 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 13 dBm in the hallway, 8 dBm in the corner, and 14 dBm in the stairway. Thus we pick the highest value and set T_2 to 14 dBm. For more details on the system parameters and their impact on the system performance, please refer to [10].

B. Reaction *Component*

The *Reaction* component takes the body shadowing effect into account, and enables a shadowed dispenser to temporally send its data packets to one of its blockers acting as a forwarder, when this dispenser indicates a new deployment. Therefore, the communication stays reliable by splitting one weak link into two stronger ones.

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 multi-hop-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



(a) Comparison of various body shadowing solutions: PDR.

(b) End-to-end delivery time using IF and DTN in an example trial.

(c) End-to-end delivery time for IF with varying number of hops.

Figure 6. Experimental Results.

blockers are in the shadowing mode. Second, load balancing among blockers can decrease the risk of single-point failure and a communication bottleneck, thus increase the system robustness. 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.

V. Evaluation

In this section, we present extensive evaluation results for our proposed solution. We conducted all experiments in the Computer Science Department at University of Virginia using the customized prototype as described in Section III-A. 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 66 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. Due to page limit, please refer to [10] for detailed hardware description.

We compare our solution with two other approaches: MANUAL and DTN. 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 of 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.

Physiological data are sent from the dispensers to active breadcrumbs at the rate of 2 packets per second to mimic the results of processing. For performance analysis purposes, in each data packet we include information such as timestamp and source node ID. Other breadcrumb system settings remain the same as in [7]. An opportunistic routing protocol is adopted to forward data packets to the base station through multiple hops and suppress flooding. Each experiment was repeated to eliminate the effect of noise.

A. PDR

The most important metric for measuring a design in 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. To investigate how system reliability is affected by body shadowing and the performance of candidate solutions, four users walked through the trace with candidate solutions. Three solutions, MANUAL, IF, and DTN, were applied separately in different experimental trials under the same settings.

Figure 6(a) shows the average and worst-case PDR using various candidate solutions. For comparison, we added the cases of one user and four users without any candidate solution, 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 outperforms 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 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 saves 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 in both average and worst-case scenarios.

B. Providing Real-time Delivery

We next compare the performance of IF and DTN in terms of meeting real-time delivery requirements. 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. 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. We recorded the timestamps 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. We measured that the maximum number of hops was five in the 20-breadcrumb chain due to the usage of opportunistic routing protocol. IF and DTN were evaluated separately.

Figure 6(b) 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. Also, 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.

Figure 6(c) 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 10 users and in total 50 breadcrumbs, the worst case for end to end delivery time through 25 hops is still within 4 seconds.

VI. Conclusions

Breadcrumb sensor networks have been emerging in mission critical application domains such as firefighting. In this paper, we have measured the serious body shadowing problem through extensive empirical results for 2.4 GHz sensor nodes, and introduced a novel *Intentional Forwarding* approach. Evaluation results indicate that our proposed solution is able to improve the end-to-end data packet delivery ratio and meet soft real-time requirements even under severe body shadowing problems.

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References

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

[2] ZigBee Alliance, URL: http://www.zigbee.org.

[3] Crossbow Inc, URL: http://www.xbow.com.

[4] CHIPCON, http://www.chipcon.com/files/CC1000DataSheet21.pdf.

[5] S. Halder, and W. Kim. Adaptive Filtering for Indoor Localization using Zigbee RSSI and LQI measurement. In IEEE Transactions on Systems, Man, and Cybernetics, 2011.

[6] L. Krishnamurthy, R. Adler, P. Buonadonna, J. Chhabra, M. Flanigan, N. Kushalnagar, L. Nachman, and M. Yarvis. Design and Deployment of Industrial Sensor Networks: Experiences from a Semiconductor Plant and the North Sea. In Proceedings of the ACM SenSys, 2005.

[7] H. Liu, J. Li, Z. Xie, S. Lin, K. Whitehouse, D. Siu, and J. A. Stankovic. Automatic and Robust Breadcrumb System Deployment for Indoor Firefighter Applications. In MobiSys, 2010.

[8] H. Liu, Z. Xie, J. Li, S. Lin, K. Whitehouse, D. Siu, and J. A. Stankovic. Efficient and Reliable Breadcrumb Systems via Coordination among Multiple First Responders. In Proceedings of IEEE PIMRC, 2011.

[9] H. Liu, A. Srinivasan, Y. Chen, K. Whitehouse, and J. A. Stankovic. Melange: Supporting Heterogeneous QoS Requirements in Delay Tolerant Sensor Networks. In Proceedings of IEEE INSS, 2010.

[10] H. Liu. Design and Implementation of an Automatic, Reliable, and Efficient Breadcrumb Sensor Network. Ph.D. dissertation, University of Virginia, August 2011.

[11] E. Miluzzo, X. Zheng, K. Fodor, and A.T. Campbell. Radio Characterization of 15.4 and Its Impact on the Design of Mobile Sensor Networks. In Proceedings of EWSN, 2008.

[12] C. Oliveira, L. Pedrosa, and R. Rocha. Characterizing On-Body Wireless Sensor Networks. In Proceedings of IEEE NTMS, 2008.

[13] M. Quwaider, J. Rao, and S. Biswas. Transmission Power Assignment with Postural Position Inference for On-Body Wireless Communication Links. In ACM Transactions on Embedded Computing Systems, 2010.

[14] M. Refaei, N. Moayeri, and M. Souryal. Interference Avoidance in Rapidly Deployed Wireless Ad hoc Incident Area Networks. In Proceedings of IEEE MCN, 2008

[15] K. Sha, W. Shi, and O. Watkins. Using Wireless Sensor Networks for Fire Rescue Applications: Requirements and Challenges. In IEEE Conference on Electro/information Technology, 2006.

[16] B. Silva, A. Natarajan, and M. Motani. Inter-User Interference in Body Sensor Networks: Preliminary Investigation and an Infrastructure-Based Solution. In Proceedings of the Sixth International Workshop on Wearable Sensor Networks, 2009.

[17] M. R. Souryal, J. Geissbuehler, L. E. Miller, and N. Moazeri. Real-time Deployment of Multihop Relays for Range Extension. In Proceedings of ACM MobiSys, 2007.

[18] A. Wapf and M. R. Souryal. Measuring Indoor Mobile Wireless Link Quality. In ICC, 2009.

[19] Z. Xie, M. Hong, H. Liu, J. Li, K. Zhu, K. Whitehouse, and J. Stankovic. Quantitative Uncertainty-Based Incremental Localization and Anchor Selection in Wireless Sensor Networks. In MSWiM, 2011.