Modeling Random Deployment in Wireless Sensor Networks for Infrastructure-less Cyber Physical Systems

Myounggyu Won, HoKyeong Ra, Taejoon Park, Sang H. Son
Daegu Gyeongbuk Institute of Science and Technology (DGIST), South Korea
Email: {mgwon, hk, tjpark, son}@dgist.ac.kr

***Abstract*—Random deployment enables rapid installation of a large number of sensors in locations of difficult access, which is important for many infrastructure-less cyber physical systems (CPS), e.g., for disaster response, battle field and extraterrestrial operations. However, random deployment results in heterogeneous sensor postures with varying antenna orientations, a source of network performance degradation. Although much is known about the effect of antenna orientations in 802.15-based wireless sensor networks (WSNs), most works assume no physical disturbance to antennas. However, heterogeneous sensor postures (e.g., overturned sensors) may cause significant disruption to the functionalities of antennas in addition to the reported variation of received signal strength (RSSI). In this paper, we provide empirical characterization of node-to-node communication in random deployment and present the first radio model that effectively captures the distinctive characteristics. Through simulations using our model, we provide a quantitative analysis of the aggregate effect of random antenna orientations of a large number of sensors with heterogeneous postures. Furthermore, we introduce a prototype sensor package that can be used to reduce the impact of random deployment.**

I. Introduction

Random deployment [1] is one of the most important deployment techniques in WSNs. In random deployment, sensors are randomly deployed (e.g., scattered from ground/aerial vehicles). Random deployment is particularly useful for deployment scenarios where manual sensor deployment is not a plausible option, which often arise in many infrastructure-less cyber physical systems, e.g., disaster response [2][3][4][5], battle field operations [6] [7], and space operations [8]. Advantages of random deployment is expected to grow as sensors become cheaper and smaller, being increasingly integrated into cyber physical systems.

An important yet underrated issue in WSNs is that random deployment results in heterogeneous sensor postures with random antenna orientations leading to network performance degradation. Fortunately, the effect of antenna orientations in 802.15-based WSNs is a well-studied topic [9][10][11]. However, these empirical studies are based on an assumption that there is no physical disturbance to antennas, ignoring the possibilities of disturbed functionalities of antennas during random deployment, i.e., when sensors are positioned in an adverse manner (e.g., upside-down and side-facing sensors).

We note that, along with this line of research, the state-of-the-art radio model for WSNs [12] characterized the irregular radio range of a sensor node caused by different antenna orientations without factoring in the potential physical disturbance to antennas during random deployment. As such, many subsequent random-deployment-based works [13][14] that relied on the radio model ended up with relatively too optimistic performance reports. In this paper, we propose the first radio model for WSNs that effectively characterizes the effect of random deployment. Also, we provide, through simulations, analytical quantification of *the aggregate effect of random antenna orientations of a large number of sensors* in contrast to existing works that focus on the investigation of the effect of antenna orientations at *an individual sensor level*. Furthermore, we present a prototype sensor package that can be used for reducing the negative impact of random deployment.

This paper is organized as follows. In Section II, we review the literature on modeling the radio range of a sensor node and the limitations of proposed schemes; a review on existing sensor packaging schemes is also presented. In Section III, we perform various real-world measurements regarding random deployment. Based on the measurements, we propose our radio model in Section IV. Based on our proposed radio model, in Section V, we perform a quantitative analysis to understand the aggregate behavior of randomly deployed sensors. Section VI discusses the first prototype for packaging a sensor designed for random deployment. Finally, we conclude in Section VII.

II. Related Work

A. Radio Model for Wireless Sensor Networks

Efforts have been made to measure the characteristics of the radio transmission of a sensor in different environmental settings [21][22][23]. However, they did not provide a network radio model based on their characterization. Zhou *et al.* [12] characterized the irregularity of a radio range and proposed a network radio model called Radio Irregularity Model (RIM) for WSNs. Since then, a large number of works (e.g., [13][14]) have adopted the model in simulating their algorithms and protocols. However, Zhou *et al.*'s RIM model does not take into account the fact that in random deployment heterogeneous sensor postures arise, which negatively affect the network performance. Later Zamalloa and Krishnamachari [24] modeled the unreliability and asymmetry of wireless links and combined their work with the RIM model; but consideration of sensor postures was not given. Fortunately, recent work [25] started to take into account the impact of sensor postures, i.e., extending the state-of-the-art radio model by considering the surface-level path loss model based on the observation that in WSNs,

978-1-4799-5387-5/14 $31.00 © 2014 IEEE
DOI 10.1109/CPSNA.2014.26

Fig. 1: Packaging using a O-ring [15][16][17]

Fig. 2: Packaging using a Pelican Box adopted by an environmental monitoring application [18]

Fig. 3: Packaging using a custom-designed cylinder-shaped cover [19][20]

nodes are usually placed on the ground, which causes the degradation of received signal strength. However, in typical random deployment scenarios, sensors are not just placed on the ground, but with various postures.

B. Sensor Package for Random Deployment

Although there is a vast body of theoretical research on random deployment [26][27], the study on a real-world random deployment seems to be relatively slow. Researchers have deployed sensors for various purposes. Allen *et al.* [15][16][17] deployed sensors for monitoring volcano eruption. For their deployment, they used an O-ring for packaging a sensor as shown in Figure 1. However, as it can be seen, this O-ring design performs well only when a sensor is manually deployed. For random deployment, the O-ring design would frequently cause undesired sensor positions. Selavo *et al.* [18] investigated an environment monitoring application, especially for monitoring a harsh and inaccessible area. Their system called Light Under Shrub Thicket for Environmental Research (LUSTER) adopted a Pelican box shown in Figure 2 to package a sensor. However, although a Pelican box is known to be water-proof, because of its rectangular shape, it is difficult to guarantee that deployed sensors maintain upright positions for optimal performance.

While some works used off-the-shelf boxes like a Pelican box, many other works employed customized sensor packages. Interestingly, a lot of packaging design adopted a box shape. However, this box-shape is not efficient for random deployment, as it does not guarantee the upright sensor positions. For example, Basha *et al.* [28] designed their own plastic box for flood detection application. Sikka *et al.* [29] also used a plastic box model for containing a sensor for their farm monitoring application. Especially, the design selected by Dutta *et al.* [30] for the development of their extreme-scale network of 10,000 nodes used a plastic box with an antenna sticking out of the box, which greatly disturbs the process of random deployment because the antenna can be easily damaged during deployment. Some researchers attempted to use a different design. Mainwaring *et al.* [19] and Szewczyk *et al.* [20] designed a customized container for their habitat monitoring application as shown in Figure 3. Hartung *et al.* [31] used a plastic cover to protect a sensor, not entirely protecting the body of a sensor. Some works like [32] did not specify what packaging scheme was used.

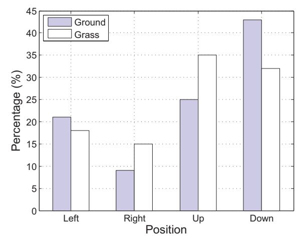

Fig. 4: Sensor postures for box type

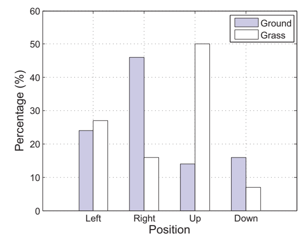

Fig. 5: Sensor postures for cylinder type

III. Characterization of Random Deployment

A measurement study is performed to characterize the radio communication in random deployment. Data measured in this section are used to design our network radio model in Section IV.

A. Frequency of Sensor Posture

We start by obtaining the frequency of different sensor postures in random deployment. According to the literature presented in Section II, a box-type [18][28][29][30] and a cylinder-type [19][20] are the two most widely used sensor packages. Thus, the two types are used in this experiment (note that other types can be easily adopted in a similar manner). We securely place a TelosB sensor in each type of sensor packages. We then randomly drop it sufficiently large number of times and record the frequency of different sensor postures. We perform the experiments in both office and outdoor (grass) environments – we acknowledge that there are different kinds of deployment environments; however, due to space constraints, the characterization for the various environments is left as future work. To ease the integration of our experimental measurements into our radio model, we generalize sensor postures into $\{\mathsf{Left}, \mathsf{Right}, \mathsf{Up}, \mathsf{Down}\}$. The sensor posture is called Down when a sensor is overturned, and Up when it is in an upright posture. Otherwise, a sensor is marked as either Left or Right. It is also worth to note that the posture types can be easily diversified depending on required granularity.

Figures 4 and 5 depict the frequency. It is not surprising to find that significantly heterogeneous sensor postures are

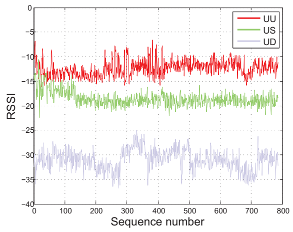

Fig. 6: RSSI for the UP posture

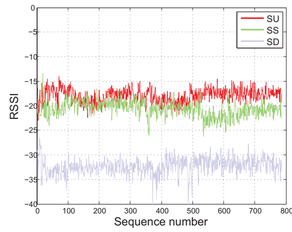

Fig. 7: RSSI for the SIDE posture

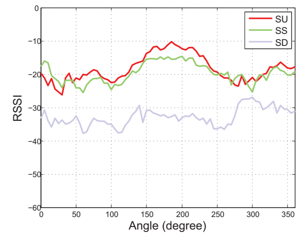

Fig. 10: RSSI for the SIDE posture per angle

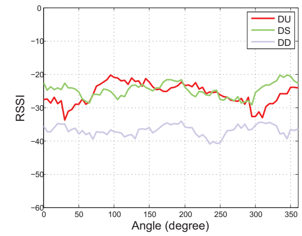

Fig. 11: RSSI for the DOWN posture per angle

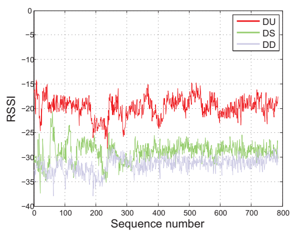

Fig. 8: RSSI for the DOWN posture

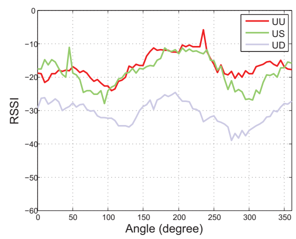

Fig. 9: RSSI for the UP posture per angle

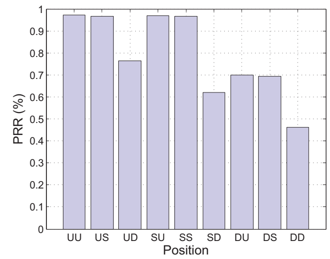

Fig. 12: Packet reception ratio as a function of sensor posture

observed in random deployment with the slightly different distribution of postures depending on a sensor package, i.e., the box type has more Up/Down postures than the cylinder type. Although the cylinder type has fewer Down postures, in both types a relatively large number of overturned sensors are observed.

B. Temporal Effect of Sensor Posture on Signal Strength

To characterize the radio communication between randomly deployed sensors, we measure Received Signal Strength Indication (RSSI) between two sensors with different postures. More specifically, RSSI is measured for all possible combinations of sensor postures, i.e., denoted by UP-UP, UP-SIDE, UP-DOWN, SIDE-UP, SIDE-SIDE, SIDE-DOWN, DOWN-UP, DOWN-SIDE, and DOWN-DOWN. For this experiment, the distance between the two sensors is set as 10 meters. Each experimental point represents an average of five measurements with different sensors.

Figures 6, 7, and 8 depict the results. We observe a similar degree of RSSI fluctuations from all sender-receiver pairs. In particular we observe that sensors have the best RSSI when they are in UP postures; when sensors are in SIDE postures, they have slightly worse RSSI. It is notable that when sensor posture is DOWN, the signal strength is significantly degraded; specifically, RSSI for DD (lowest) was up to 75% smaller than UU (highest). These results indicate that in addition to the traditional empirical results on the effect of antenna orientations [9][10][11], the impact of sensor postures (i.e., physical disruption on the functionalities of antennas) must be taken into account in designing a radio model for random deployment. Thus, the numbers obtained from this experiment will be integrated into our proposed radio model.

C. Spatial Effect of Sensor Posture on Signal Strength

In this experiment, we measure RSSI by varying the angular direction with respect to the sender, i.e., varying antenna orientations for all combinations of sensor postures. Figures 9, 10, and 11 present the results. Conforming to the results of existing works [9][10][12], sensors have different RSSIs for varying angles. However, an interesting observation is made from sensor pairs with the DOWN postures: they have significantly smaller RSSI fluctuations (see Figure 11 in particular). These results indicate that reported degree of signal fluctuations depending on antenna orientations must be reconsidered for random deployment, i.e., *considering the effect of antenna orientations separately for sensor postures.* We will incorporate the empirical data into our radio model. The details will be discussed in Section IV.

D. Effect of Sensor Posture on Packet Reception Ratio

We now show how RSSI difference due to heterogeneous sensor postures affects the network performance. We measure Packet Reception Ratio (PRR) for different sensor postures. Figure 12 depicts the results. We observe that PRR is noticeably degraded when sensor posture is DOWN, while the SIDE posture has relatively smaller impact on the network performance.

IV. Modeling Random Deployment

Now given the obtained empirical data, we design a network radio model for random deployment. The proposed model is built upon the basis of the Radio Irregularity Model (RIM) [12]. Zhou *et al.* [12] defines DOI (Degree of Irregularity) as maximum path loss percentage variation per unit degree change in the direction of radio propagation. For example, if DOI is 0 the communication range is a perfect sphere, and as

TABLE I: DOI measurement

	node1	node2	node3	node4	node5	Average
UU	0.222	0.444	0.545	0.400	0.444	0.4110
US	0.244	0.442	0.363	0.392	0.400	0.4282
UD	0.135	0.272	0.228	0.400	0.224	**0.2518**
SU	0.238	0.474	0.545	0.263	0.444	0.3928
SS	0.245	0.412	0.500	0.216	0.391	0.3728
SD	0.128	0.263	0.315	0.428	0.153	**0.2574**
DU	0.157	0.316	0.144	0.451	0.100	**0.2336**
DS	0.184	0.166	0.145	0.176	0.121	**0.1584**
DD	0.079	0.153	0.301	0.170	0.100	**0.1606**

DOI becomes larger, the communication range becomes more irregular.

We derive DOI values for each type of sender/receiver pair (i.e., UU, US, ...) using the empirical data obtained from Section III-C. Table I shows calculated DOI values for each type; specifically, we take an average DOI of five measurements with a different sensor. For the DOI computation, we use '5 degree' as the unit degree. (However, it can be easily extended to the case with 1 degree as the unit degree). Note that when either sender or receiver has the DOWN posture, the DOI values become significantly small, which coincides with the results presented in Section III-C.

Our path-loss model is based on a simple isotropic radio model [33]. Now given the calculated DOI values, our model makes modifications to the pass-loss model. More precisely, we define 9 types of path-loss models for each type of sensor pairs, i.e., for UU, US, UD, SU, SS, SD, DU, DS, and DD. An appropriate path-loss model is selected based on the distribution of sensor postures according to the results presented in Section III-A. For example, since UP, SIDE, and DOWN positions appear 37.5%, 32%, and 30%, respectively, the UU pair is selected about 37.5×37.5%, the US pair 37.5×32%, and so on.

In order to formulate our model, let us denote received signal strength by RS, transmission power by TX, path loss by PL, and fading by FD, where the fading is modeled as a random process [33]. Note that the isotropic radio model defines received signal strength RS as follows:

$$RS = TX - PL + FD.$$

Now if we take into account the DOI values for different sensor positions, we have RS_{Pos}, where $Pos = \{\mathsf{UU}, \mathsf{US}, \mathsf{UD}, ..., \mathsf{DD}\}$, defined as follows (e.g., RS_{UU} means received signal strength for the UU pair).

$$RS_{Pos} = TX - PL \cdot K_i^{Pos} + FD, \tag{1}$$

where, i represents an angular direction with respect to the sender such that $0 < i < 360$ ($i \in \mathbb{N}$) (i.e., received signal strength is defined for each angle, more precisely, in our simulation settings, every 5 degrees, implementing the irregular communication range). More specifically,

TABLE II: Simulation setup

Traffic Type	CBR
Terrain	500×500 (meter)
Deployment	Uniformly at random
Bandwidth	200kbps
Tx Power	-5.0dBm
MAC Protocol	CSMA (802.11)

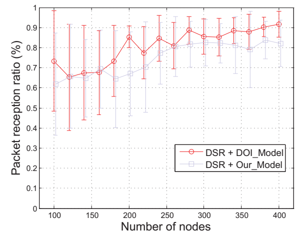

Fig. 13: Effect of random deployment on packet reception ratio

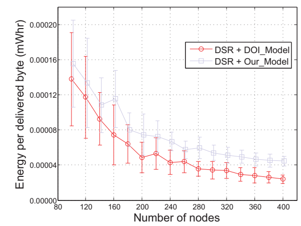

Fig. 14: Effect of random deployment on energy consumption

$$K_i^{Pos} = \begin{cases} 1, & \text{if } i = 0 \\ K_{i-1}^{Pos} \pm Rand \cdot DOI^{Pos}, & \text{if } 0 < i < 360. \end{cases}$$

In addition to considering various irregularity of radio ranges depending on sensor postures, we also need to take into account the signal attenuation caused by sensor postures. Thus, we apply a factor I_{Pos} $(0 < I < 1)$ to Equation 1 and obtain the following:

$$RS_{Pos} = (TX - PL \cdot K_i^{Pos} + FD) \cdot I_{Pos}. \tag{2}$$

The factor I_{Pos} is defined based on the measurements performed in Section III-B. More specifically, We first compute an average RSSI for each sender-receiver pair and normalize them with the average RSSI of the UU pair as the reference point (i.e., a value of 1).

V. Quantitative Analysis

While the effect of sensor postures on the network performance at an individual link level is presented in Section III-D, the network-wide effect is still not known. In this section, using our proposed radio model, we investigate the aggregate impact of a relatively large number of randomly deployed sensors.

A. Analysis Setup

As the network performance, we measure packet reception ratio (PRR), end-to-end delay, number of control packets, and energy consumption for running a network protocol: in our simulation, we choose to use DSR [34]. We use the total number of sensors in the network as a control parameter since we want to see the impact of random antenna orientations (potentially with physical disturbances to them) of a large number of sensors. To understand the degree of network performance degradation due to random deployment, we compare the performance metrics against the RIM model which

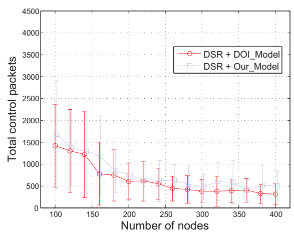

Fig. 15: Effect of random deployment on control packet overhead

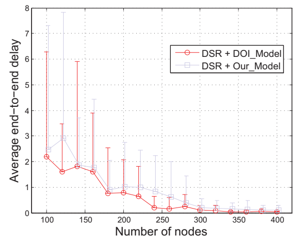

Fig. 16: Effect of random deployment on end-to-end delay

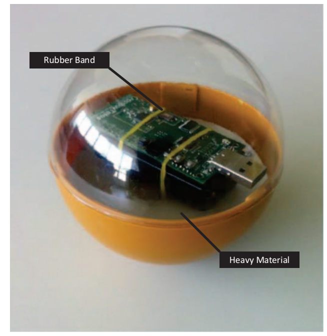

Fig. 17: A prototype of RolyPoly

assume all sensors are in their upright positions (i.e., an ideal environment).

We randomly deploy different numbers of sensors in a network of 500×500 m^2. We then select 6 sender-receiver pairs uniformly and randomly from the deployed sensors. Each sender sends a data packet of 50 Bytes every 30 seconds to its corresponding receiver. Each simulation lasts for a period of an hour. Each data point in our simulation results represents an average of 30 times of running experiments with different seeds. Our simulation set-up is summarized in Table II.

B. Packet Reception Ratio

Figure 13 depicts the packet reception ratio (PRR) of the two radio models. We observe that with higher network density, we get better PRR. Note that the variance of PRR is relatively high with small node density because in a sparse network, many unstable links are formed, which cause frequent packet drops. We also observe that our radio model has *up to 58% smaller PRR* than the RIM model, reflecting the significant aggregate impact of random antenna orientations and physical disturbance to the antennas.

C. Energy Consumption

We measure the consumed energy of the two radio models. For simplicity, we do not consider duty cycling mechanisms and assume that all sensors are awake at all times. So, in our simulations, the main source of energy consumption comes from data packet transmissions. Thus, we focus on measuring energy consumed for transmitting a data packet– more precisely, consumed energy per byte. Figure 14 shows the results. Compared with the RIM model, our model has higher energy consumption *by up to 122%,* which indicates that random deployment may bring significant performance degradation, *the cause of which cannot be explained only by the effect of random antenna orientations* [9]. We also find that this higher energy consumption is mainly due to a large number of packet re-transmissions caused by unstable links (i.e., represented by weak RSSIs).

D. Protocol Overhead (Control Packet)

The number of control packets used for the DSR routing protocol is measured for both radio models. Figure 15 shows that our model uses more control packets than the RIM model *by up to 80%*. We observe that the reason is because our model incurs more *route error* [34] packets due to frequent routing path changes, especially for sensors with DOWN positions. In addition, our model often results in unreachable destinations.

E. End-to-End Delay

Figure 16 depicts average end-to-end delay for the 6 data streams. The unexpectedly high average end-to-end delay for the first few network density happens because in a sparse network more packets tend to be dropped. In such cases, a next data packet is buffered after 30 seconds, therefore increasing the delay by 30 seconds. It is also important to note that our model results in significantly higher average end-to-end delay than the RIM model, which proves that the state-of-the-art radio model needs to be revisited when it is to be applied to random deployment.

VI. Discussion

In this section, going further from proposing the radio model, we discuss a potential solution for the issue of heterogeneous sensor postures in random deployment. One easy, non-intrusive, and immediately-applicable solution is to develop a sensor package that ensures the upright position of a sensor. So we introduce the first prototype of a sensor package, called Rolypoly (motivated by the fact that our sensor package leverages the property of a rolypoly), aiming for rapid and reliable random deployment. We acknowledge that there can be various other approaches in designing a sensor package; however, by introducing our prototype, we expect to inspire the research and development with respect to the sensor package design in random deployment for infrastructure-less CPS. The following objectives can be referred to when designing the package:

1) Prevent sensors from overturning, the main cause of network performance degradation in real-world random deployment
2) Effectively protect sensors from the physical damage during deployment
3) Be water-proof
4) Accommodate any types of sensor shapes
5) Improve network performance, e.g., by appropriately lifting a sensor from the ground
6) Be cost-effective

A picture of an example prototype design called Rolypoly is shown in Figure 17. To equip our sensor package with the property of a rolypoly, heavy material is placed in the bottom part of Rolypoly, i.e., preventing a sensor in Rolypoly from overturning (Item 1). A sensor is placed about 5 cms away from the bottom of Rolypoly in order to provide better communication capability [25] (Item 5). The rubber band is used to hold different types of sensors (Item 4). Rolypoly is, as can be seen in the figure, water-proof (Item 3). Rolypoly is also very cost-effective, costing about only 5 dollars for each (Item 6). The surface of Rolypoly can be covered by soft material so that a sensor in Rolypoly is protected from physical damage from the ground upon random deployment (Item 2). Also, the top of Rolypoly can be designed with a different geometric shape so that it does not roll when it is deployed (although the current design does not allow a sensor to roll much since it contains heavy material at the bottom of its body).

VII. Conclusions

We have presented detailed characterization of random deployment and proposed a novel radio model that effectively captures the characteristics. As future work, we will perform a large-scale real-world random deployment in more various environments to support the accuracy of our proposed model. We are also interested to investigate other environmental factors (e.g., temperature) affecting our proposed model.

Acknowledgment

This research was supported in part by the DGIST Research and Development Program of the Ministry of Science, ICT and Future Planning of Korea (CPS Global Center).

References

[1] J. Vales-Alonso, F. Parrado-Garca, P. Lpez-Matencio, J. Alcaraz, and F. Gonzlez-Castao, “On the optimal random deployment of wireless sensor networks in non-homogeneous scenarios,” *Ad Hoc Networks*, vol. 11, no. 3, pp. 846 – 860, 2013.

[2] E. Gelenbe and F.-J. Wu, “Future research on cyber-physical emergency management systems,” *Future Internet*, vol. 5, no. 3, pp. 336–354, 2013.

[3] E. Gelenbe, G. Gorbil, and F.-J. Wu, “Emergency cyber-physical-human systems,” in *Proceedings of ICCCN*, 2012, pp. 1–7.

[4] R. R. Murphy, K. L. Dreger, S. Newsome, J. Rodocker, E. Steimle, T. Kimura, K. Makabe, F. Matsuno, S. Tadokoro, and K. Kon, “Use of remotely operated marine vehicles at minamisanriku and rikuzentakata japan for disaster recovery,” in *Proceedings of SSRR*, 2011, pp. 19–25.

[5] H. Chenji, W. Zhang, M. Won, R. Stoleru, and C. Arnett, “A wireless system for reducing response time in urban search amp; rescue,” in *Proceedings of IPCCC*, 2012, pp. 215–224.

[6] T. Bokareva, W. Hu, S. Kanhere, B. Ristic, T. Bessell, M. Rutten, and S. Jha, “Wireless sensor networks for battlefield surveillance,” in *Proceedings of the Land Warfare Conference*, 2006.

[7] R. Rajkumar, “A cyber–physical future,” *Proceedings of the IEEE*, vol. 100, no. Special Centennial Issue, pp. 1309–1312, 2012.

[8] A. T. Klesh, J. W. Cutler, and E. M. Atkins, “Cyber-physical challenges for space systems,” in *Proceedings of ICCPS*, 2012, pp. 45–52.

[9] D. Lymberopoulos, Q. Lindsey, and A. Savvides, “An empirical characterization of radio signal strength variability in 3-d ieee 802.15. 4 networks using monopole antennas,” in *Wireless Sensor Networks*. Springer, 2006, pp. 326–341.

[10] S. Yang and H. Cha, “An empirical study of antenna characteristics toward rf-based localization for ieee 802.15. 4 sensor nodes,” in *Wireless Sensor Networks*. Springer, 2007, pp. 309–324.

[11] M. Wadhwa, M. Song, V. Rali, and S. Shetty, “The impact of antenna orientation on wireless sensor network performance,” in *Proceedings of CSIT*, 2009.

[12] G. Zhou, T. He, S. Krishnamurthy, and J. A. Stankovic, “Models and solutions for radio irregularity in wireless sensor networks,” *ACM Transactions on Sensor Networks*, vol. 2, no. 2, pp. 221–262, 2006.

[13] P. Padhy, R. K. Dash, K. Martinez, and N. R. Jennings, “A utility-based adaptive sensing and multihop communication protocol for wireless sensor networks,” *ACM Transactions on Sensor Networks*, vol. 6, no. 3, pp. 27:1–27:39, 2010.

[14] M. Rahman and L. Kleeman, “Paired measurement localization: A robust approach for wireless localization,” *IEEE Transactions on Mobile Computing*, vol. 8, no. 8, pp. 1087–1102, 2009.

[15] G. Werner-Allen, J. Johnson, M. Ruiz, J. Lees, and M. Welsh, “Monitoring volcanic eruptions with a wireless sensor network,” in *Proceeedings of EWSN*, 2005, pp. 108–120.

[16] G. Werner-Allen, K. Lorincz, M. Ruiz, O. Marcillo, J. Johnson, J. Lees, and M. Welsh, “Deploying a wireless sensor network on an active volcano,” *IEEE Internet Computing*, vol. 10, no. 2, pp. 18–25, 2006.

[17] G. Werner-Allen, K. Lorincz, J. Johnson, J. Lees, and M. Welsh, “Fidelity and yield in a volcano monitoring sensor network,” in *Proceedings of OSDI*, 2006, pp. 381–396.

[18] L. Selavo, A. Wood, Q. Cao, T. Sookoor, H. Liu, A. Srinivasan, Y. Wu, W. Kang, J. Stankovic, D. Young, and J. Porter, “Luster: wireless sensor network for environmental research,” in *Proceedings of SenSys*, 2007, pp. 103–116.

[19] A. Mainwaring, D. Culler, J. Polastre, R. Szewczyk, and J. Anderson, “Wireless sensor networks for habitat monitoring,” in *Proceedings of WSNA*, 2002, pp. 88–97.

[20] R. Szewczyk, A. Mainwaring, J. Polastre, J. Anderson, and D. Culler, “An analysis of a large scale habitat monitoring application,” in *Proceedings of SenSys*, 2004, pp. 214–226.

[21] D. Ganesan, B. Krishnamachari, A. Woo, D. Culler, D. Estrin, and S. Wicker, in *Technical Report UCLA/CSD-TR 02-0013*.

[22] A. Cerpa, J. L. Wong, M. Potkonjak, and D. Estrin, “Temporal properties of low power wireless links: modeling and implications on multihop routing,” in *Proceedings of MobiHoc*, 2005, pp. 414–425.

[23] J. Zhao and R. Govindan, “Understanding packet delivery performance in dense wireless sensor networks,” in *Proceedings of SenSys*, 2003, pp. 1–13.

[24] M. Z. n. Zamalloa and B. Krishnamachari, “An analysis of unreliability and asymmetry in low-power wireless links,” *ACM Transactions on Sensor Networks*, vol. 3, no. 2, Jun. 2007.

[25] P. K. Chong and D. Kim, “Surface-level path loss modeling for sensor networks in flat and irregular terrain,” *ACM Transactions on Sensor Networks*, vol. 9, no. 2, pp. 15:1–15:32, 2013.

[26] P. Balister and S. Kumar, “Random vs. deterministic deployment of sensors in the presence of failures and placement errors,” in *Proceedings of INFOCOM*, 2009, pp. 2896–2900.

[27] H. Zhang and J. Hou, “Is deterministic deployment worse than random deployment for wireless sensor networks?” in *Proceedings of INFOCOM*, 2006, pp. 1–13.

[28] E. A. Basha, S. Ravela, and D. Rus, “Model-based monitoring for early warning flood detection,” in *Proceedings of SenSys*, 2008, pp. 295–308.

[29] P. Sikka, P. Corke, P. Valencia, C. Crossman, D. Swain, and G. Bishop-Hurley, “Wireless ad hoc sensor and actuator networks on the farm,” in *Proceedings of IPSN*, 2006, pp. 492–499.

[30] P. Dutta, M. Grimmer, A. Arora, S. Bibyk, and D. Culler, “Design of a wireless sensor network platform for detecting rare, random, and ephemeral events,” in *Proceedings of IPSN*, 2005, pp. 497–502.

[31] C. Hartung, R. Han, C. Seielstad, and S. Holbrook, “Firewxnet: a multi-tiered portable wireless system for monitoring weather conditions in wildland fire environments,” in *Proceedings of MobiSys*, 2006, pp. 28–41.

[32] G. Barrenetxea, F. Ingelrest, G. Schaefer, M. Vetterli, O. Couach, and M. Parlange, “Sensorscope: Out-of-the-box environmental monitoring,” in *Proceedings of IPSN*, 2008, pp. 332–343.

[33] P. M. Shankar, “Introduction to wireless systems,” in *John Wiley and Sons, Inc*, 2001.

[34] D. B. Johnson and D. A. Maltz, “Dynamic source routing in ad hoc wireless networks,” in *Mobile Computing*. Kluwer Academic Publishers, 1996, pp. 153–181.