IPSJ SIG Technical Report

Vol.2011-MBL-57 No.21
Vol.2011-UBI-29 No.21
2011/3/7

Cost-Efficient Sensor Placement for Full Coverage of 3D Indoor Space with Moving Obstacles

Marc T. Kouakou,[†1] Shinya Yamamoto,[†2]
Keiichi Yasumoto[†1] and Minoru Ito[†1]

In this paper, we tackle the problem to achieve *mobile k-coverage* of a target indoor space, that is, for arbitrary position of a moving obstacle, any point located in the target monitoring area has a line-of-sight to and is located in the sensing range r_s of at least k sensors. We propose a heuristic algorithm for computing a deployment pattern achieving the mobile k-coverage in an arbitrary 3D target space with stationary and moving obstacles, while minimizing the overall deployment cost. In our method, first we provide a sufficient condition for mobile k-coverage: the half-sphere of radius r_s centered at a monitoring point bounded by the vertical plane containing the point includes at least k sensor nodes. Based on this condition, we propose a heuristic algorithm that puts at least one sensor node in each $\frac{\pi}{k+1}$ spherical wedge for each monitoring point. Using the proposed method, we have computed the sensor nodes position in an existing indoor environment and confirmed that the obtained WSN deployment in the real space accurately achieves mobile k-coverage.

1. Introduction

Indoor 3D WSNs have gained increasing interests due to their various uses in context-aware applications (home automation, smart environment monitoring, etc). One of the key challenges for 3D WSNs is how to achieve full coverage of the target monitoring space and sufficient network connectivity between sensor nodes while maintaining a low deployment cost.

A lot of studies have been carried out on the optimal positioning of the nodes in the indoor WSN to achieve the coverage of the target area and the connectivity between the sensor nodes. However, those studies have not considered the influence of the obstacles (static or mobile) existing in the indoor environment. In the deployment of a WLAN system for instance, the optimal positioning of the access points to cover the whole area is crucial. Nonetheless, the existence of mobile objects, such as people, could have an effect on the performance of the system[1)–3)]. In indoor localization systems for instance, a human body obstructing the line-of-sight between two sensors can greatly interfere on the measured signal strengths, which can result in inaccurate estimation of locations. Moreover, both for economic and technical reasons, the deployment method must minimize the overall cost.

It is actually difficult and expensive to find the optimal WSN deployment in a given indoor environment in terms of sensing coverage and network connectivity, since the 3D WSN coverage problem is NP-hard[⋆1] even without obstacles. In 4), 5), we proposed for 3D indoor spaces with only stationary obstacles a heuristic algorithm that computes the minimal cost sensor deployment satisfying full-coverage and wireless connectivity.

In this paper, we tackle a 3D WSN coverage problem when moving obstacles exist. First, we formulate the *mobile k-coverage* problem that is for any position of the mobile obstacle, any point in the monitoring area has a line-of-sight to and is located in the sensing range of at least k sensors. To solve this problem, we first discretize the problem by representing the 3D target monitoring space by a set of grid points called *monitoring points* and similarly, the sensor deployable areas such as ceiling and walls to a set of grid points called *deployable points.* Since the modified problem is still NP-hard, finding the optimal pattern requires huge computational time. For this reason, we propose heuristics to derive a near-optimal solution in a reasonable amount of time. Considering a monitoring point located near the mobile obstacle, we provide a sufficient condition for mobile k-coverage: the half-sphere of radius r_s centered at the monitoring point bounded by the vertical plane containing the point includes at least k sensor nodes. Based on this condition, we propose an algorithm that determines for each monitoring point its covering spherical wedges with angle $\frac{\pi}{k+1}$ and radius r_s and puts at least one sensor node in each wedge: the algorithm (i) computes, for each deployable point, its per-cost volume (a quotient when dividing the number of spherical

---

†1 Nara Institute of Science and Technology
†2 Tokyo University of Science Yamaguchi

[⋆1] It implies the minimum set covering problem, known to be NP-hard.

wedges containing the point by the deployment cost of the point), and (ii) puts sensor nodes one by one at the deployable points in the descending order of their per-cost volumes until all the spherical wedges contain at least one sensor node.

To investigate the correctness of our method, we have implemented the proposed algorithm in the tool proposed in 4), 5). We used the tool to carry out the deployment of Zigbee devices (Xbee modules) in an existing indoor environment. We then set a tag node at some selected monitoring points to measure the strength of the signal sent from the tag node at the deployed nodes. We confirmed that for every monitoring point and every position of human standing near the point, there was a sufficient number of nodes whose signal strength was greater than the minimum required signal strength showing that our algorithm accurately achieves mobile k-coverage.

2. Related Work

Alam and Haas studied the problem of coverage and connectivity for 3D spaces in 6). They suggested a deployment pattern that generates the Voronoi tessellation of truncated octahedron in 3D space. Moreover, Bai et al. designed several sets of lattice patterns to achieve full-coverage and k-connectivity in three dimensional space and proved their optimality under constraints of regularity7),8). Further work focused on the full coverage problem in 3D regions and provided an algorithm to repair the coverage holes9).

The above studies suppose that the sensor nodes can be placed at any point of the 3D space and do not consider the deployment cost at each point in the target space. Moreover, the suggested deployment patterns do not take into account the obstacles that may exist in the target space. In 4), 5), a cost-efficient deployment method for full-coverage and connectivity in indoor 3D WSNs was proposed. However, this method focused only on the influence of the static obstacles in the indoor environment.

The human body shadowing significantly affects the signal propagation in indoor environments1),3). Collonge et al. presented several measurements of the 60 GHz propagation in the presence of human activity and their results confirm that human bodies are significant obstacles for the signal propagation2). Similarly, in 10), Obayashi and Zander highlighted the influence of the human body shadowing on indoor radio communication and introduced a practical model to estimate its effects. Furthermore, Varshney et al. addressed the effects of the mobility of entities like people in the vicinity of wireless communication on the channels characteristics and the wireless network performance11).

However, there is no approach that focuses on the indoor WSN deployment method that takes into account the human-body shadowing effects.

3. 3D coverage problem with mobile obstacles

In this section, we give assumptions in our proposed method and formulate the mobile k-coverage problem.

We summarize the symbols that are used in this section in **Table 1**.

Table 1 Symbols used in the problem formulation

Notation	Meaning
A	target area
A_d	sensor node deployable area ($A_d \subseteq A$)
A_m	monitoring area ($A_m \subseteq A$)
$cost(p)$	cost for deploying a sensor node at location p
O_{static}	set of static obstacles
O_{mobile}	set of mobile obstacles
S	set of sensor nodes
$s.pos$	location where sensor node s is deployed($s \in S$)
r_s	sensor node's sensing radius
r_c	sensor node's communication radius
$sink$	sink node that collects data from all deployed sensor nodes

3.1 Assumptions

3.1.1 Target space for deploying WSN

We denote the target 3D space by A. In A, there are some objects called *obstacles* that may obstruct communication and/or sensing by sensor nodes. Obstacles that do not move are called *static obstacles*, and those that move are called *mobile obstacles*. We denote the set of static obstacles and the set of mobile obstacles by O_{static} and O_{mobile}, respectively.

We call the subarea to be monitored in A, *monitoring area* and denote it by A_m. The subarea of A where sensor nodes can be installed is called *deployable area* and we denote it by A_d. The cost for installing a sensor node changes depending on the location[⋆1] in A_d. Let $cost(p)$ denote the cost for installing a sensor node at location $p \in A_d$.

3.1.2 Sensor nodes

We consider only static nodes to be deployed in the 3D WSNs. Each sensor node has wireless communication capability. Its sensing range and communication range are represented by a sphere with the node at its center. We assume that all the sensor nodes have identical sensing radius r_s and communication radius r_c. We denote the sensing range of sensor node s by $s.range$.

Sensing range and communication range of each sensor node can be obstructed by obstacles. We assume that the sensor node cannot sense the information from the shadow area in the sensing region generated by obstacles. Moreover, we assume that two sensor nodes within distance r_c can communicate with each other only if the line-of-sight (LoS) exists between them, that is, no obstacle obstructs the straight line between the nodes.

3.1.3 Moving obstacle

We consider only human body as moving obstacles. The region in which the moving obstacle can horizontally move, called *moving region* is identical to the monitoring space.

3.2 Problem formulation

Given a three dimensional indoor space A, a set O of static and and mobile obstacles ($O = O_{static} \cup O_{mobile}$) in A, sensor node deployable area A_d ($\subseteq A$) with cost function $cost(p)$ ($\forall p \in A_d$), the monitoring area $A_m (\subseteq A)$, a sink node *sink* and its position *sink.pos*, our target problem is to determine the number of sensor nodes and their installing positions to achieve the mobile k-coverage of A_m and the connectivity of all sensor nodes to *sink* while minimizing the total sum of deployment cost.

Let S denote the set of sensor nodes for deployment. Each sensor node $s \in S$ must be deployed at some location in A_d. When we denote the deployed position of sensor node s by $s.pos$, the following equation must hold.

$$\forall s \in S, s.pos \in A_d \tag{1}$$

3.2.1 Mobile k-coverage

Each monitoring point m ($m \in A_m$) is *covered* by the sensor node s only if it is located within the sensing range $s.range$ and not in the shadow area. m is *k-covered* when it is covered by at least k sensor nodes.

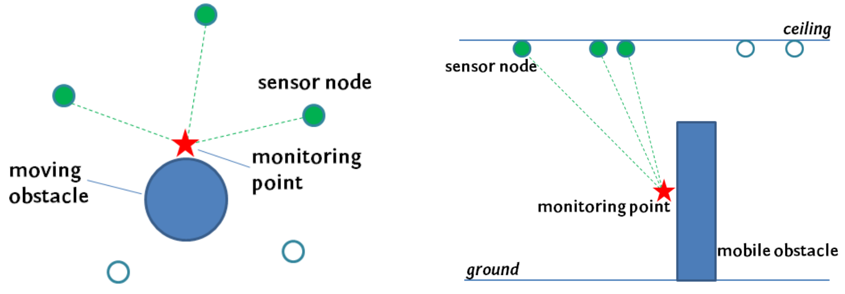
We say that the monitoring area is *mobile k-covered* if, for any location of mobile obstacle, each monitoring point m is k-covered as shown in Fig. 1. The following equation must hold.

$$\forall m \in A_m, \forall mobile\_pos \in A_m, \mid \{s \mid s \in S \wedge m \in s.range \backslash Shadow(s, mobile\_pos)\} \mid \geq k \tag{2}$$

Here, $Shadow(s, mobile\_pos)$ represents the shadow area in $s.range$ when a mobile obstacle exists at position *mobile_pos*.

3.2.2 Connectivity

We say that a sensor node s is *connected* when it has a connected path to the sink node *sink*. To ensure the connectivity of the whole WSN, the following equation must hold.



(a) Top view (b) Side view

Fig. 1 Mobile k-coverage (k=3).

[⋆1] In general, installing on ceiling/wall will be cheaper than in the air.

$$\forall s \in S, connected(s, sink) = true \tag{3}$$

where

$$\begin{aligned} connected(s, s') \overset{def}{=} & \mid (s, s') \mid \leq r_c \wedge LoS(s, s', O) = true \\ & \vee \exists s_1, \ldots, s_i \in S (1 \leq i), \\ & \mid (s, s_1) \mid \leq r_c \wedge LoS(s, s_1, O) = true \\ & \wedge \mid (s_1, s_2) \mid \leq r_c \wedge LoS(s_1, s_2, O) = true \wedge \ldots \\ & \wedge \mid (s_i, s') \mid \leq r_c \wedge LoS(s_i, s', O) = true \end{aligned} \tag{4}$$

Here, $LoS(s, s', O)$ is the boolean function that becomes true only if no obstacles of O obstruct the straight line between s and s'.

3.2.3 Objective function

Our target problem is to derive the set of sensor nodes S with their deployment positions that minimizes the overall deployment cost while taking into account the effects of the obstacles. Thus, using the above constraints, we define the objective function of our problem by the following equation:

$$\begin{aligned} & \textbf{minimize} \sum_{s \in S} cost(s.pos) \\ & \textbf{subject to constraints } (2) - (4) \end{aligned} \tag{5}$$

3.3 Complexity

Each deployable point p in A_d has a *cover-set* of monitoring points that is covered when a sensor node is deployed at p. The above defined problem is to derive a sub-family of cover-sets that covers all the monitoring points with the minimum overall deployment cost. Thus, if we assume that the constraint on the wireless connectivity between sensor nodes always holds, the above defined problem is equivalent to the minimum set cover problem known as a NP-hard problem. That means the above problem is also NP-hard.

4. Minimal cost mobile k-coverage algorithm

We propose a heuristic algorithm for computing a deployment pattern achieving the mobile k-coverage and wireless connectivity in an arbitrary 3D target space with stationary and moving obstacles, while minimizing the overall deployment cost.

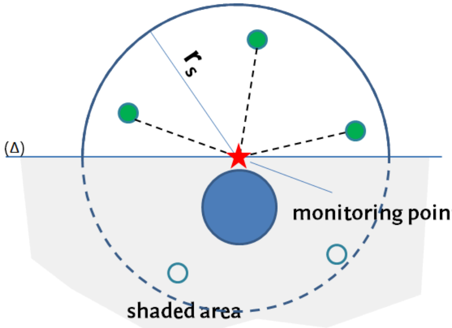


Fig. 2 Condition for mobile k-coverage (top-view, k=3).

4.1 Preliminaries

Considering a monitoring point located near a mobile obstacle at a given time, we define the *shaded area* as the half-space, that contains the mobile obstacle and bounded by the vertical plane (Δ) tangent to the monitoring point and orthogonal to the line between this point and the mobile obstacle. The sensor nodes located in that shaded area cannot sense the considered monitoring point due to the influence of the mobile obstacle. We then provide a sufficient condition for mobile k-coverage: the half-sphere of radius r_s centered at the considered

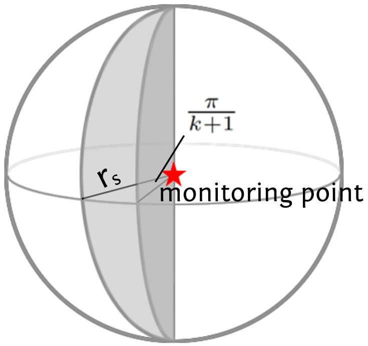


Fig. 3 Spherical wedge

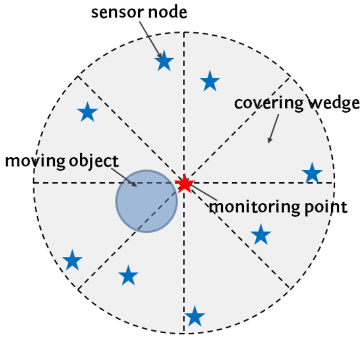


Fig. 4 Covering wedges (k=3)

monitoring point, that is not in the shaded area, contains at least k sensor nodes as shown in Fig. 2. Based on this condition, we propose an algorithm that determines for each monitoring point its covering spherical wedges of angle $\frac{\pi}{k+1}$ and radius r_s as shown in Figs. 3 and 4, and puts at least one sensor node in each wedge. The algorithm then adjusts the position of each unconnected sensor node and/or adds extra nodes taking into account obstacles influence.

For any location of a mobile object, each target monitoring point has to be sufficiently covered. For that purpose, we first determine the covering wedges for each uncovered monitoring point.

A monitoring point is considered to be k-covered if there is at least one sensor node located in each of its covering spherical wedges, and there is no obstacle that obstructs LoS to the monitoring point. Then, we count the number of covering wedges to which each deployable point belongs. Given the cost of each deployable point, our algorithm computes, for each deployable point, its per-cost volume that is the quotient of the number of spherical wedges containing the point by the deployment cost of the point. It then puts the sensors one by one at the deployable grid points in the descending order of their per-cost volumes until the target monitoring space is fully covered.

4.2 Mobile k-coverage algorithm

The pseudo code of the algorithm is given in Algorithm 1.

M and D are the sets of monitoring and deployable points, respectively. W is the set of the covering wedges.

For each deployable point, the *per-cost volume* is the number of covering wedges in which it is located per unit deployment cost. The *per-cost volume* of the deployable point d is defined by:

$$\textit{per-cost volume}(d) = \frac{|\{W_i \mid W_i \in W \wedge d \in W_i\}|}{\textit{cost}(d)} \tag{6}$$

At first, for each monitoring point, the algorithm computes its covering spherical wedges (lines 3 to 6). Then, the per-cost volume dc for each deployable point is computed and the deployable point with the highest per-cost volume is selected (lines 7 to 17).

At each iteration, the algorithm updates the status of each covering wedge and checked whether the target monitoring space is sufficiently covered (lines 18 and 19). The status of a covering spherical wedge is a boolean function that returns true if at least one sensor is deployed inside the considered spherical wedge. The above steps are repeated until M is mobile k-covered.

Algorithm 1 Minimal cost mobile k-coverage algorithm

```
1:  $W = S = \emptyset$
2:  while $M$ is not mobile $k$-covered do
3:      for each $m \in M$ do
4:          $Wm = coveringWedges(m)$
5:          $W = W \cup Wm$
6:      end for
7:      $maxdc = 0$
8:      for each $d \in D$ do
9:          $dc = numberOfCoveringWedges(W, d)/deploymentCost(d)$
10:         if $maxdc < dc$ then
11:             $maxdc = dc$
12:             $d^* = d$
13:         end if
14:     end for
15:     $s.pos = d^*$
16:     $S = S \cup \{s\}$
17:     $D = D \setminus \{d^*\}$
18:     $updateWedgesStatus(W)$
19:     $updateCoverageLevel(M, S)$
20: end while
21: $C = connectedSensors(S)$
22: $U = S \setminus C$
23: while $U$ is not empty do
24:     $s_u = closestUnconnectedSensor(C, U)$
25:     $s_c = closestSensor(C, s_u)$
26:     $moveSensors(s_u, s_c)$
27:     if not $connected(s_u, s_c)$ then
28:         $addMoreSensors(S, s_u, s_c)$
29:     end if
30:     $U = U \setminus \{s_u\}$
31:     $C = C \cup \{s_u\}$
32: end while
```

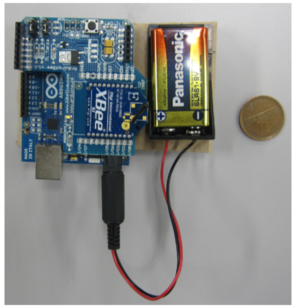


Fig. 5 Wireless device.

To achieve the desired connectivity in the deployed WSN, we use the same *point refinement* algorithm as described in 4) (lines 21 to 32).

5. Evaluation: Deployment in an existing indoor environment

In order to confirm the correctness of sensor deployment computed by the proposed method, we constructed a WSN testbed by deploying sensor nodes in a seminar room of the Ito Laboratory, NAIST. We then evaluated the coverage at different points of the monitoring area.

5.1 Experimental settings

As a sensor node, we used a XBee module mounted on an Arduino Uno board. A 9V battery supplies the power to the device. The device is shown in Fig. 5.

The specifications of the XBee module are given in the Table 2.

Table 2 XBee Specifications

Commercial Name	XBee 802.15.4 low-power module with chip antenna
Transmission power	1mW
Indoor/Urban range	Up to 30m
RF data rate	250 Kbps
Receiver sensitivity	-92dBm

In order to use the device as a sensor whose sensing radius is 5m, we calibrated the device on the lowest transmission power level and measured the $rssi_0$, that is the average Received Signal Strength Indicator (RSSI) of a packet sent from another ZigBee device placed at 5m distance. $rssi_0$ was -60dBm as shown in Table 3.

Table 3 Measured RSSI values.

Distance (m)	3	4	5	6
RSSI value(dBm)	-56	-60	-60	-63

After the deployment, measuring the RSSI at a certain sensor node of a message sent from a target point will allow us to confirm whether this target point is covered by the considered sensor node: if the measured RSSI is greater than $rssi_0$, then the target point is covered by the sensor node.

After deploying the sensor nodes in the indoor environment, a node (tag node) with wireless capability, that broadcasts a 32-bit beacon, is set at different monitoring points in the target area. When a sensor node receives a beacon message, it computes and sends the value of the RSSI along with its own ID *node_id* to the sink node, as shown in Fig. 6. The message with (node_id, rssi) is then processed and saved to a log file with the timestamp. The X-CTU program provided by DIGI[15] was used to configure the parameters of the XBee modules. The program to compute the RSSI value at the sensor node is written using the Arduino 0021 application[12] with the xbee-arduino open-source library[13]. Moreover, to process the incoming data at the sink node, we developed an application based on the

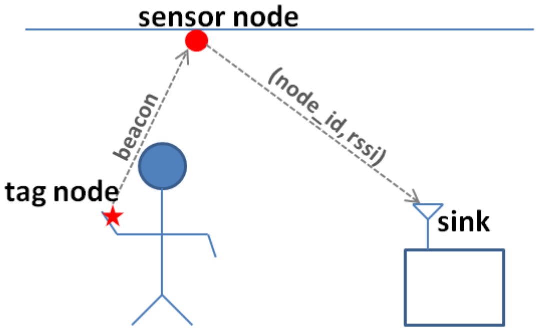


Fig. 6 Coverage measurement.

xbee-api Java API[14)].

5.2 Deployment for 3-coverage with mobile obstacles

In indoor localization systems, each monitoring point must be covered by at least 3 sensor nodes (3-coverage constraint). Additionally, the human shadowing effect can highly affect the communication between the tag node and the sensor nodes, thus leading to some detection errors.

Supposing an indoor localization system, in this experiment, we deployed a WSN to achieve a mobile 3-coverage of a target monitoring area (2.5m x 2.5m) as shown in Fig. 7.

We took into consideration the effect of the human body on the communication and checked the coverage level at different positions. The target monitoring area is a horizontal plane located 1m above the floor. Given the sensing range r_s=5m, our algorithm output the positions of the 9 sensor nodes to achieve the mobile 3-coverage of the monitoring area. After deploying the sensor nodes, we set the tag node at 4 positions in the target area (P1 to P4) as shown in Fig. 7. To generate the human body shadowing effect, the user stands near the tag node at a distance of 5 to 10 cm. The user changed position among UP1 to UP4 as shown in Fig. 8, and for each position, we measured the RSSI values at the sensor nodes.

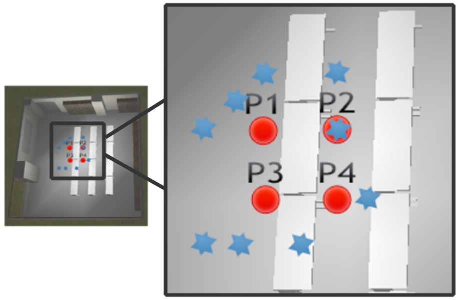


Fig. 7 Top view of the target area.

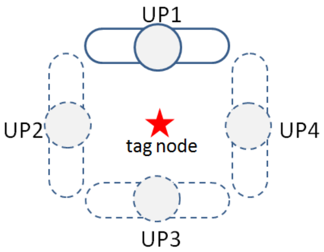


Fig. 8 User's position around the tag node.

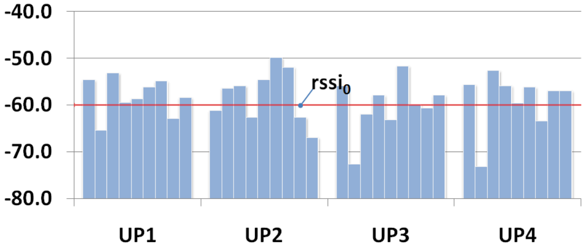


Fig. 9 RSSI measurement at P1.

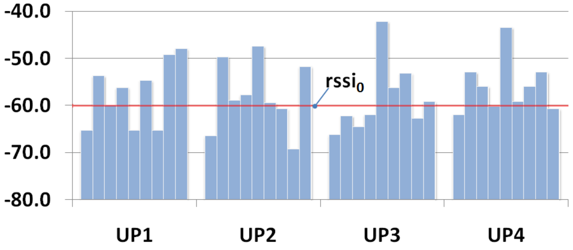


Fig. 10 RSSI measurement at P2.

In Figs. 9, 10, 11 and 12, we show the RSSI measured at the 9 sensor nodes for UP1, UP2, UP3, and UP4, respectively. In the graphs, the red line represents the threshold $rssi_0$, and the bars beyond the line indicate that the corresponding sensor nodes covered the monitoring point. At some positions, the RSSI value is lower than -76dBm, and this shows the influence of the human body shape on ZigBee communication.

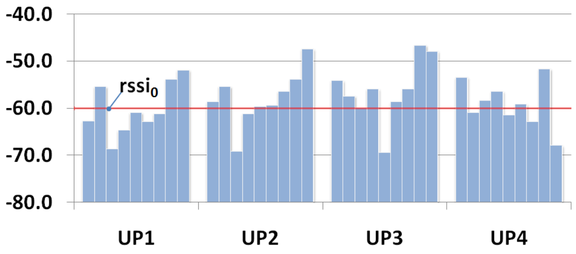


Fig. 11 RSSI measurement at P3.

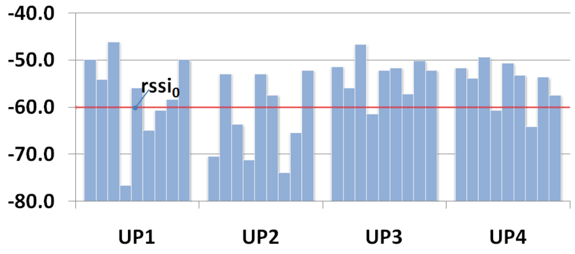


Fig. 12 RSSI measurement at P4.

However, at every position in the target area, there are at least 3 sensors at which the RSSI value is higher than $rssi_0$. This suggests that our method can compute accurate WSN deployment that achieves the mobile k-coverage in an actual indoor space.

6. Conclusion

In this paper, we studied the problem of sensor nodes deployment of three-dimensional WSNs and proposed a heuristic algorithm that computes WSN deployment ensuring mobile k-coverage of the target monitoring space. Through experiments to deploy actual sensor nodes in an existing indoor space, we confirmed that the computed deployment achieves mobile k-coverage.

As part of the future work, we will consider the sensing range shape other than sphere as well as physical quantity types other than radios.

References

1) M. Klepal, R. Mathur, A. McGibney, and D. Pesch, “Influence of People Shadowing on Optimal Deployment of WLAN Access Points,” *60th IEEE Vehicular Technology Conference 2004-Fall, VTC2004-Fall*, pp. 4516–4520, Sep. 2004.
2) S. Collonge, G. Zaharia, and G. Zein, “Influence of the human activity on wide-band characteristics of the 60 GHz indoor radio channel,” *IEEE Trans. Wireless Commun., vol. 3, no. 6*, pp. 2396–2406, Nov. 2004.
3) M. Flament and M. Unbehaum, “Impact of shadowing fading in a mm-wave band wireless network,” *Proc. Int. Symp. Wireless Personal Multimedia Communications (WPMC 2000), vol. 1*, pp. 427–432, Nov. 2000.
4) M. T. Kouakou, S. Yamamoto, K. Yasumoto, M. Ito, “Cost-Efficient Deployment for Full-Coverage and Connectivity in Indoor 3D WSNs,” *Proc. IPSJ Dicomo 2010*, pp. 1975–1982, July 2010.
5) M. T. Kouakou, S. Yamamoto, K. Yasumoto, M. Ito, “Deployment Planning Tool for Indoor 3D-WSNs,” *Adj. Proc. of UbiComp 2010*, pp. 369–370, Sep. 2010.
6) S. M. N. Alam and Z. J. Haas, “Coverage and connectivity in three-dimensional networks,” *Proc. of ACM MobiCom 2006*, pp. 346–357, Sep. 2006.
7) X. Bai, C. Zhang, D. Xuan, J. Teng, and W. Jia, “Low-Connectivity and Full-Coverage Three Dimensional Wireless Sensor Networks,” *Proc. of ACM MobiHoc 2009*, pp. 145–154, May 2009.
8) X. Bai, C. Zhang, D. Xuan, and W. Jia, “Full-Coverage and k-Connectivity (k = 14, 6) Three Dimensional Networks,” *Proc. of IEEE INFOCOM 2009*, pp. 388–396, April 2009.
9) M. K. Watfa and S. Commuri, “A coverage algorithm in 3D wireless sensor networks,” *Proc. of the 1st Int’l. Symp. on Wireless Pervasive Computing (ISWPC 2006)*, pp. 10–16, Jan. 2006.
10) S. Obayashi and J. Zander, “A body-shadowing model for indoor radio communication environments,” *IEEE Trans. Antennas Propagat., vol. 46*, pp. 920–927, June 1998.
11) M. Varshney, J. Zhengrong, M. Takai, and R. Bagrodia, “Modeling environmental mobility and its effect on network protocol stack,” *Wireless Communications and Networking Conference, 2006 (WCNC 2006)*, pp. 587–592, April 2006.
12) Arduino 0021 Application, `http://arduino.cc/en/Main/Software`
13) xbee-arduino Library, `http://code.google.com/p/xbee-arduino/`
14) xbee-api Library, `http://code.google.com/p/xbee-api/`
15) Digi International Inc.: “X-CTU Configuration and Test Utility Software: User’s Guide,” (2008). `http://www.digi.com/support/productdetl.jsp?pid=3352&osvid=57&s=316&tp=5&tp2=0`