K-BARRIER COVERAGE WITH A DIRECTIONAL SENSING MODEL

Kuo-Feng Ssu, Wei-Tong Wang, Feng-Kuang Wu, Tzu-Ting Wu
Department of Electrical Engineering
National Cheng Kung University

Abstract- The use of wireless sensor networks to protect sensitive facilities or international borders has attracted more and more attention. In contrast to previous studies in which the barrier coverage problem was solved under the assumption of an omni-directional sensing model, the current study presents a scheme for constructing k-barrier coverage using randomly deployed sensors with directional sensing model. The performance of the proposed scheme was evaluated using the ns-2 network simulator and compared with that of an omni-directional sensing scheme. Overall, the results show that for a given sensing range, the proposed directional sensing scheme achieved k-barrier coverage with a fewer number of active sensor nodes than the omni-directional sensing method. Moreover, the directional sensing scheme demonstrates a more robust ability than the omni-directional sensing method in constructing k-barrier coverage as the length of the belt increases or the node density within the sensing field decreases.

Index terms: Wireless sensor networks, directional sensing model, barrier coverage.

I. INTRODUCTION

Wireless sensor networks (WSNs) are a particular class of ad-hoc networks comprising battery-operated microsensor nodes with basic signal processing and computational capabilities. These nodes collect the data of interest within the sensing field and transmit them to a sink, typically located outside of the sensing field, for further processing. Typical WSNs comprise hundreds or even thousands of individual sensor nodes and are generally deployed in large-scale, unstructured environments which are difficult to be monitored manually. Typical applications of WSNs include environmental and process monitoring, forest fire encroachment, battlefield surveillance, traffic control, health-care, target tracking, and so forth. However, the sensors in such networks are battery-powered and therefore have a finite life since it is generally impossible to replace the batteries once the sensors have been deployed. Consequently, when designing and implementing WSN applications, a major concern is to optimize the coverage and reliability of the network

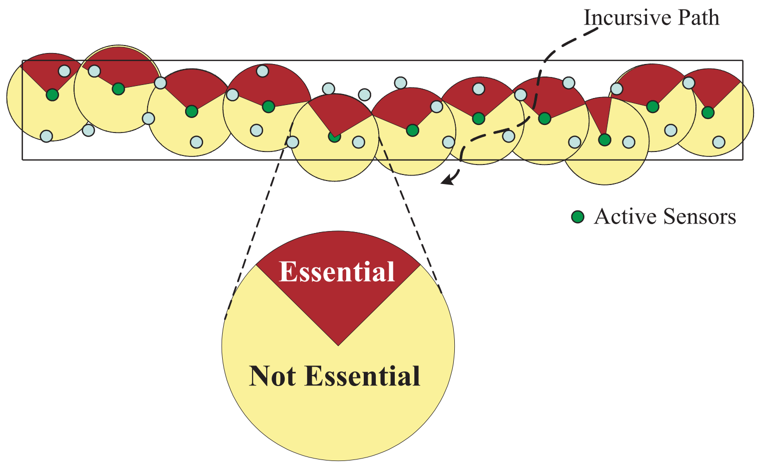

Figure 1. Barrier coverage using sensors with omni-directional sensing model.

whilst simultaneously minimizing the energy consumed during the sensing operation. This is commonly achieved using sophisticated adaptive scheduling mechanisms in which the bare minimum of active nodes required to cover the sensing field is maintained at all times while the remainders are allowed to sleep.

A common application of WSNs is border surveillance in which the sensor nodes are deployed in a long, narrow region along the boundary of interest with the aim of detecting unauthorized intrusions. This type of application is conventionally referred to as barrier coverage [8] and has attracted increasing interest in the literature in recent years as the requirement to protect sensitive military facilities and international borders has grown.

Figure 1 presents a typical example of a barrier coverage application. In this example, the barrier coverage is constructed using an omni-directional sensing model, i.e. each sensor is assumed to have a perfectly disk-like sensing area. However, it can be seen that only an upper sector of each sensing area is actually required to create a continuous barrier. The energy consumed in maintaining a sensing operation over the remainder of the sensing area is effectively wasted, and thus the network fails to meet one of the primary goals of WSN implementations, namely the need to minimize the energy consumption within the network.

In practice, it is desirable to build a certain degree of redundancy into the barrier coverage network in order to ensure that the detection capability can be maintained even in the event that some of the sensors fail (e.g. as a result of malfunction, malicious damage, battery life expiry,

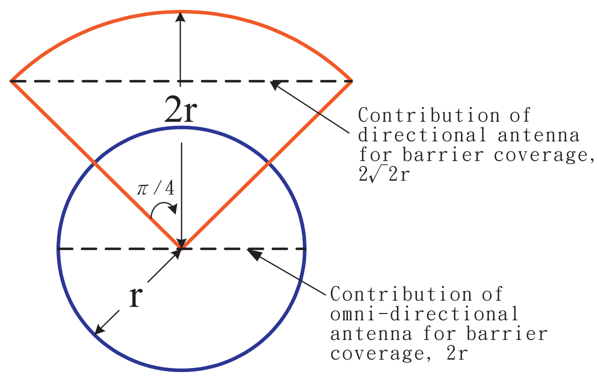

Figure 2. Relative contributions to coverage path of sensors with omni-directional and directional sensing model, respectively.

and so forth). Thus, the capabilities of WSN border detection schemes are generally described in terms of their *k*-barrier coverage property, where *k* indicates that the object penetrating the network will be detected by a minimum of *k* distinct sensors before it exits the monitored area. As discussed above, the use of sensors with the omni-directional sensing model inevitably wastes a major part of the energy invested in the network. A more energy-efficient solution can be obtained by using sensors equipped with directional antennae orientated in such a way that the sensing area covers just a limited sector of the boundary length. By activating appropriate nodes within the network, the entire boundary length can thus be continuously monitored at a energy consumption lower than that incurred in an omni-directional sensing scheme. Figure 2 compares the contribution to the coverage path of two sensors with an omni-directional antenna and a directional antenna with a beam width of $\pi/4$, respectively. As shown, for an equivalent sensing energy consumption, the directional antenna yields a greater contribution to the overall coverage path.

This study presents a scheme for the construction of *k*-barrier coverage within a long, belt-like region containing randomly deployed directional sensor nodes. In constructing the barrier coverage, the proposed scheme considers both the location and the antenna directions of the nodes within the sensing field. A series of simulations were performed to investigate the effectiveness of the proposed scheme in constructing *k*-barrier coverage under various belt length, node density and sensing range conditions. The performance of the proposed directional sensing scheme is compared with that of a conventional omni-directional method in terms of the number of active nodes required to satisfy the specified *k*-barrier coverage requirement and the success rate in constructing the *k*-barrier coverage. Overall, the results show that given the assumption that the directional nodes and the omni-directional nodes have an equivalent sensing range, the directional sensing scheme requires significantly fewer active nodes to construct the specified *k*-barrier coverage and has a more robust ability to construct *k*-barrier coverage as the length of the belt increases or the node density decreases.

II. RELATED WORK

The WSN coverage problem generally involves evaluating the number of sensors required to cover a defined sensing field with the specified degree of redundancy. O'Rourke [6] considered the coverage problem within the context of an art gallery and showed that the problem could be optimally solved when specified in a 2D plane, but became NP-hard when extended to 3D space. Previous studies have generally focused on the requirement to achieve the complete coverage of a specified field [5, 7, 9, 13, 15]. In such schemes, the goal is to ensure that every point of the monitored area is covered by active sensor nodes.

The concept of barrier coverage was first discussed by Gage [8] in the context of control schemes for multi-robot systems. In essence, the fundamental difference between the conventional coverage problem and the barrier coverage problem lies in the fact that in the latter case, the subject to be covered is not explicitly known prior to sensor deployment and the coverage model is no longer a simple 0/1 model. Rather, each point in the monitored area is assigned a positive value to indicate how it is monitored by the deployed sensors.

Kumar *et al.* [8] showed that the *k*-barrier coverage problem is equivalent to the problem of establishing *k* node-disjoint paths between two vertices in a graph. The authors concluded that it was impossible to verify whether a given belt region was *k*-barrier covered using local determination schemes. However, they showed that when the sensors were deployed deterministically, the optimal deployment pattern which ensured *k*-barrier coverage was simply to deploy *k* rows of sensors across the width of the belt region along its total length and to space the sensors such that the sensing ranges of adjacent sensors abutted one another.

Ma and Liu [10] proposed a systematic method for the deployment of sensor nodes with directional sensing model. They also considered the connectivity problem of sensors with directional communication model. They showed that to achieve the same coverage probability, less number of

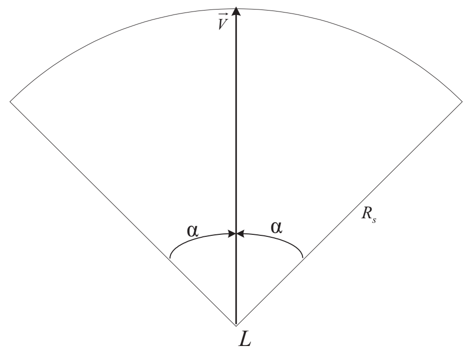

Figure 3. Directional Sensing Model.

directional sensors is needed than the omni-directional ones. Ai and Abouzeid [1] investigated the maximum coverage with minimum sensors (MCMS) problem for the case of a network containing randomly deployed directional sensors. The authors solved the problem using a distributed greedy algorithm (DGA) and then modified the DGA to take account of the sensors' residual energy in order to develop a sensing neighborhood cooperative sleeping (SNCS) scheme to enable adaptive sensor scheduling over a longer time frame.

III. SYSTEM MODEL AND ASSUMPTIONS

All of the deployed nodes are assumed to be functionally equivalent and are aware of their positions. They are static and randomly deployed in the sensor field with uniformly distribution. The omni-directional communication model is used here. The communication range of each sensor is more than twice of the sensing range.

This study considers the problem of establishing *k*-barrier coverage within a thin, belt-like boundary region containing randomly deployed directional sensors. The analysis is based upon a two-dimensional sensing field in which the sensing area covered by each sensor s is represented by the 4-tuple $(L_s, R_s, \overrightarrow{V_s}, \alpha_s)$, where L_s is the location of *s*, R_s is the sensing radius, $\overrightarrow{V_s}$ is the sensing direction of *s*, and α_s is the offset angle of the sensing beam of *s* (see Figure 3). Clearly, the conventional omni-directional sensing model is simply a special case of this model in which the beam width, α, has a value of π.

In the directional sensing model, a point P is said to be covered by the sensor s if and only if the following conditions are met:

1) $d(L_s, P) \leq R_s$, where $d(L_s, P)$ is the Euclidean distance between the sensor, s, and the

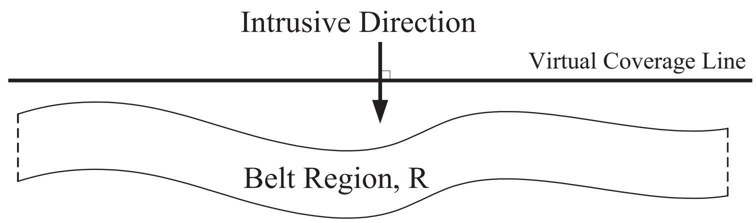

Figure 4. Virtual coverage line and intrusive vector.

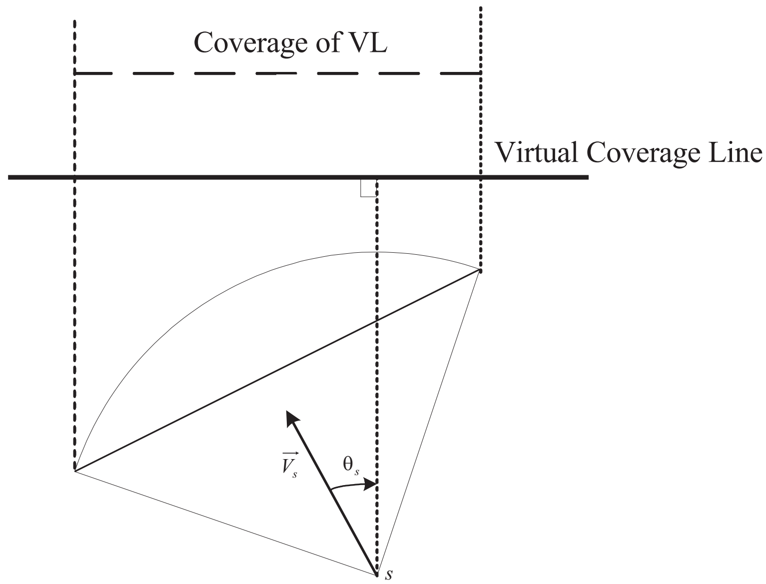

Figure 5. Coverage angle.

point, P.

2) The angle between $\overrightarrow{L_sP}$ and $\overrightarrow{V_s}$ lies within the interval $[-\alpha_s, \alpha_s]$, which means $\overrightarrow{L_sP} \cdot \overrightarrow{V_s} \geq \|\overrightarrow{L_sP}\| \cos \alpha_s$

Definition 1 (Virtual Coverage Line - VL*):* The straight line that connects the right and left ends of the belt region (Fig. 4).

Definition 2 (Intrusive direction): The direction from which the intruder approaches the deployed sensor network. It is orthogonal to the virtual coverage line.

Definition 3 (Coverage Angle of a sensor): The angle which is between the intrusive direction and the sensing direction of the sensor. As shown in Figure 5, the coverage angle of s is θ_s.

Definition 4 (Coverage Line of a sensor on VL *- CL):* The contribution made by the sensor s to the barrier coverage is given by the projection of the sensing sector on virtual coverage line.

As shown in Figure 5, the coverage line provided by the sensor s is denoted as CL_s, where $CL_s = (2R_s \cos\alpha_s) \times \cos\theta_s$.

Definition 5 (1-barrier Coverage): If each point on the *VL* is covered by at least one sensor, the belt region is said to have 1-barrier coverage.

Definition 6 (k-barrier Coverage): If there are k sets of sensors, namely $S_1, S_2, ..., S_k$, and $S_i \cap S_j = \emptyset, \forall i, j \in \{1, ..., k\}, i \neq j$ and S_i ($i = 1, \ldots, k$) constructs 1-barrier coverage, then the sensing field is k-barrier coverage.

IV. CONSTRUCTION OF K-BARRIER COVERAGE IN RANDOMLY DEPLOYED SENSOR FIELD

This section develops a distributed algorithm for constructing k-barrier coverage in randomly deployed sensor fields containing directional sensors. The algorithm commences by selecting a single node within the network as the initial active node. This node not only forms the starting node in the first barrier within the sensing field, but is also used as the basis from which to select starting nodes for each of the remaining (k-1) barriers within the network. Having identified starting nodes for all k-barriers, a node activation procedure is performed to select appropriate active nodes to extend each barrier along the length of the belt-like sensing field. In constructing the barriers, a ”roll back” mechanism is used to route the barrier around sparse areas of the sensing field and to prevent the intersection of neighboring barriers when required.

A. Selection of Initial Starting Node within WSN

The distributed k-barrier construction scheme commences by selecting an initial node (designated as the elected node, E_i) from which to determine a suitable starting node within the WSN. Each of the deployed sensors, i, is assumed to have a particular power level, P_i.

Initially, every node in the network nominates itself as the elected node and broadcasts its ID and power level to all of the other sensors within its communication range. Upon receiving these messages, each node retains only the ID of the node with the highest power level. It then rebroadcasts this information to all of the nodes within its own communication range. Ultimately, all of the nodes possess the ID of the sensor with the highest power level. This node is then recognized as the elected node within the network.

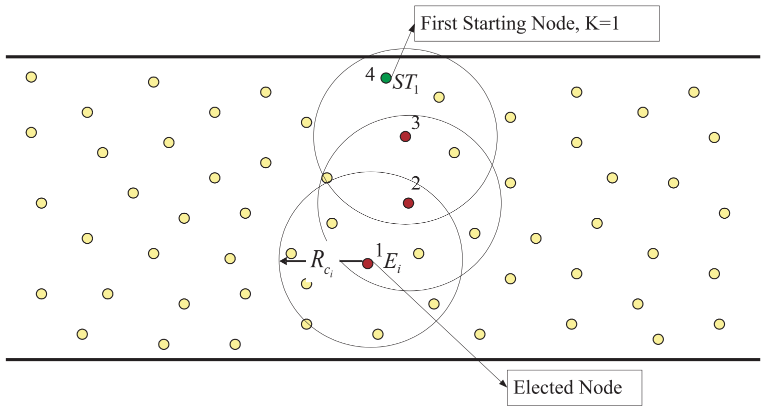

Figure 6. First Starting Node Selection.

The elected node, E_i, examines the positions of all of the sensors within its communication range, R_{c_i}, and nominates the node located closest to the external boundary of the sensing field as the next elected node. This node then repeats the same procedure to locate the next elected node. This iterative procedure continues until there are no neighboring nodes closer to the boundary than the current elected node. Once this condition has been achieved, the current elected node nominates itself as the first starting node, ST_1, in the network (see Figure 6).

B. Selection of Remaining Starting Nodes within WSN

The first starting node chosen in Section IV-A is used to construct the first sensor barrier (i.e. $k = 1$) within the sensing field. However, to satisfy the requirement for k-barrier coverage, $k - 1$ more starting nodes are required. The selection process commences by specifying a search range, μ, defined as $\mu = min\{B/k, R_c\}$, where B is the width of the sensing field, k is the number of required barriers, and R_c is the communication radius of each sensor. Subsequently, the starting node, ST_1, examines the positions of all the nodes located within μ and selects the node located at the greatest distance from the external boundary of the WSN as the next starting node (see Figure 7). Starting node ST_1 then sends a "RE-SN" (remaining starting node) message to the selected node together with its own location information. The new starting node, ST_2, examines all of the nodes located within μ from its own position and then selects the node located at the greatest distance from the previous starting node, ST_1, as the next starting node. This process is repeated iteratively until no more nodes can be found located at a greater distance from the

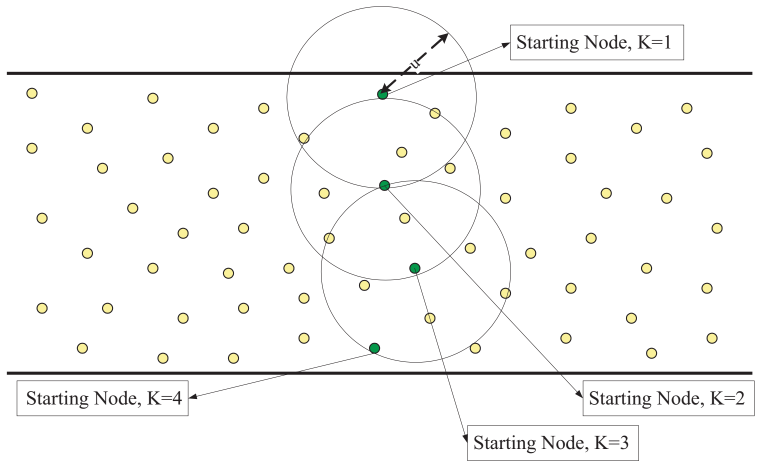

Figure 7. Remaining Starting Node Selection.

previous starting node than the current node.

C. Active Node Selection

After selecting the starting nodes for each barrier, these nodes are then used to activate appropriate nodes to extend the barrier toward the left- and right-hand end boundaries of the sensing field. In practice, each starting node initially computes two active node positions since the barrier must be extended in both the left and the right directions. Suppose the location of the starting node is L_s, the optimal position of the neighboring starting node is $L_{s_{opt}}$. The starting node then computes $L_{s_{opt}}$ by the following conditions:

1) The distance between L_s and $L_{s_{opt}}$ is $\sqrt{2}R_s$.
2) The vector which is formed by position of starting node and optimal position is orthogonal with the direction vector of the antenna of starting node. $\overrightarrow{L_s L_{s_{opt}}} \cdot \overrightarrow{V_s} = 0$

The starting node calculates the two optimal positions. Base on the $L_{s_{opt}}$, the starting node will choose the node which is closer to the $L_{s_{opt}}$ than others.

Having chosen appropriate active nodes on the left- and right-hand sides of the starting node (see Step 2 in Figure 8), the starting node sends the message ”ACT_SN” and the barrier serial number (i.e. $k = 1, 2, 3, \ldots, n$) to the nodes to activate them. Both nodes then repeat the procedure described above to activate new nodes to extend the barrier toward the corresponding end boundary of the sensing field (see Step 3 in Figure 8). The procedure is repeated iteratively until the sensing sectors of the current active nodes cover the two end boundaries.

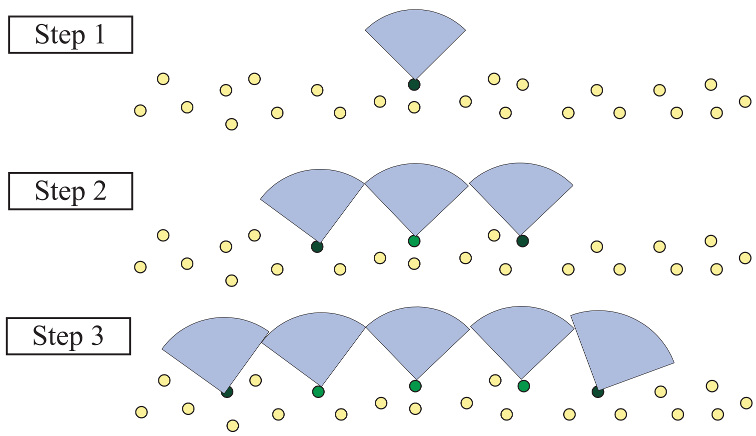

Figure 8. Active Node Selection.

D. Roll Back

In developing the *k*-barrier coverage construction scheme, an assumption is made that the sensors are randomly deployed with a uniform distribution. However, in a large-scale, real-world sensing field, the node density is liable to vary from one region of the network to another. If the node density falls below a certain threshold, it is possible that the current active sensor will be unable to locate a sensor within its communication range with which to extend the barrier along the length of the sensing field, and thus the barrier construction process fails. In addition, it is necessary to prevent the individual barriers from intersecting with one another since the intersection of two coverage paths will break the requirement of k-coverage.

A ”Roll Back” mechanism is employed to resolve both scenarios described above by finding an alternative coverage path within the network. If the current active node i discovers that there is no candidate node within its communication range or the only available next active node will cause the coverage path of i to intersect with another coverage path, it sends the message RB_i to the previous active node j and switches to an inactive state. Node j then marks node i as ”UNAVAILABLE” in its candidate list and restarts the ”Active Node Selection” procedure to locate an alternative new active node.

TABLE I

PARAMETERS FOR SIMULATIONS

simulator	ns-2.30
number of scenes	200
simulation time (sec)	40
transmission range (m)	35
beam width of directional model (m)	$\pi/4$
sensing range of directional model (m)	14
sensing range of omni-directional model (m)	7
number of barriers (K)	1, 2, 3
simulation area (m^2)	600 x 30
number of nodes	600

V. PERFORMANCE EVALUATION

A. Simulation Environment

In this study, the performance of the *k*-barrier construction scheme described in the previous section was evaluated and compared with that of a conventional omni-directional scheme using network simulator tool (NS-2) [12]. The aim of the simulations was to examine the efficiency and efficacy of the two schemes in constructing k-barrier coverage under various belt length, sensor density and sensing range conditions. The basic simulation parameters are presented in Table I.

The performance of the directional and omni-directional barrier construction schemes was evaluated using the following metrics:

- *Number of Active Sensors*: the number of active sensors required to establish the specified k-barrier coverage.
- *Success Ratio*: the percentage of simulation runs that the construction scheme successfully accomplished the specified k-barrier coverage.

B. Simulation Results

1) Various Belt Length: The simulations considered a total of nine different belt lengths ranging from 200*m* to 1000*m*. In every case, the width of the sensing field was specified as 30*m*, the

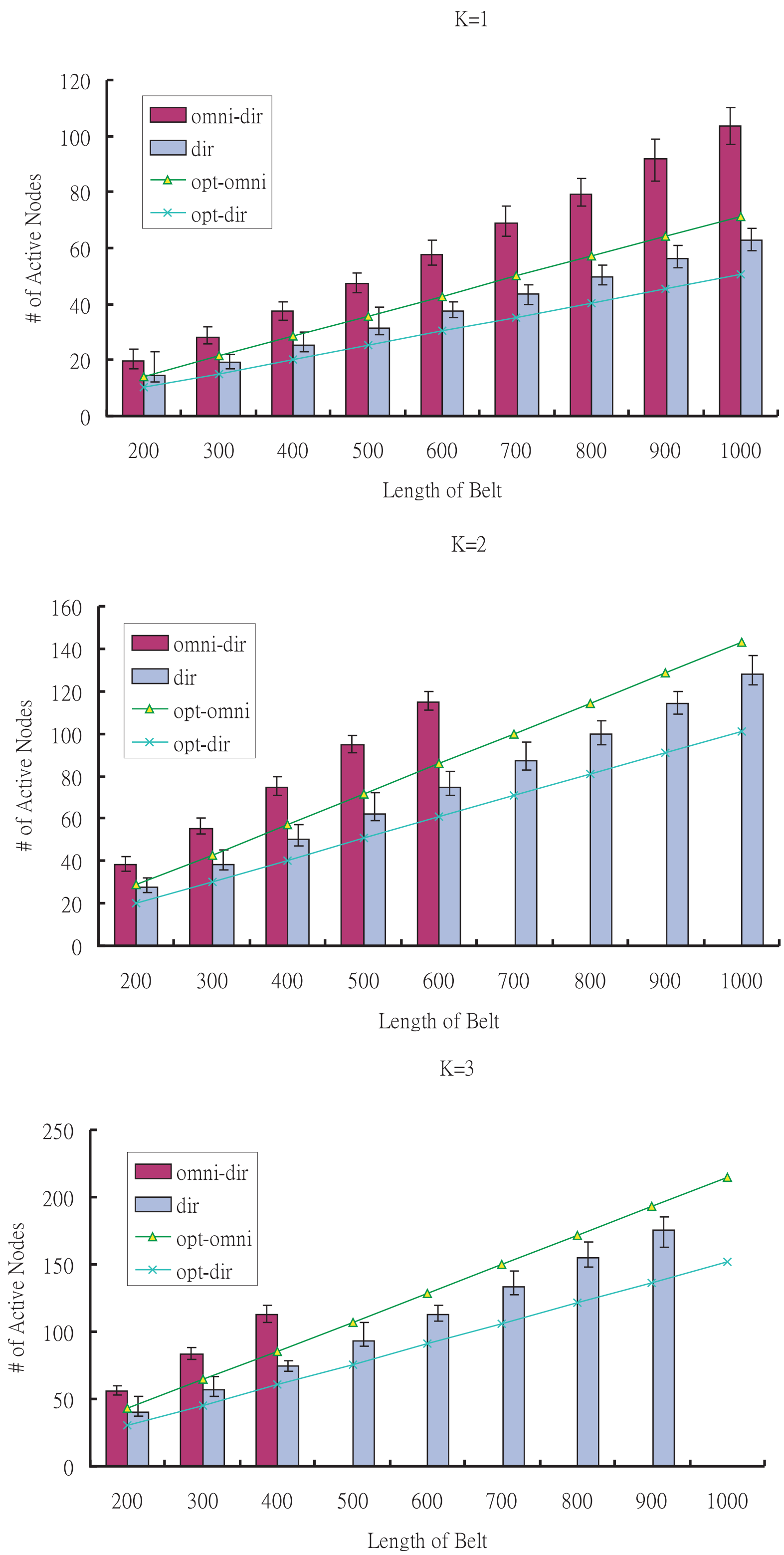

Figure 9. Active Node Number in Different Length of Belt.

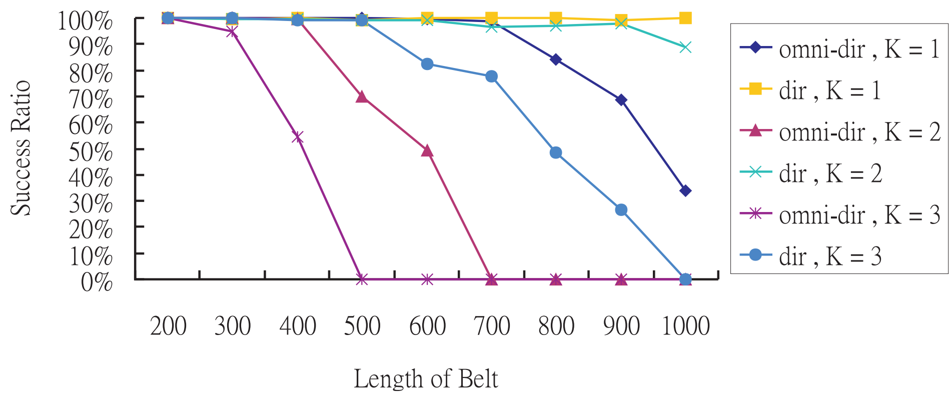

Figure 10. Success Ratio in Different Length of Belt

sensing field contained a total of 600 nodes.

Figure 9 illustrates the number of active nodes required under the directional and omni-directional models to construct k-barrier coverage in each of the nine sensing fields. The figure also shows the optimal number of active nodes required in each case when the sensors (both directional and omni-directional) were deployed using a deterministic strategy. It can be seen that for a given belt length, the number of active nodes required when using the directional sensing model is less than that of the omni-directional sensing model. The difference in the number of active nodes between the two construction schemes increases as the belt length increases. It can also be seen that the number of active nodes increases as the number of barriers, k, increases.

Figure 10 shows the success ratios of the two schemes with the specified k-barrier coverage in each of the nine belt-length scenarios. In general, the results show that the success ratios of both schemes reduce as the belt length increases. For a given simulation scenario, it is clear that the directional sensing model achieves a higher success ratio than the omni-directional model. The success ratio of the directional sensing model decreases more slowly with an increasing belt length than the omni-directional model. Hence, the directional sensing model has a more robust barrier construction capability.

It can be seen that when k is more than 1, the scheme with omni-directional sensing model cannot meet the coverage requirement while the proposed scheme can still meet the requirement because of the roll back procedure.

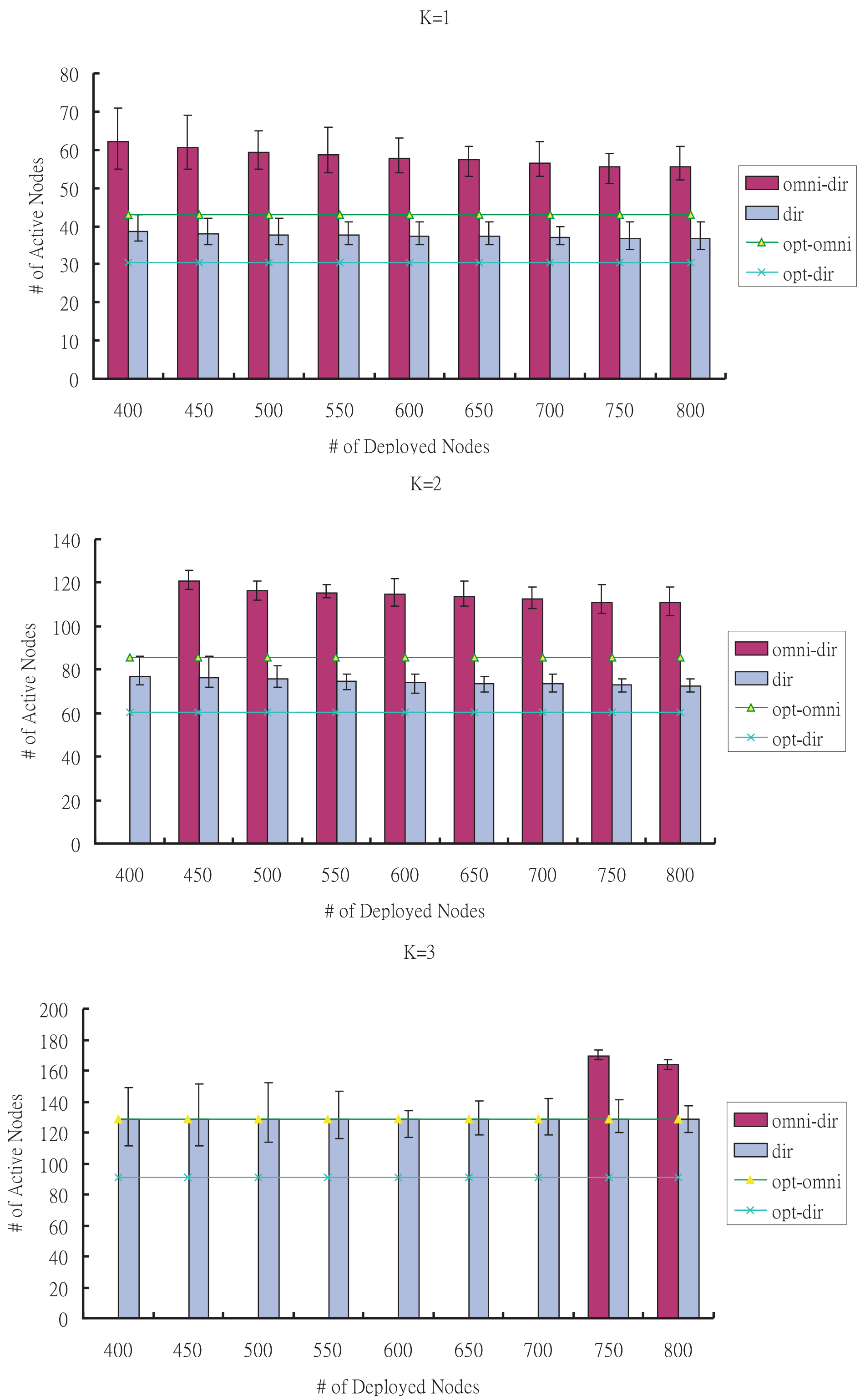

Figure 11. Active Node Number in Different Number of Deployed Sensors.

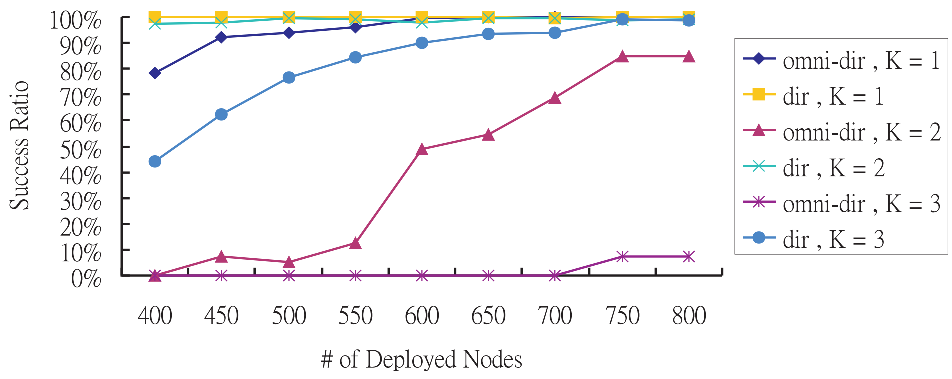

Figure 12. Success Ratio in Different Number of Deployed Sensors

2) Various Number of Deployed Nodes: Figure 11 illustrates the number of active nodes required to construct the specified k-barrier coverage with different numbers of the deployed sensors. The optimal results obtained from the deterministic deployment strategy are again presented for comparison purposes. The results clearly show that for a given simulation scenario, the number of active nodes required under the directional sensing model is lower than that under the omni-directional model. It is also found that in both schemes, the number of active nodes decreases slightly as the number of deployed nodes increases. It is because that when there are more deployed nodes, there exist more nodes that are closer to the optimal location.

Figure 12 shows the success ratios of the two coverage construction schemes as the number of deployed nodes is increased from 400 to 800. In general, the success ratio of both methods increases as the number of deployed nodes increases. However, for a given number of deployed nodes, it can be seen that the directional sensing model has a greater success ratio than the omni-directional model. The enhanced performance of the directional sensing model becomes particularly evident as the number of barriers is increased.

3) Various Sensing Range: Finally, a series of simulations was performed to compare the performances of the two coverage construction schemes for different values of the sensing range. In every simulation, the belt length was specified as 600 m and a total of 600 sensors were randomly deployed within the sensing field.

Figure 13 illustrates the number of active nodes required to construct the specified k-barrier coverage as the sensing range is increased from 12 to 18. The results show that for a given

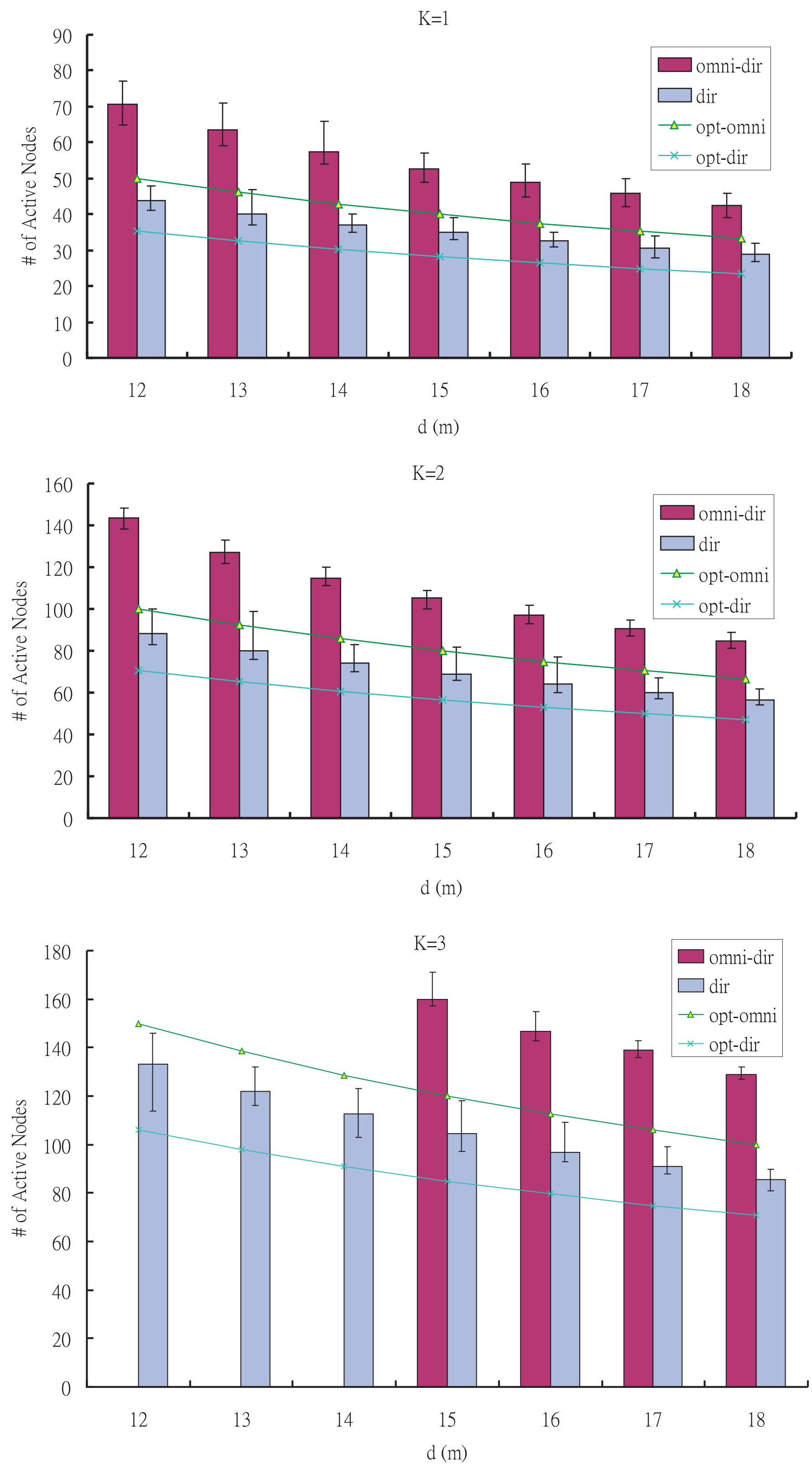

Figure 13. Active Node Number in Different Sensing Range.

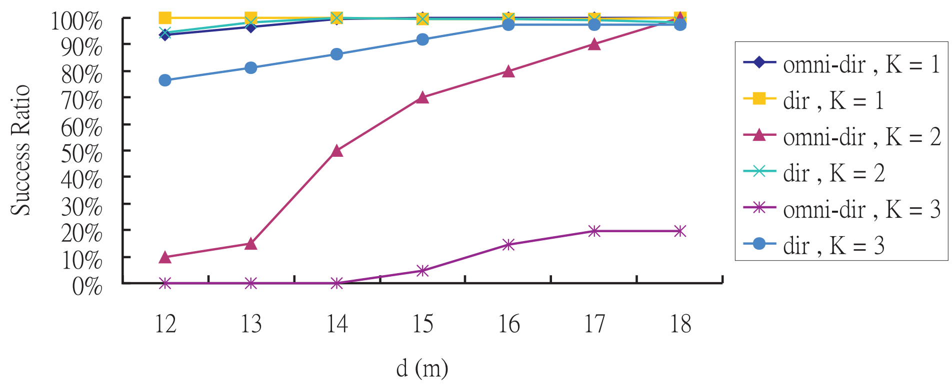

Figure 14. Success Ratio in Different Sensing Range

sensing range, the number of active nodes required under the directional sensing scheme is less than that required under the omni-directional sensing model. The enhanced performance of the directional sensing scheme becomes increasingly evident at lower values of the sensing range, which means the energy consumption could be reduced. For the 1-barrier coverage case and the sensing range of 12, the omni-directional sensing scheme requires around 28 more active nodes than the directional model. When the sensing range is increased to 18*m*, the difference reduces to around 15 nodes.

Figure 14 illustrates the success ratios of the two schemes in establishing the specified k-barrier coverage under different values of the sensing range. In both cases, the success ratio increases as the sensing range increases. However, for the same sensing range, the directional sensing model demonstrates an improved ability to construct the specified k-barrier coverage.

VI. CONCLUSION

This paper has presented a scheme for establishing k-barrier coverage within a long, narrow belt-like sensing field containing randomly deployed directional sensor nodes. The performance of the proposed scheme has been evaluated under various belt length, sensor node density and sensing range conditions and has been compared with that of a traditional omni-directional sensing model. The simulation results have shown that the directional sensing scheme demonstrates a greater success rate and fewer active sensors than the omni-directional model in satisfying the specified k-barrier coverage requirement under various belt length, sensor node density and sensing range conditions. Overall, the improved performance of the directional sensing model is attributed to the fact that the directional antenna constrains all of the sensing energy in the desired direction and thus increases the contribution of each sensor to the barrier coverage. The results have shown that the enhanced performance of the directional scheme is particularly apparent as the belt length and number of specified barriers increase, or as the node density and sensing range decrease.

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