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Multipath-based Relocation Schemes Considering Balanced Assignment for Hopping Sensors

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Abstract— **When sensors in wireless sensor networks fail or become energy-exhausted, redundant mobile sensors might be moved to cover the sensing holes created by the failed sensors. Within rugged terrains where wheeled sensors are unsuitable, other types of mobile sensors, such as hopping sensors, are needed. In this paper, we address the problem of relocating hopping sensors to the sensing holes. Recent study for this problem considered moving sensors along the shortest path. The shortest path might be used repeatedly and therefore create other sensing holes. In order to overcome these weaknesses, we propose multipath-based schemes considering the balanced assignment for the relocation of hopping sensors. Simulation results show that the proposed schemes guarantee a more balanced migration distribution of efficient sensors and a higher movement success ratio of required sensors than those of the shortest path-based schemes.**

I. INTRODUCTION

A Wireless Sensor Network (WSN) is a core technology that may improve interactions between humans and the environment in applications such as ubiquitous computing, military surveillance, smart homes, and office automation [1]. In order to accurately and energy-efficiently observe the phenomena of the requested sensing tasks, sensors must be initially deployed suitably [2]. WSNs usually consist of static sensors; nevertheless, imagine deploying a WSN by static sensors over environments such as remote harsh terrains, hostile territories, toxic regions, or disaster areas. Even if advanced methods such as airplanes can deploy the sensors safely and easily, there exist factors such as wind and physical obstacles that can disrupt deployment. Moreover, when some sensors become energy-exhausted, network coverage may be degraded. As a result, mobile sensors may be needed [3][4].

Mobile sensor nodes may move to a specific emergent area, or replace the power exhausted nodes. Early work on mobile sensors focused on designing algorithms to initially deploy mobile sensors [5]-[7]. In addition, they only consider sensor networks where all nodes are mobile, which limits the applicable sensor networks. Thus, the static sensors in [8] guide the mobile sensor nodes. In [9], authors also implement wheeled mobile sensors with Mica2/TinyOS. In practice, however, sensor mobility is limited within the physical environment. That is, if a sensor chooses to move to a desired location, it cannot do so without any limitation in the movement distance[10]. Moreover, it is not suitable for wheeled mobility to migrate in many rugged environments. In order to overcome these limitations, for example, a class of Intelligent Mobile Land Mine Units (IMLM) to be deployed across battlefields have been developed by DARPA [11][12]. The IMLM is based on a hopping mechanism. A hopping sensor with a bionic mobility design, such as a grasshopper or a frog, throws itself high and toward the target direction. In the IMLM, the hopping movements are described as a prototype minefield hopping robot. The prototype is 12 cm in diameter, 11 cm tall, weighs 1.8 kg. It can make 100 hops without refueling and can hop as high as 3 m.

In the lifetime of a WSN, if some sensors in a certain area are depleted faster than those of other areas, the areas are called sensing holes. Redundant sensors are allocated initially in the sensor field through a well planned deployment; thus, if a sensing hole is detected, some sensors could be moved to the sensing hole. In this paper, the problem of relocating the required hopping sensors to the detected sensing holes is studied. In [13], when a static sensor node may fail, the wheeled sensor node can move to the position of the failed node to replace it temporarily. In [14], the authors propose two shortest path-based relocation schemes based on the hopping movement. They also analyze the impact of wind under aerodynamic conditions. One scheme merely uses the shortest path considering minimum hops, while the other scheme uses a balancing the differences of hops among the relayed clusters in the obtained path. However, other sensing holes may occur easily or some sensors may exhaust quickly, because specific areas on the shortest path could be used repeatedly.

Due to the weakness of the shortest path-based scheme, it becomes necessary to consider the use of multiple paths. Multipath routing has been discussed extensively in literature to achieve load balancing and fault tolerance in computer networks. Load balancing splits traffic among multiple reliable paths connecting the source to the destination. Thus fault tolerance or robustness is an inherent feature of multipath routing [15]. Likewise, this paper proposes the multipath-based schemes considering balanced assignment in order to relocate hopping sensors to the sensing hole. Simulation results show that the proposed schemes guarantee a more balanced migration distribution of efficient sensors and a higher movement success ratio of required sensors than those of the shortest path-based schemes.

The remainder of this paper is organized as follows. Section II explains previous work. Section III presents details of the proposed schemes. Section IV evaluates our proposal

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by employing a simulation; and finally, Section V concludes this paper.

II. Previous Work

A. System, Sensors, and Hopping Inaccuracy Models

In [3], authors adopt a Grid-Quorum solution to locate the closest redundant sensors in a prompt manner. Quorum or broadcast based approaches can be used to match the cluster containing redundant sensors and the sensing hole cluster, which are called the supplier and consumer, respectively. In the proposed hopping model, we assume that a set of clusters is included in the WSN field, and the sensors are attached to each cluster. A cluster head is capable of the responsibility of properly distributing the sensors, detecting sensor deficiency, and selecting redundant sensors among the clusters. The problem of detecting sensing holes is studied in [7], [16], and [17].

We assume that hopping sensors are capable of adjusting their hopping direction. The sensors are also assumed to have a fixed propelling force for hopping. Compared with wheeled mobility, hopping sensors may lack accuracy of movement. In [14], the authors first analyze the impact of wind under aerodynamic condition and prove that the wind factors cannot heavily affect the performance; however, it is trivial for the hopping movement to be more susceptible to air disturbance than the wheeled mobility. In addition, hopping sensors could be more adaptable than wheeled sensors in such as harsh terrains. Here, probabilistic methods are used to express the movement inaccuracies along the hopping course.

In order to determine the model of landing accuracy between hops, we use a multivariate normal distribution. Let T and L be the targeted location and the actual landing location vectors, respectively. The displacement vector D can be expressed as $D = T - L$. Here, D is modeled by the two-dimensional normal distribution with the probability density function f_{XY}. We define an acceptable landing area as a disk S around the targeted location.

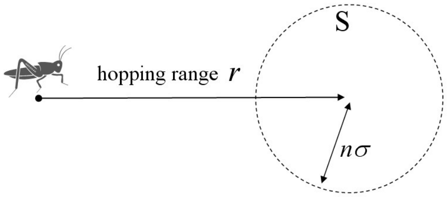


Fig. 1. A hopping accuracy model

As shown in Fig. 1, the radius of S is given as $n\sigma$ where, n is a multiplying factor. Hence, the probability that the hopping sensor lands in the acceptable landing area S can be represented as follows.

$$P(S) = \int\int_S f_{XY}(x,y)dxdy \tag{1}$$

Let l be the distance between clusters. The upper bound of the number of hops is as follows.

$$N_u = \left\lceil \frac{l}{r - n\sigma} \right\rceil \tag{2}$$

where, r is the hopping range. Therefore, a consumer cluster needs R sensors and can request E sensors from its previous cluster. E is calculated as follows.

$$E = \left\lceil R \cdot P(S)^{-N_u} \right\rceil \tag{3}$$

B. Shortest Path-based Relocation Schemes

If some sensing holes occur, the redundant sensors could be moved. At this time, system usually considers the shortest path in order to cover the sensing holes. For wheeled mobility, authors of [13] implement a mobile sensor to recover the failed static sensor node. For hopping mobility, the authors of [14] first propose two relocation schemes, called the MinHopsExt, based on the shortest path. In order to transport the requested sensors, the first scheme ($\gamma = 0$ in MinHopsExt) uses Dijkstra's shortest path algorithm according to the number of hops between clusters. The second proposed scheme modifies the first one by adding an additional adjusting process using the parameter γ, ($0 \leq \gamma \leq 1$). In order to adjust, the scheme tries to minimize a fraction of the sum of the weights along the path and a fraction of the difference of the maximum and minimum weights of the edges, the number of hops between clusters, along the path. In [18], the authors propose a Relocation Algorithm using the Most Disjointed Paths (RAMDiP), for multiple suppliers. The RAMDiP is also based on the shortest path and takes into account the number of relocations of each cluster in order to avoid the path collision as much as possible. They first analyze the impact of using multiple suppliers to relocate the hopping sensors compared with the MinHopsExt.

Since specific clusters on the shortest path could be used repeatedly, some sensors' hopping capabilities may exhaust quickly and other sensing holes may occur. Hence, we must consider the alternate method instead of the shortest path method; thus, a use of multipath considering balanced assignment is suggested in this paper.

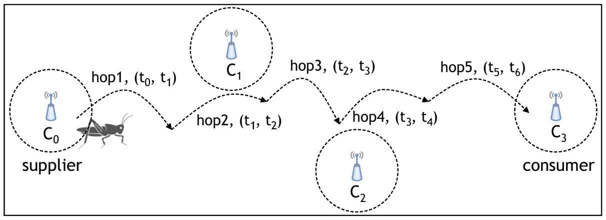
III. Multipath-based Relocation Scheme Considering Balanced Assignment

In this section, we discuss the route planning to move the hopping sensors from supplier cluster to consumer cluster. In the following subsection, three types of hopping strategies are explained briefly.

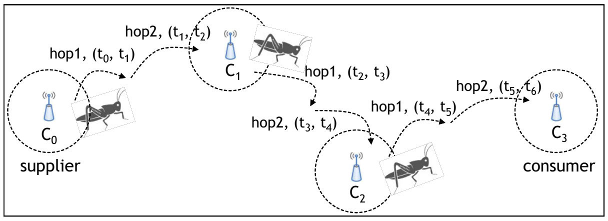
A. Hopping Strategies

As shown in Fig. 2, there are three possible migration strategies, and (t_i, t_j) represents the time interval such that $t_i \leq t \leq t_j$. The first strategy is to move the sensors directly from the supplier (C_0) to the consumer (C_3) as in Fig. 2(a). However, each sensor's hopping capability may deteriorate due to the long distance movement. In order to overcome this, the second strategy uses intermediate clusters as relay clusters. As described in Fig. 2(b), the sensor in C_0 moves to C_1, the sensor in C_1 moves to C_2, and the sensor in

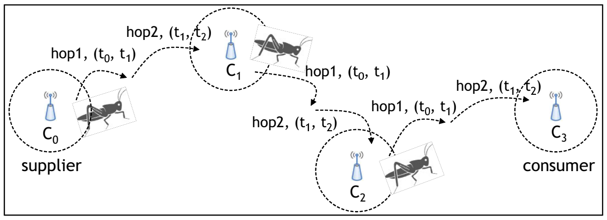
C_2 moves to C_3, in regular sequence. The number of hops executed among the sensors can be balanced; however, the delay is still high. Finally, in cascaded movement, messages are first exchanged among clusters. Then the sensors move simultaneously as depicted in Fig. 2(c). In order to migrate quickly, cascaded movement could be employed [3].



(a) Direct hopping



(b) Relayed hopping

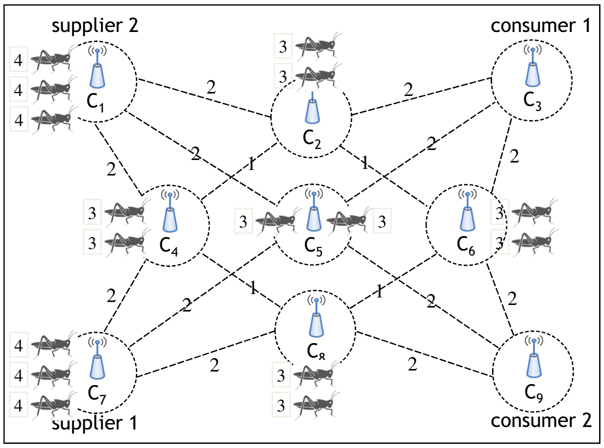


(c) Cascaded hopping

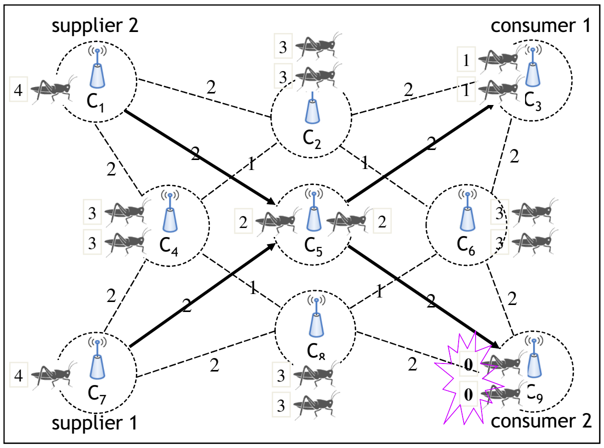
Fig. 2. Three hopping strategies

B. Multipath-based Relocation Schemes

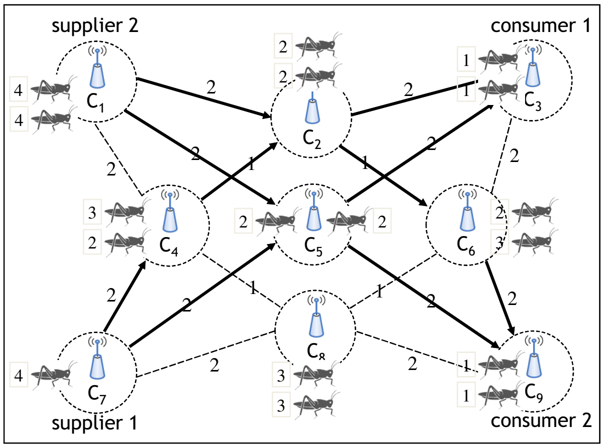
In this paper, we assume that the multiple paths are node disjoint. Fig. 3 illustrates the reason we use multipaths to overcome the drawback of using a fixed shortest path. There is a given network in Fig. 3(a) and the needed number of hops to move between clusters is shown on each edge. The hopping capability of each sensor is written in the small square. C_3 and C_9 clusters are sensing holes that request 2 sensors (E) from C_7 and C_1 suppliers, respectively. In the shortest path-based scheme, specific clusters are used repeatedly. As shown in Fig. 3(b), the cluster C_5 relays sensors twice. This means the total number of sensors' movement related on C_5 is 4 ($E \cdot 2$times); thus, the sensors in C_9 might become mobility-exhausted in the end. See the star in Fig. 3(b). In order to avoid the mentioned continuous lump movement, we can apply the multipath-based scheme. As depicted in Fig. 3(c), the number of hops of each sensor is evenly distributed against the shortest-based migration, although the total number of sensors moved is a few higher than that of Fig. 3(b).



(a) Given network



(b) Movement based on shortest path



(c) Movement based on multipath

Fig. 3. Two movement types under the relayed hopping

Before describing the proposed algorithm for the relocation of hopping sensors, we first define the network model and the detailed pseudo code is as follows. A WSN can be represented by a weighted graph $G(V, W)$ with n clusters and l edges, where V is a set of clusters and W is a set of edges. Each edge is associated with the estimated number of hops needed, as indicated in (3). Finally, S is a set of supplier clusters and t is a consumer cluster.

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Multipath-based Scheme $\Big(G(V,W),S,t,E\Big)$
p ← ∅; $P_i$ ← ∅; $length_p$ ← 0;
For $^\forall s \in S$
    $G'(V',W') \leftarrow G(V,W)$;
        While(1)
            If($length_p$ == 1) break; // just single path
              $p \leftarrow Dijkstra(G',s,t)$;
              // a path is obtained
            If($p \neq \emptyset$)
              $P_i \leftarrow p$; // $p$ is added to multipath
              $length_p \leftarrow |p|$; // the length of the path
              Delete all clusters on $p$ in $V'$;
              Delete all adjacent edges of the erased
              clusters in $W'$;
              $++i$;
            Else break;
The requested $E$ sensors are evenly assigned using $P_i$;
```

We assume that there exist N disjoint paths between consumer and supplier clusters. When we consider the balanced assignment over multiple paths, we are able to adopt the Chebyshev sum inequality to measure how well the given load is balanced. The Chebyshev sum inequality is defined as follows. For two vectors α and β, where $\alpha = (a_1, a_2, \ldots, a_n)$, $\beta = (b_1, b_2, \ldots, b_n)$, if $a_1 \geq a_2 \geq \ldots \geq a_n$ and $b_1 \geq b_2 \geq \ldots \geq b_n$, then

$$n\sum_{k=1}^{n} a_k b_k \;\geq\; \Big(\sum_{k=1}^{n} a_k\Big)\Big(\sum_{k=1}^{n} b_k\Big) \tag{4}$$

We use the well-known fairness index ϕ to evaluate the level of assignment balancing over N different multipaths.

$$\phi(\tau) \;=\; \frac{\Big(\sum_{i=1}^{N}\tau_i\Big)^2}{N\sum_{i=1}^{N}\tau_i^2} \tag{5}$$

where, $\tau_i = e_i/q_i$, $E = \sum e_i$, and E is the number of requested sensors. Here, the path quality q_i is defined as the average number of sensors that each cluster has on the path. If the function ϕ reaches its global maximum of 1, the assignment is perfectly balanced. This is a known property of (4). Therefore, in order to obtain the perfectly balanced assignment, each number of assigned sensors for each path has to be given by $e_i = E \cdot \frac{q_i}{\sum q_i}$. In addition, if the qualities q_i are partially the same, then we first consider the maximum of minimums among the numbers of sensors that each cluster obtains on each path.

IV. PERFORMANCE EVALUATION

We analyze some numerical results that can be used for comparing the performance of the proposed multipath-based and MinHopsExt [14] algorithms. In order to compare, these algorithms are implemented in C and the main parameters are described in Table I. We generate 15 different random sensor networks. For simplicity, the probability that the hopping sensor lands in the acceptable landing area is assumed to be 1. Four hundred events are generated continuously. For each event, a supplier and a consumer cluster are randomly chosen.

TABLE I
SIMULATION VARIABLES

Network size	$300\ m \times 300\ m$
Network density ($clusters/m^2$)	0.005
Number of total hopping capability without refueling	15
Hopping capability per sensor initially	30
Hopping range	$3\ m$
Sensors per cluster initially deployed	20
Number of requiring sensors for each event (E)	6

Fig. 4 shows a graph of each scheme's normalized sensors that are still alive according to the generated events. In the MinHopsExt, $\gamma = 0$ and $\gamma = 1$ mean that it merely considers the minimum hops and the minimum difference of hops between clusters using Dijkstra's shortest path algorithm, respectively. However, we can regard that γ is incapable of affecting the performance. The reason is that the shortest path-based schemes still use the specific path obtained by γ. Since the multipath-based scheme more efficiently disperses the sensors than the shortest path-based scheme, the sensors slowly waste the hopping capability.

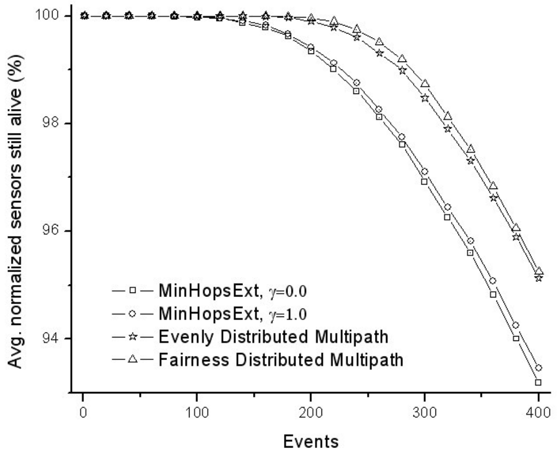


Fig. 4. Normalized sensors still alive under the relayed hopping.

Under the relayed hopping environment, the movement success ratio of the requested sensors is important when the path between a supplier and consumer clusters is especially long. If the path is long, probably the number of migrated sensors in the sensing hole are relatively smaller than the sensors initially required by the consumer. Since the success ratio is dependent on the status of a path or sensor, a use of only specific path has to take the risk of failure for relocation. Hence, the multipath-based schemes cannot help but outperform the MinHopsExt, as shown in Fig. 5.

As depicted in Fig. 6, the movement distribution of the proposed scheme might be distributed well against the shortest path-based scheme. The histogram displays the number of clusters as the frequency in terms of each number of sensors.

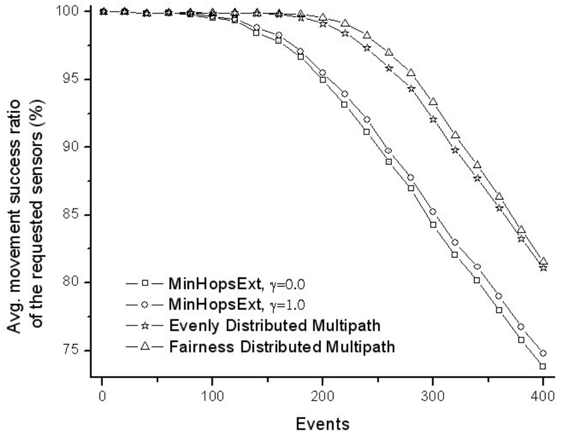
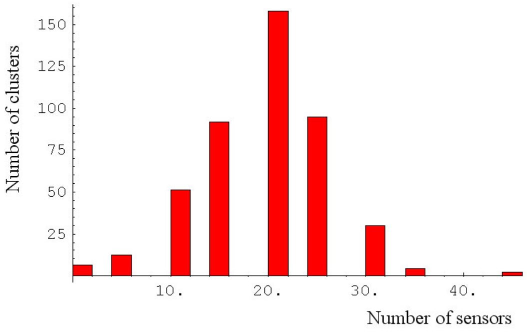
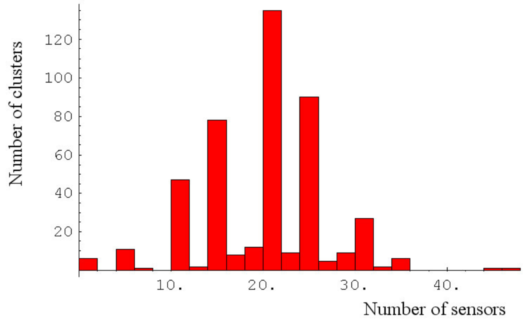


Fig. 5. Movement success ratio of the requested sensors under the relayed hopping.

Initially, every cluster has twenty sensors, $i.e.$, the frequency of 20 is 450 (because the density is 0.005 $clusters/m^2$ for 300m×300m); thus, the histogram is obtained after 400 events continuously. As might be expected, the advantage of using the multipath method versus the shortest path method can be clearly seen in these histograms.



(a) MinHopsExt with $\gamma = 0$



(b) Multipath-based scheme

Fig. 6. Histograms for sensors distribution after 400 events under the relayed hopping.

After this, the results under the cascaded hopping environment are obtained in the same way as above. Here, we can note that the similar results are obtained like the relayed hopping, as depicted in Fig. 7 and 8, respectively.

As shown in Fig. 9(c), the gray color explains the level of the number of sensors that each cluster has. Actually, sensors in a multipath-based scheme have more migration than the sensors in a shortest path-based scheme. However, as described in Fig. 9, the distribution of migration in the multipath-based scheme is better than that of the shortest path-based scheme. In addition, the number of clusters similar to sensing holes, such as white clusters in Fig. 9(a), is smaller than that of Fig. 9(b). As a result, the use of multipath has an effect on the efficiency of sensors' migration for relocation hopping sensors.

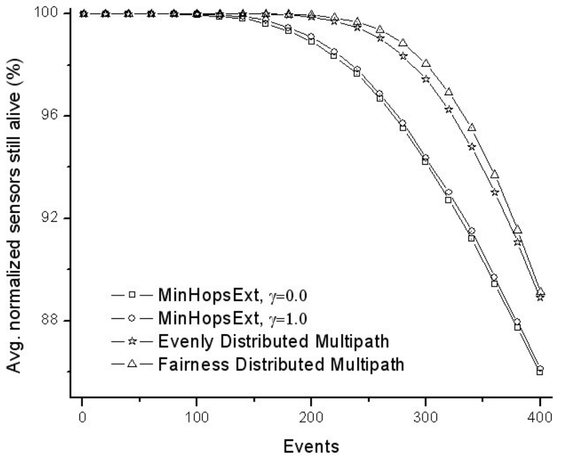


Fig. 7. Normalized sensors still alive under the cascaded hopping.

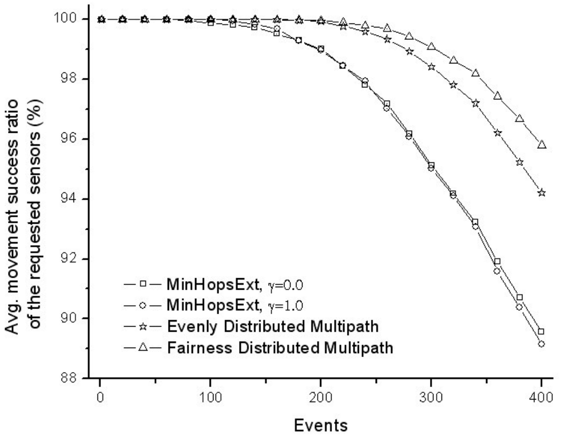
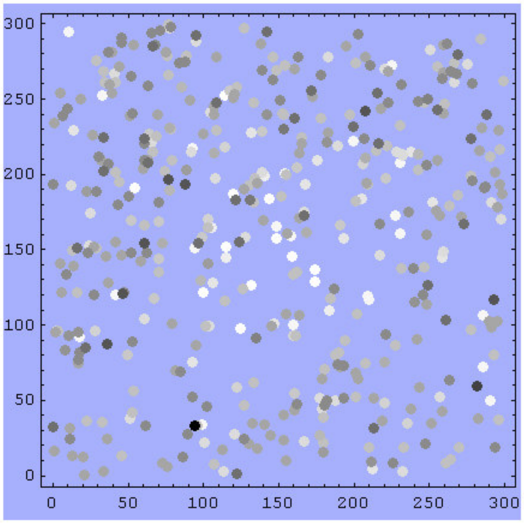


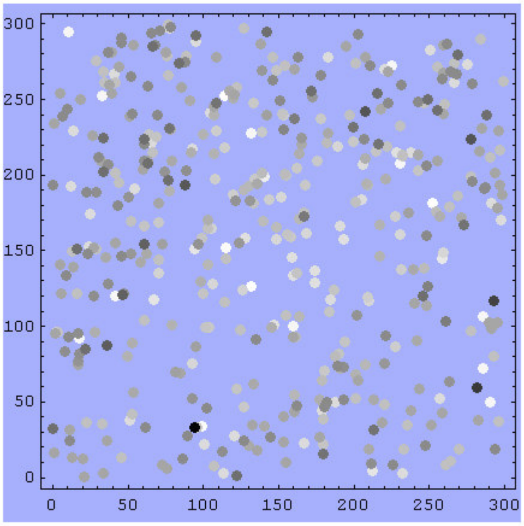
Fig. 8. Movement success ratio of the requested sensors under the cascaded hopping.

V. CONCLUSION

Hopping sensors are more adaptable to many potential working environments, such as remote harsh terrains, toxic regions, disaster areas, and hostile territory than wheeled mobile sensors. In the lifetime of a WSN, sensing holes may often occur. In order to supply the required sensors to the sensing hole, the shortest path-based scheme provides the minimal amount of hopping; thus the total movement of hopping is efficient. However, since it repeatedly uses the same path as the shortest path, the mobility distribution is



(a) MinHopsExt with $\gamma = 0$



(b) Multipath-based scheme

(c) Hopping capability level

Fig. 9. Distribution of hopping sensors for each cluster after 400 events under the cascaded hopping.

imbalanced; thus some sensors' hopping capability may deteriorate quickly and another sensing hole may occur easily. In order to overcome this problem, this paper proposes a multipath-based transport schemes for relocation of hopping sensors. The proposed algorithms are capable of evenly and fairly distributing sensors to provide the ones requested to a consumer of the sensing hole. We have compared the shortest path-based schemes through simulation experiments and have proved that the performance of the multipath-based scheme is superior to the shortest path-based scheme. This proves that the proposed algorithm guarantees a balanced migration distribution of efficient sensors and the higher movement success ratio of requested sensors.

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