A Network Lifetime Enhancement Method for Sink Relocation and Its Analysis in Wireless Sensor Networks

Chu-Fu Wang, Jau-Der Shih, Bo-Han Pan, and Tin-Yu Wu

***Abstract*— Recent advances in micromanufacturing technology have enabled the development of low-cost, low-power, multifunctional sensor nodes for wireless communication. Diverse sensing applications have also become a reality as a result. These include environmental monitoring, intrusion detection, battlefield surveillance, and so on. In a wireless sensor network (WSN), how to conserve the limited power resources of sensors to extend the network lifetime of the WSN as long as possible while performing the sensing and sensed data reporting tasks, is the most critical issue in the network design. In a WSN, sensor nodes deliver sensed data back to the sink via multihopping. The sensor nodes near the sink will generally consume more battery power than others; consequently, these nodes will quickly drain out their battery energy and shorten the network lifetime of the WSN. Sink relocation is an efficient network lifetime extension method, which avoids consuming too much battery energy for a specific group of sensor nodes. In this paper, we propose a moving strategy called energy-aware sink relocation (EASR) for mobile sinks in WSNs. The proposed mechanism uses information related to the residual battery energy of sensor nodes to adaptively adjust the transmission range of sensor nodes and the relocating scheme for the sink. Some theoretical and numerical analyze are given to show that the EASR method can extend the network lifetime of the WSN significantly.**

***Index Terms*— Energy-aware routing, mobile sink, sink relocation, wireless sensor networks.**

I. Introduction

A WSN consists of small-sized sensor devices, which are equipped with limited battery power and are capable of wireless communications. When a WSN is deployed in a sensing field, these sensor nodes will be responsible for sensing abnormal events (e.g., a fire in a forest) or for collecting the sensed data (temperature or humidity) of the environment. In the case of a sensor node detecting an abnormal event or being set to periodically report the sensed data, it will send the message hop-by-hop to a special node, called a *sink node*. The sink node will then inform the supervisor through the Internet. As shown in Fig. 1, sensor node e detects an abnormal event and then it will send a warning message to the sink to notify the supervisor via a predetermined routing path, say $P_{ea} = e - d - c - b - a$. Note that the routing path may be static or dynamic, depending on the given routing algorithm.

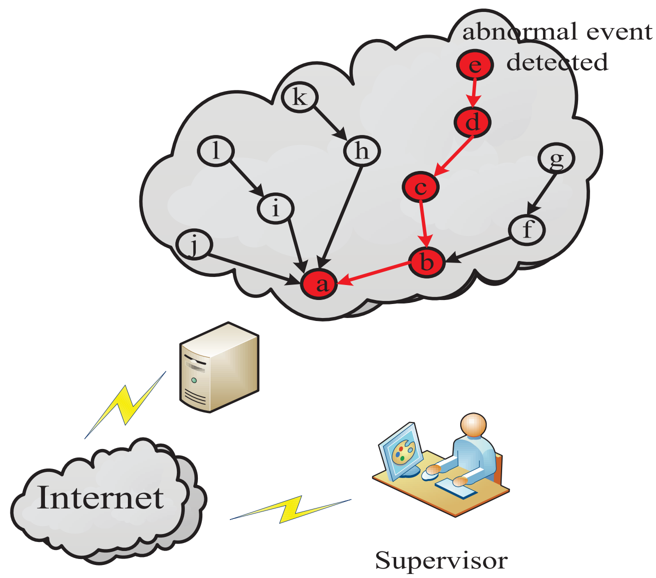

Fig. 1. An operating scheme of a WSN.

The applications of WSNs are broad, such as weather monitoring, battlefield surveillance, inventory and manufacturing processes, etc. [1]–[5]. In general, due to the sensory environments being harsh in most cases, the sensors in a WSN are not able to be recharged or replaced when their batteries drain out of power. The battery drained out nodes may cause several problems such as, incurring coverage hole and communication hole problems. Thus, several WSN studies have engaged in designing efficient methods to conserve the battery power of sensor nodes, for example, designing duty cycle scheduling for sensor nodes to let some of them periodically enter the sleep state to conserve energy power, but not harming the operating of the sensing job of the WSN [6]–[8]; designing energy-efficient routing algorithms to balance the consumption of the battery energy of each sensor node [9]–[15]; or using some data aggregation methods

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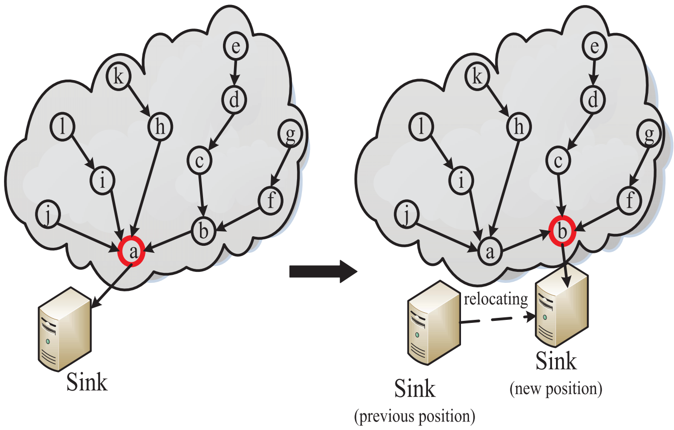

Fig. 2. Sink relocation of a WSN.

to aggregate similar sensory data into a single datum to reduce the number of transmitted messages to extend the network lifetime of the WSN [16], [17]. Note that most of these approaches can coexist in the operating of the WSN.

The other energy conserving approach is to use mobile sensors to adjust their locations from a region with a high level of total battery energy of nodes to a low energy region [18]–[24]. Although this approach can extend the network lifetime of a WSN, the relocation of sensor nodes will also expand their battery energy. A compromise approach is to use a mobile sink to relocate its position instead of relocating the sensor nodes [25]–[31]. As shown in the left part of Fig. 2, the sensor node a near the sink will quickly drain out its battery power after relaying several rounds of sensed data with reported tasks being performed by other sensor nodes, and consequently the WSN will die. We call node a a hot-spot. In the case of the sink being capable of moving, before the hot spot node a drains out all of its battery energy, the sink can move to another position to relieve the situation of heavy energy consumption of node a. As in the example of the right part of Fig. 2, the sink relocates its position from the nearby node a to node b. In such a way, the role of the hot spot will be interchanged from one node to another node and consequently the network lifetime will be extended.

In this paper, we propose a sink relocating scheme to guide the sink when and where to move to. Some mathematical performance analyses are given to demonstrate that the proposed sink relocating scheme can prolong the network lifetime of a WSN. We have also conducted simulations to investigate the performance of the EASR method against some traditional methods by numerical simulation. The organization of this paper is as follows. In the next section we will briefly describe some background related to the considered problem, which includes the energy model of a WSN, the energy-efficient routing scheme that will be incorporated into the EASR scheme, and the related works of sink relocation. In Section 3, we will describe the EASR scheme in detail. The performance analysis, which includes both theoretical and numerical analyse is presented in Section 4. The concluding remarks are given in the final section.

II. The Background and Related Works for the Sink Relocation

The EASR scheme mainly focuses on when the sink will be triggered to perform the relocation process and where to move to. Besides the sink relocation scheme, the entire operation of the WSNs for environment monitoring also needs to incorporate the routing method for reporting the sensed data from the source to the sink, as well as the energy consumption model. In this section, we will firstly briefly describe the energy consumption model for message relaying. Then, the energy-aware routing method (the MCP [11]) that is adopted in the EASR method will be illustrated using a numerical example. At the end of this section, some related research works for sink relocation will also be addressed.

A. The Energy Consumption Model for WSNs

In our considered energy consumption model, we adopt the first order radio model [1]–[3] for later performance simulation. Let $E_{Tx}(k,d)$ (and $E_{Rx}(k)$) denote the total energy required in a sensor node to transmit (and receive) a k-bits length message to (and from) a neighboring sensor node at distance d away, respectively. The energy consumed for message transmitting ($E_{Tx}(k,d)$) can be partitioned into two. The first part is the energy consumed in the transmitted electronic component and is equal to $E_{elec} \times k$, where E_{elec} denotes the energy consumed for driving the transmitter or receiver circuitry. The second part is the energy consumed in the amplifier component and is equal to $\epsilon_{amp} \times k \times d^n$, where ϵ_{amp} denotes the energy required for the transmitter amplifier. Note that, the receiving process performed in a sensor node only includes the first part of the energy consumption. Summarizing the above descriptions, the total energy consumption for message transmitting and receiving is as follows.

$$E_{Tx}(k,d) = E_{elec} \times k + \epsilon_{amp} \times k \times d^n \quad (1)$$

$$E_{Rx}(k) = E_{elec} \times k \quad (2)$$

Note that, in this paper, we let $n = 2$, $E_{elec} = 50nJ/bit$, and $\epsilon_{amp} = 100pJ/bit/m^2$ in Equations (1) and (2) for later simulation.

B. The Energy-Efficient Load-Balanced Routing Protocol (the Maximum Capacity Path, MCP)

As discussed previously, in order to prolong the network lifetime of a WSN, energy saving is the key design issue. Routing protocol designs of message reporting in a WSN can generally be classified into two categories: static routing and dynamic routing. For the static routing type, when as the message reporting paths are determined, each sensor node will report its sensed data along the predetermined path to the sink at any time (for example, the tree shown in Fig. 1). On the other hand, a dynamic routing protocol might alter the routing paths in each transmission round according to the current state of the sensor nodes' residual battery energy. Due to the fact that the dynamic routing protocols can balance the load on each sensor node, it performs better for network lifetime prolonging than the static routing protocols. In this

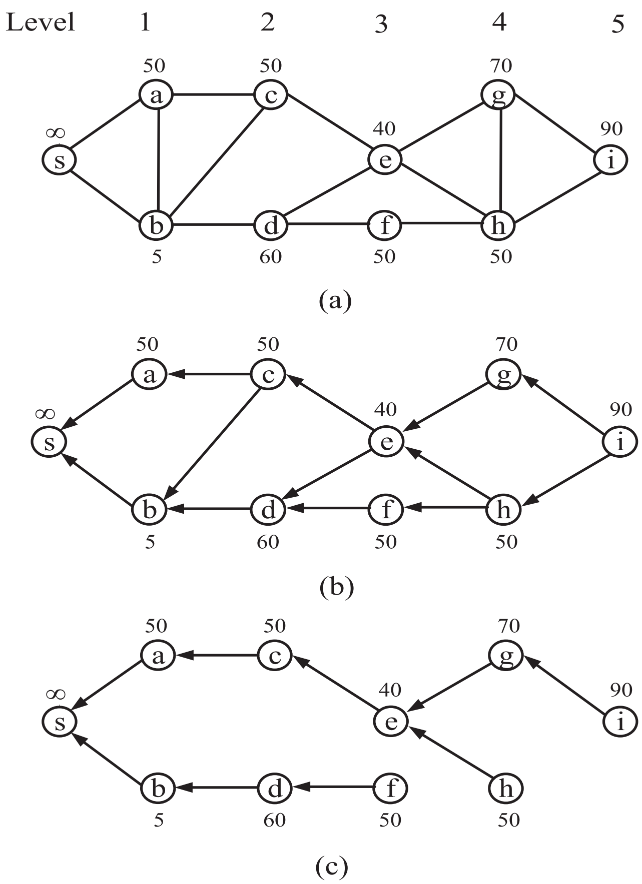

Fig. 3. An illustration of the MCP routing [11].

paper, we use a dynamic routing protocol, called Maximum Capacity Path (MCP), as the underlying routing protocol of the proposed sink relocation method. The MCP is proposed by Huang and Jan [11] and has also been demonstrated to perform well in prolonging network lifetime in a WSN. In the following, we will use an example to illustrate the procedure steps of the MCP routing algorithm.

A WSN and its current residual battery energy state of sensor node can be modeled by a capacity graph $G = (V, E)$, where set V denotes the collection of sensor nodes and E denotes all of the possible direct communication between sensor nodes. And let $r : V \rightarrow R^+$ be the residual battery energy function to represent each sensor's residual battery energy. For example, as shown in Fig. 3(a), node s stands for the sink with infinity energy due to the fact that it can plug in to a power line or is equipped with an extremely large capacity battery compared to that of the sensor nodes. The value that is associated with node a is equal to 50, which stands for the current residual battery energy of sensor node a. The MCP mainly consists of three procedure steps. They are, (1) layering graph G into a layered network N; (2) determining the maximum capacity path for each sensor node; and (3) routing performed and residual energy updated. The MCP will iteratively perform the above three steps for each round of message reporting.

Detailed operations for layering the graph in the first step are as follows. Let level number L_v with respect to each sensor node $v \in V$ denote the shortest path length from v to the sink s. For the example in Fig. 3(a), since the shortest path length from nodes g and h to node s are both 4, $L_g = L_h = 4$. The layered network N can be obtained from graph G by deleting the edges $(u, v) \in E$ such that $L_u = L_v$. For example, as shown in Fig. 3(a), since $L_a = L_b = 1$ and $L_g = L_h = 4$, then edges (a, b) and (g, h) will be deleted from G. Then the layered network N obtained from G is a directed graph, such that for all of the remaining edges $(u, v) \in E$ after the deleting operation, the directed edge (u, v) from node u to node v, if $L_u = L_v + 1$. Fig. 3(b) shows the resulting network obtained from G in Fig. 3(a).

Let $P_{us} = u, u_1, u_2, \ldots, u_l, s$ be a path from node u to the sink s in N. And we let the capacity $c(P_{us})$ of path P_{us} be the minimum value of residual battery energy in path P_{us}; that is, $c(P_{us}) = \min\{\, r(u), r(u_1), r(u_2), \ldots, r(u_l)\}$. Let P^*_{us} be the maximum capacity path with the maximum capacity value among every path from node u to s. The resulting graph of the union of each maximum capacity path P^*_{us}, $\forall u \in V$ will be the routing paths for message reporting. For example, Fig. 3(c) shows the resulting maximum capacity paths obtained from the layered graph N of Fig. 3(b). The above operations are the second procedure steps of the MCP. Now, as a sensor node u detects an abnormal event or has sensed data to report to the sink node s, then the message will be relayed along the maximum capacity path P^*_{us} to s. For example, the maximum capacity path $P^*_{gs} = g, e, c, a, s$. After the message relaying from node g to s along path P^*_{gs}, the residual battery energy of each sensor node in the path is updated accordingly. The above three procedure steps will be repeated for each transmission round until one of the nodes drains out its battery energy.

C. Sink Relocation and Related Works

In general, WSNs can be classified into two categories, stationary and relocatable WSNs, depending on whether the nodes are capable of moving or not. When a stationary WSN is deployed in a sensing field, each sensor node locates at a fixed position to perform round-and-round of sensing and message reporting/relaying tasks until a sensor node (or a portion of the sensor nodes) drain out their battery energy; then the WSN dies. For the category of relocatable WSNs, sensor nodes or the sink are capable of moving. As the total energy level of a region drops down to a low level state or there are some sensing holes or communication holes in the region due to some sensor nodes draining out their battery energy, then some mobile sensors can relocate their locations and move into this region to relieve the above problem. Although this approach can prolong the network lifetime of the WSN, the relocating sensors will also consume their battery energy to perform the relocating task. As discussed previously, sink relocation is a compromise approach for prolonging network lifetime and the sensor nodes remain stationary to conserve battery energy. Several research works have proposed mechanisms for the sink relocation policy [25]–[35]. These studies can be roughly classified into two categories, the predetermined sink mobility path [25]–[27] and autonomous sink movement [28]–[31].

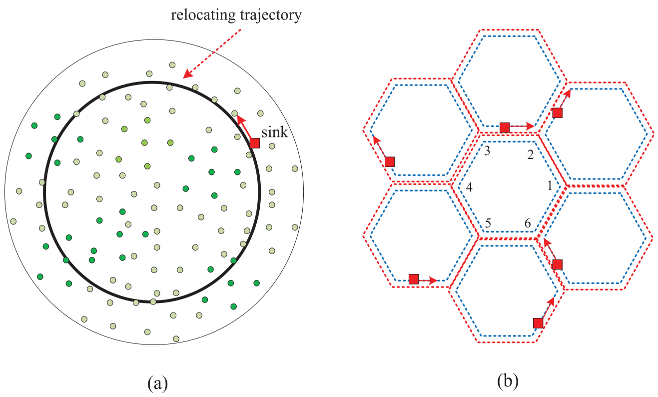

Fig. 4. The predetermined sink mobility path schemes [25], [26].

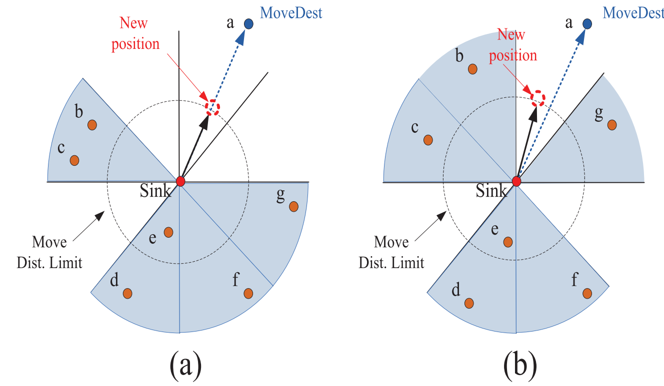

Fig. 5. A portion of the sink relocating policies in [28].

For the previous category of sink mobility scheme, the sink will regularly move along a pre-determined trajectory. Luo and Hubaux [25] proposed a Joint sink Mobility and Routing strategy (JMR) for data collection in a WSN. The JMR uses a circular trajectory at the periphery of the WSN [see Fig. 4(a)]. Note that the circular trajectory in Fig. 4(a) (shown by a bold circle) is a predetermined trajectory for the sink relocation. The sink will use a constant velocity to circle the trajectory. Marta and Cardei [26] proposed a multiple sink relocation scheme with multiple pre-determined hexagon trajectories [see Fig. 4(b)]. Each trajectory has a mobile sink constantly relocating itself along the hexagon path. As a sink passes through a sensor node, then the sensor can relay the sensed data to the mobile sink. This category of sink relocation scheme is easy to implement and the sensor node can easily predict the sink's position due to the fact that its moving velocity is constant and the trajectory is pre-determined. However, this category of relocation scheme does not adapt to taking the current residual battery energy of sensor nodes into consideration, which is important information, and it might give better performance results for relocation methods.

In the other category of sink relocation, the autonomous sink movement scheme [28]–[31], the sink will constantly collect nearby sensor nodes' related information (such as the residual battery energy) and then, based on this information, plan when to move and where to move to. In the following, we will introduce two sink relocation schemes of this category. Sun et al. [28] proposed a mobile sink relocation scheme to drive the sink to the next position by taking the conditions of nearby nodes' residual battery energy. The method firstly partitions the nearby sensing region of the sink into 8 fan-shaped sectors. The sensor node with the maximum residual battery energy is called the MoveDest [see node a in Fig. 5(a)]. The sector containing the MoveDest is called the Dest sector. If the residual battery energy of a sensor node is below a given threshold, then this node is called a quasi-Hotspot [for example, the sensor nodes b, c, d, e, f, and g in Fig. 5(a)]. A sector containing at least one quasi-Hotspot is called a miry sector [the gray sector in Fig. 5(a)]; otherwise, it is called a clean sector [the white sector in Fig. 5(a)].

The next new relocating position of the sink will be primal based on the intersection point between the line from the current position of the sink to the MoveDest and the border of the given transmission range (Move Dist. Limit) [see Fig. 5(a)]. Then, based on the possible state (miry or clean) outcomes of the two neighboring sectors of the Dest sector, the new sink relocating position will be slightly minor adjusted accordingly. The proposed method provides 6 adjusting plans based on all of the possible outcomes. For example, as shown in Fig. 5(a), the two neighboring sectors of the Dest sector are both clean, then the sink will relocate itself to the new position as stated above and there is no need for it to be adjusted. In the other case of both of the neighboring sectors of the Dest sector being miry [see Fig. 5(b)], then the new relocating position of the sink will be the intersection between the border of the transmission range with the center line of the Dest sector. For the other 4 possible cases of sink relocation, one can refer to [28] for more details.

Sun et al. [29] proposed two autonomous sink movement schemes, the One-step and the Multi-step moving schemes. The methods firstly compute a position for the destination of moving, which can be determined by the total residual battery energy of the sensor nodes. When a moving destination is determined, the One-step moving scheme will drive the sink to directly move to the destination despite the distance. For the Multi-step moving scheme, the sink will relocate its position iteratively from one intermediate moving destination to the other, and the distance of each relocating step will be limited to the transmission range of the sink.

For each of the relocating steps, the determination criteria for selecting an intermediate moving destination are as follows. At first, the sink collects the residual battery energy from each sensor node within the communication range of the sink. Then, it choose the sensor node in the direction heading to the moving destination and within the transmission range of the sink, such that it has the maximum residual battery energy value among the sensor nodes. Set the intermediate moving destination to be the position of the chosen node and to relocate the sink to this position. Along this way, the mobile sink will relocate itself from one intermediate moving destination to the other and finally it will reach the moving destination. At last, as the sink enters to the communication range of the moving destination, it will move circularly around 6 points at the communication range border [see the 6 points

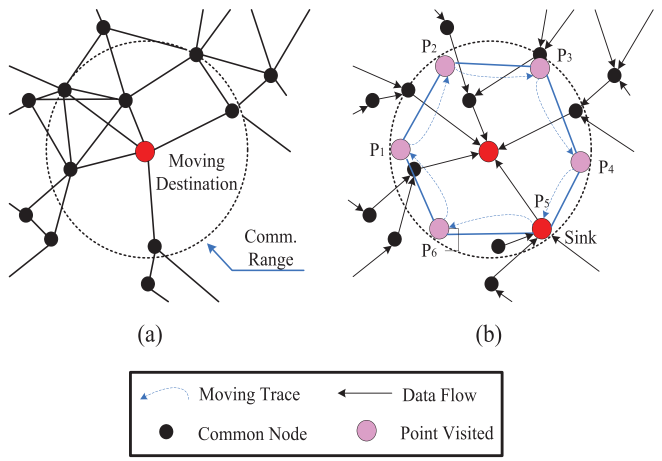

Fig. 6. The sink relocating policy in [29].

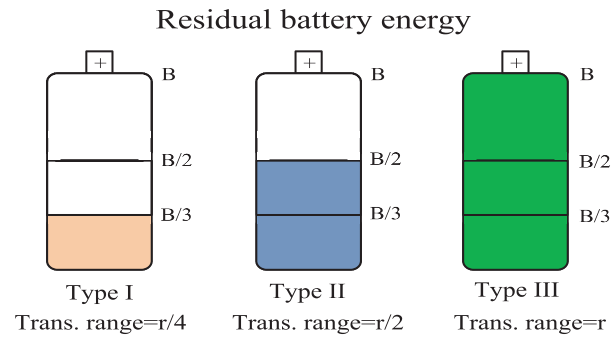

Fig. 7. The energy-aware transmission range adjusting mechanism.

$P_1, P_2, \ldots, P_6$ in Fig. 6(b)]. In the case of a point $P_i^* \in \{P_1, P_2, \ldots, P_6\}$ being able to receive the largest amount of data compared to the other points, then the sink will remain stationary until another relocating event occurs (e.g., the residual battery energy of sensor nodes near the sink drops below a given threshold). If such an event occurs, the sink relocation scheme will again be invoked to repeat the above processes to the other moving destination.

Note that the above sink relocation mechanisms generally take the nearby sensor nodes' residual battery energy into consideration and then drive the sink to a position with a larger amount of total residual energy than others. These proposed methods usually use an intuitive idea for algorithm design and they generally do not incorporate the routing methods. However, as one knows, the routing protocol does greatly affect the resulting performance (such as prolonging the network lifetime). Besides, they generally do not give theoretical inference to demonstrate the effectiveness of the proposed methods, but only give numerical results. In our proposed approach, we have designed a sink relocation scheme called the Energy-Aware Sink Relocation (EASR) method, which incorporates the routing method and the topology control method as well. In addition, we also give mathematical analysis to demonstrate that the EASR method can effectively enlarge the network lifetime of a WSN, which will be given in Section 4.

III. The Proposed Energy-Aware Sink Relocation (EASR) Method

In the EASR method, we incorporate the technique of energy-aware transmission range adjusting to tune the transmission range of each sensor node according to its residual battery energy. In the case of the residual battery energy getting low after performing rounds of message relaying and environment sensing tasks, then its transmission range will be tuned to be small for energy saving. Moreover, the relocating decision made by the sink will take the MCP [11] routing protocol, (which has been described in the previous section) as the underlying message routing in order to gain the merit of prolonging network lifetime. Note that the underlying message routing method may affect the performance of the entire operating scheme (the sink relocating and the message routing) significantly as the parameters of the routing algorithm vary. Although the EASR method can be incorporated with any existing routing method, we chose the MCP as the underlying routing method to limit the above influence since the only parameter of the MCP is the same as the decision parameter of the proposed EASR method; that is the residual battery energy of the sensor nodes. The proposed EASR consists of two components, the energy-aware transmission range adjusting and the sink relocation mechanism that are described as follows.

- **Energy-aware transmission range adjusting**

In general, a larger transmission range set for a sensor node will increase the number of neighbors and consequently enhance the quality of the energy-aware routing; however, it also bring the drawback of longer distance message relaying, which will consume more battery energy of a sensor node. On the contrary, for a shorter range of communication, although it does not help too much for routing, it can conserve the usage of the residual battery energy. In the proposed method, the transmission range adjusting will depend on the residual battery energy of a sensor node. We classify sensor nodes into three types by the 'healthy' state of their battery and adjust their transmission range accordingly. Let B be the battery energy value when the battery energy is full in the beginning and $r(u)$ denotes the current residual battery energy of a sensor node $u \in V$. In the case of $0 \le r(u) < B/3$ (and $B/3 \le r(u) < B/2$), then sensor node u belongs to type I (and II) sensor node and we set its transmission range to $\gamma/4$ (and $\gamma/2$), respectively, where γ denotes the initial transmission range of a sensor node. For the case of $B/2 \le r(u) \le B$, the sensor node u is very healthy for its battery energy (type III node) and we set its transmission range to γ (see Fig. 7). Intuitively, a 'healthy' sensor node can adapt a larger transmission range to shorten the routing path, while a sensor node with only a little residual battery energy can tune the transmission range to be small to conserve its residual energy. Thus an adaptable transmission range adjusting mechanism can enlarge the lifetime of a sensor node and the network lifetime.

- **The sink relocation mechanism**

This mechanism consists of two parts. The first is to determine whether to trigger the sink relocation by determining

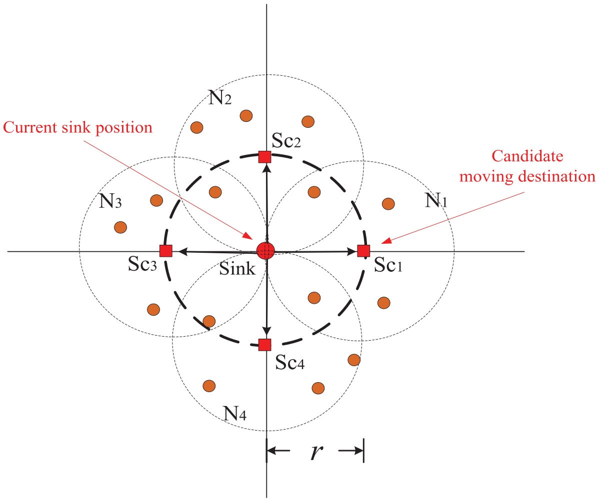

Fig. 8. An illustration of the four candidate moving destinations for sink relocation.

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Procedure Energy-aware-transmission-range-adjusting(sensor node u);
Input:
   γ: initial transmission range;
   B: initial battery energy;
   r(u): current residual battery energy of u;
   t: transmission range;
{
   /* transmission range adjusting */
     while (true) {
       if (0 ≤ r(u) < B/3) then
            t = γ/4;
       else if (B/3 ≤ r(u) < B/2) then
            t = γ/2;
       else if (B/2 ≤ r(u) < B) then
            t = γ;
   } // end while (true) loop
}
```

Fig. 9. The procedure steps for the energy-aware-transmission-range-adjusting in the sensor node.

whether a relocation condition is met or not. The second part is to determine which direction the sink is heading in and the relocation distance as well. For the relocation condition, the sink will periodically collect the residual battery energy of each sensor node in the WSN. After the collecting process is completed, the sink will use the MCP routing protocol to compute the maximum capacity path P^*_{us} with respect to each sensor neighbor u of sink s. For each maximum capacity path P^*_{us}, we denote the maximum capacity value with respect to P^*_{us} as $c(P^*_{us})$. Let the collection of the sensor neighbors of s be N. Then the relocation condition will be met when one of the following conditions occurrs: (1) when one of the capacity values $c(P^*_{us})$ with respect to the sensor neighbor u in N drops below $B/2$; or (2) the average residual battery energy of the neighbor set drops below $B/2$. That is, when either the

$$1.\ \exists u \in N,\ \text{such that}:\ c(P^*_{us}) < B/2 \text{ or} \tag{3}$$

$$2.\qquad \textstyle\sum_{u \in N} r(u)/|N| < B/2 \tag{4}$$

condition occurs, which means the residual energy of the nearby sensor nodes of the sink become small or the residual energy bottleneck of some routing paths falls below a given threshold ($B/2$). Then the sink relocation mechanism will be performed to relocate the sink to a new position, which can enlarge the network lifetime.

In the case of the sink having to relocate, it will firstly determine the positions of the moving destination. The moving destination has 4 candidate positions, S_{C_1}, S_{C_2}, S_{C_3}, and S_{C_4}, which are located in the right, up, left, and down direction γ distance away from the current position of the sink [see Fig. 8]. Let the neighbor subset N_i with respect to each moving destination candidate S_{C_i} $(1 \le i \le 4)$ be the collection of sensor nodes that is located within the circle centered at node S_{C_i} with radius γ, respectively. Let a weight value w_i that is associated with each neighbor subset N_i, $1 \le i \le 4$ be

$$w_i = \min\{c(P^*_{us}) | u \in N_i\},\ \text{where } c(P^*_{us}) \text{ denotes the maximum capacity value of } P^*_{us} \tag{5}$$

Then, the relocating position $S_{C_{i^*}}$ will be chosen from S_{C_1}, S_{C_2}, S_{C_3}, and S_{C_4}, such that the weight value w_{i^*} with respect to $S_{C_{i^*}}$ is the maximum value among w_i $(1 \le i \le 4)$. Now the sink s will relocate itself to position $S_{c_{i^*}}$. Intuitively, the weight value w_i of a candidate position represents the residual energy lower bound among the bottleneck value of the routing paths to the sink when the sink relocate itself to the candidate position S_{C_i}. Thus the EASR method will drive the sink to the candidate position with the greatest w_i value among the four candidate positions by adopting 'healthy' routing paths to transmit the message to enhance the network lifetime. After the sink relocates to the new position, the above processes (the residual battery energy collecting, the relocating condition checking) will be iteratively performed. In the case of the relocation condition once again being met, then the relocation process will also be invoked again. Detailed procedure steps of the Energy-aware transmission range adjusting for the sensor node and the relocating method for the sink are illustrated in Figs. 9 and 10, respectively.

IV. Analysis

A. Theoretical Analysis for Prolonging Network Lifetime by Sink Relocation

Generally, not only the sink relocation may enhance the network lifetime of a WSN, but the underlying network routing protocol and the applications (abnormal event reporting or constant sensed data collecting) running in a WSN will all significantly affect the performance of the network lifetime. Thus, the network lifetime modeling of a WSN for sink relocation is very complicated. In this subsection, we will propose a simplified hierarchy network model to represent the logical view of a WSN. As shown in Fig. 11, each grid node u in the network represents a group of sensor nodes, which are located within a ring area centered at the geographical position x_u with radius γ. Note that, the collection of sensor nodes within the ring area is approximately equal to the previously mentioned neighbor subset N_u. A value $k(u)$ is associated with grid node u to represent the total residual battery energy of

Procedure Energy-aware-sink-relocation(sink s);
Input:
V: the set of sensor node in the WSN;
N: the neighbor set of s with range γ;
B: initial battery energy;
$r(u)$: current residual battery energy of u;
{
while (true) {
/* data collecting */
collecting the residual battery energy $r(u), \forall u \in V$;
determine the communication graph G of the WSN after performing the transmission-range-adjusting in each sensor node;
compute the maximum capacity path P^*_{us} and its maximum capacity value $c(P^*_{us}), \forall u \in V$;
/* relocating condition checking */
if $((\exists u \in N, c(P^*_{us}) < B/2)$ or $(\sum_{u \in N} r(u)/|N| < B/2))$
then {
/* perform the sink relocating */
determine the moving destination candidates S_{c_1}, S_{c_2}, S_{c_3}, and S_{c_4};
compute the neighbor subset N_1, N_2, N_3, and N_4;
compute the weight value w_i with respect to each neighbor subset N_i $(1 \le i \le 4)$;
let $S_{c_{i*}}$ be the moving destination candidate with the maximum weight value among w_1, w_2, w_3, and w_4;
relocate the sink s to the position $S_{c_{i*}}$;
}
} // end while (true) loop
}

Fig. 10. The procedure steps for the energy-aware-sink-relocation in the sink.

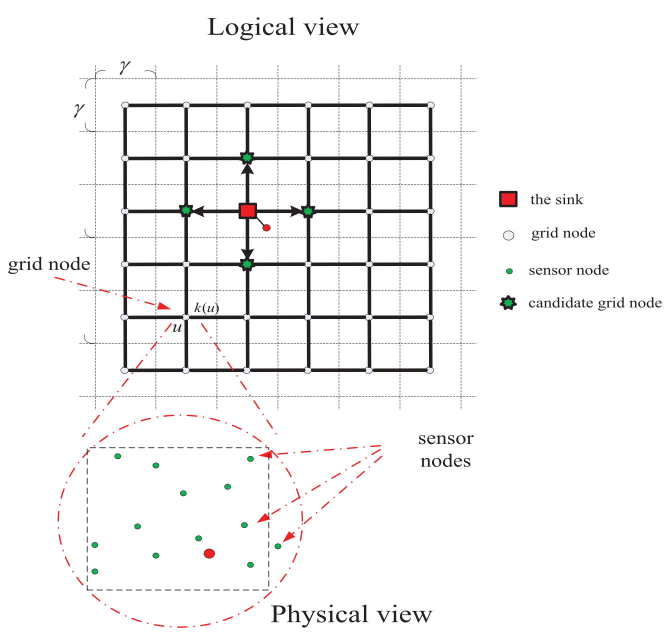

Fig. 11. The network model to represent the abstraction view of sink relocating.

each sensor node in N_u; that is,

$$k(u) = \sum_{u \in N_u} r(u). \tag{6}$$

This abstraction network model has the following features:

1) The value $k(u)$ with respect to a grid node u represents the total battery energy condition in an area of a circle region with radius γ.

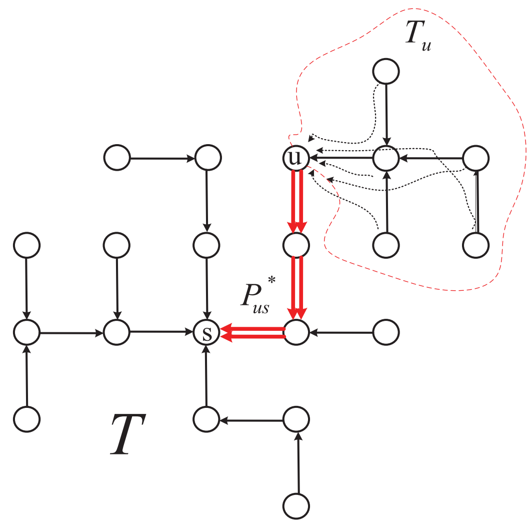

Fig. 12. An illustration of the message routing.

2) The respective circle regions of two neighboring grid nodes have an overlapping area in common, which fits to the fact that the two neighboring subsets have some sensor nodes in common in the overlapping area.
3) A circle region with respect to a grid node where the sink is located, is the most heaviest energy consuming area.

The above summarized characteristics of the abstraction model, have a strong relationship with our considered realistic WSN. Although there is a gap between a simplified model and a realistic situation, it will help to proceed with the theoretical analysis. In the following, we will use this model (the grid network) to demonstrate that the proposed sink relocation can prolong the network lifetime of the WSN.

When an event (abnormal event reporting or sensed data gathering) occurs at a grid node u, then an informed message will be transmitted from u to the grid area which contains the sink s (for ease of discussion, we also use s to represent the respective grid node) along path P^*_{us} [see Fig. 12]. Note that, the routing path can be predetermined by some routing protocol. In this paper, we use the MCP method to determine the routing path in the grid network, which has been discussed in Section 2. We use $G_g = (V, E)$ to denote the grid network and T to denote the collection of all maximum capacity routing path P^*_{us} with respect to each grid node u. From an probability point of view, for long-term event processing, the energy consumption with respect to a grid node u will be proportional to the number of nodes in subtree $T_u \subset T$, where T_u denote the subtree rooted at node u in T [see Fig. 12]. This is because any sensor node $v \in T_u$, which wants to submit a message to the sink has to pass through node u. And assume that the chance of submitting a message to the sink of each sensor node is equal to a constant value. Thus, the energy consumption of a node u is proportional to the number of sensor nodes in T_u (i.e., $|T_u|$). Based on this assumption, we give the following definitions for estimating the network lifetime of a WSN.

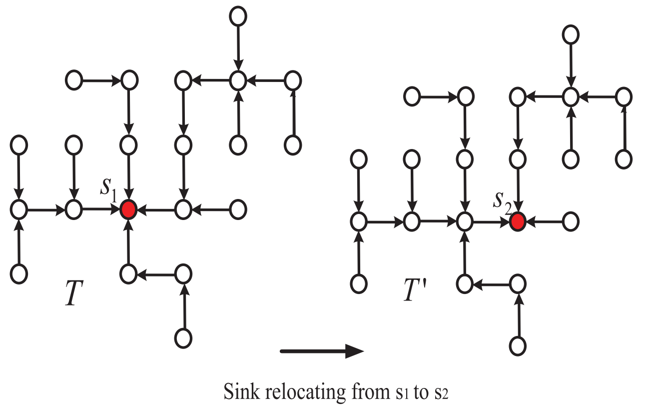

Fig. 13. An illustration of the resulting routing tree after sink relocation.

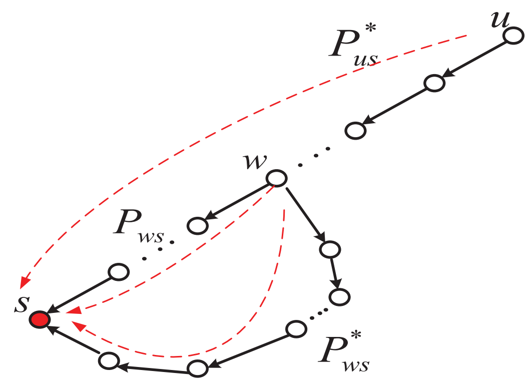

Fig. 14. An illustration of the routing tree of the MCP.

- Definition 1. The *energy consumption load* ($l(u)$) per unit time of node u is defined as $l(u) = \alpha \cdot |T_u|$, where α represents the energy consumed parameter per unit time.
- Definition 2. The lifetime of node u ($LT(u)$) is defined as $LT(u) = k(u)/l(u)$, where $k(u)$ denotes the total residual battery energy with respect to u.
- Definition 3. The network lifetime of a WSN ($LT(T)$) is defined as $LT(T) = \min_{u \in T} LT(u) = \min_{u \in T} k(u)/(\alpha \cdot |T_u|)$.

Assume that the sink is currently located at grid node s_1 and the routing tree for message transmitting is T rooted at node s_1. According to Definition 3, if the sink is stationary and stays at grid node s_1, then the network lifetime of the WSN will be $LT(T)$. However, a sink relocation from grid node s_1 to a neighboring grid node s_2 [see Fig. 13] will alter the transmitting paths for some grid nodes. Let the resulting routing path be T' that is rooted at node s_2. Consequently the network lifetime after relocating will be $LT(T')$. In the case of the sink relocation prolonging the network lifetime of a WSN, then we call it a network lifetime non-decrease (or increase) sink relocation. A formal definition is given as follows.

- Definition 4. A network lifetime non-decrease (and increase) sink relocation from grid node s_1 to grid node s_2, iff $LT(T) \leq LT(T')$ (and $LT(T) < LT(T')$), where T and T' denotes the routing tree rooted at node s_1 and s_2, respectively.

Due to the EASR method which adopts the MCP routing protocol as the underlying method for message reporting, in the following theorem we will firstly demonstrate that the collection of each routing path in our grid structure network model forms a tree structure.

Theorem 1. Let P^*_{us} be the MCP maximum capacity path from $u \in V$ to the grid node s, then $U = \bigcup_{u \in V} P^*_{us}$ forms a tree structure.

Proof.

Suppose U does not form a tree, then $\exists u, w \in V$ such that $w \in P^*_{us}$, but $P^*_{ws} \nsubseteq P^*_{us}$ [see Fig. 14], where P^*_{us} (and P^*_{ws}) are the maximum capacity paths from u (and w) to s, respectively. Let $c(P)$ denote the minimum residual battery energy node value among a path P; i.e., $c(P) = \min_{x \in P} k(x)$. Let P_{ws} be the subpath in P^*_{us}; i.e., $P_{ws} \subseteq P^*_{us}$. According to the definition of $c(P)$, we have the following inequalities:

$$c(P^*_{ws}) > c(P_{ws}) \tag{7}$$

$$c(P_{ws}) \geq c(P^*_{us}) \tag{8}$$

$$\text{and } c(P^*_{us} - P_{ws}) \geq c(P^*_{us}) \tag{9}$$

From inequalities (7) and (8), we have that

$$c(P^*_{ws}) \geq c(P^*_{us}). \tag{10}$$

And from inequalities (9) and (10), we have that $c(P^*_{ws} \cup (P^*_{us} - P_{ws})) \geq c(P^*_{us})$. Since $P^*_{ws} \cup (P^*_{us} - P_{ws})$ forms another $u - s$ path, thus $c(P^*_{ws} \cup (P^*_{us} - P_{ws})) \leq c(P^*_{us})$. Now, we conclude that $c(P^*_{us}) = c(P^*_{ws} \cup (P^*_{us} - P_{ws}))$. If we replace path P^*_{us} by $P^*_{ws} \cup (P^*_{us} - P_{ws})$ in set U, then a tree structure will be obtained. Hence the theorem. □

Recall that, the EASR method will drive the sink from a lower battery energy region to the region with the greatest total battery energy with respect to a circle region with radius γ. In the following theorems, we will demonstrate that the EASR mechanism can enhance the network lifetime of the WSN.

Theorem 2. Assume that the sink is currently located in grid node u. Grid node v is a neighbor of u in the grid network and $k(v) \geq k(u)$. Then moving the sink from u to v is a network lifetime non-decreasing sink relocation.

Proof.

Let the neighbor subset of u be $N(u) = \{u_1, u_2, \ldots, u_k, v\}$, and let T_{u_i} (and T_v) denotes the subtree of T rooted at node u_i (and v), respectively [see Fig. 15]. Note that, in our considered model, the value $k = 3$. Let $LT(x)$ and $LT'(x)$ denote the lifetime of node $x, \forall x \in V$ when the sink is located at grid node u (before sink relocation) and v (after the sink relocation), respectively. And let T (and T') denote the rooted tree with root u (and v), respectively. Note that, $|T| = |T'|$. According to the definitions, we have that,

$$LT(u) = \frac{k(u)}{\alpha \cdot |T|} \tag{11}$$

$$LT(v) = \frac{k(v)}{\alpha \cdot |T_v|} \tag{12}$$

$$LT'(u) = \frac{k(u)}{\alpha \cdot |T - T_v|} \tag{13}$$

$$LT'(v) = \frac{k(v)}{\alpha \cdot |T'|} \tag{14}$$

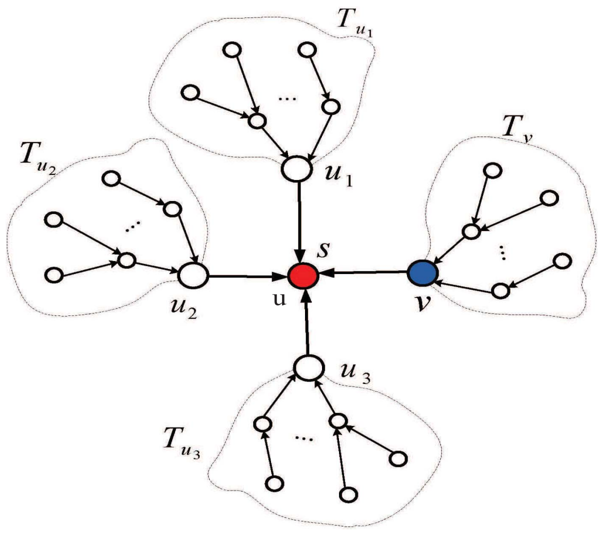

Fig. 15. An illustration of the proof of Theorem 2 (before sink relocation).

$$\text{and } LT'(x) = LT(x), \forall x \in V - \{u, v\} \tag{15}$$

From Equations (11) and (13), we have that

$$LT'(u) = \frac{k(u)}{\alpha \cdot |T - T_v|} > \frac{k(u)}{\alpha \cdot |T|} = LT(u). \tag{16}$$

Similarly, by Equations (11), (14), and the fact of $k(v) \geq k(u)$, we have that

$$LT'(v) = \frac{k(v)}{\alpha \cdot |T'|} \geq \frac{k(u)}{\alpha \cdot |T|} = LT(u). \tag{17}$$

By inequalities (15)–(17), we can conclude that

$$\begin{aligned} LT'(T') &= \min_{x \in V} LT'(x) \\ &= \min\{LT'(u), LT'(v), \min_{x \in V - \{u,v\}} LT'(x)\} \\ &\geq \min\{LT(u), LT(v), \min_{x \in V - \{u,v\}} LT(x)\} \\ &= LT(T) \end{aligned} \tag{18}$$

Thus the sink relocation from grid node u to v is a network lifetime non-decreasing sink relocation. □

Corollary 3. If $k(v) > k(u)$ and $LT(x) > LT(u)$, $\forall\ x \in V - \{u\}$. Then, relocating the sink from grid node u to v is a network lifetime increase sink relocating.

Proof.

From inequalities (16) and (17) and the fact of $k(v) > k(u)$, we have that $LT'(u) > LT(u)$ and $LT'(v) > LT(u)$. Since $LT'(x) = LT(x) > LT(u), \forall x \in V - \{u, v\}$. Thus, $LT'(T) = \min_{x \in V} LT'(x) > LT(u) \geq LT(T)$. Hence the corollary. □

The time complexity analysis

The proposed EASR consists of two components, the energy-aware transmission range adjusting and the energy-aware sink relocation. It is obvious that the first component only takes constant time of operation steps, thus the time complexity is equal to $O(1)$. For the second component, the energy-aware sink relocation procedure firstly performs the residual-energy data collecting and also invokes the MCP to determine the maximum capacity path with respect to each node. Finally the relocating condition checking is performed. Since the relocating condition checking only takes constant time of operation steps, and the time complexity for performing the MCP algorithm dominates the time complexity for performing the residual-energy data collecting, the time complexity of the EASR equals the time complexity of the MCP.

Note that the MCP mainly consists of the following two steps, the layered network construction and the maximum capacity paths determination. Since the major operations are to determine the shortest path lengths for each node to the sink in the layered network construction, which takes $O(n^2)$ operation steps, the maximum capacity paths determination takes $O(n)$ operation steps, since the layered network is a DAG. Therefore, the time complexity of the MCP is equal to $O(n^2)$ $(= O(n^2) + O(n))$. Concluding the above discussions, we have that the time complexity of the EASR is equal to $O(n^2)$.

B. Numerical Analysis

In order to investigate the performance of the EASR scheme, we conducted several simulations in four different scenarios which will be described later. The compared methods are the EASR, One-Step Moving scheme [29] and the stationary sink scheme. The stationary sink scheme assumes that the sink is not capable of moving and remains stationary at all times. In our simulations, the proposed method and the other two compared methods all adopt the MCP [11] routing protocol as the underlying routing for message reporting. The comparison factor is the network lifetime of a WSN, for which the network lifetime is defined to be the number of message reporting rounds performed before the first sensor node drains out its battery energy. The simulation environment settings are as follows. We assume that the sensor nodes are all stationary after the deployment, but the sink is capable of moving except for the stationary sink scheme. The transmission range (γ) of the sensor nodes and the sink are fixed for the One-step Moving scheme and the stationary sink scheme, while the transmission range is tunable in the EASR method, which has been discussed in Section 3. The energy depletion during the execution of the message reporting is according to the first-order radio model.

The four simulation scenarios of 1, 2, 3 and 4 compared the resulting network lifetime performance of algorithms by varying the number of sensor nodes, the initial battery energy of the sensor nodes, the size of the simulation areas, and the transmission ranges, respectively. In each simulation instance, we conducted the experiment 100 times and then took the average value of the comparison factor (the network lifetime). The detailed simulation settings for simulation scenarios 1, 2, 3, and 4 are given in Tables I and II.

Simulation scenarios 1 and 2 investigate the network lifetime under the environment settings of the description in TABLE I when the number of sensor nodes and the initial battery energy varies, respectively. Fig. 16 gives the comparison results when the number of sensor nodes varies. As shown in this figure, the EASR outperforms the other

TABLE I

LIST OF PARAMETER SETTINGS FOR SIMULATION SCENARIOS 1 AND 2

Simulation scenarios	Sim1	Sim2
Initial battery energy (J)	1000	500, 750, 1000, 1250, 1500
Transmission range (m)	25	25
Simulation area (m^2)	$100 \cdot 100$	$100 \cdot 100$
Number of nodes	50, 75, 100, 125, 150	100

TABLE II

LIST OF PARAMETER SETTINGS FOR SIMULATION SCENARIOS 3 AND 4

Simulation scenarios	Sim3	Sim4
Initial battery energy (J)	1000	1000
Transmission range (m)	25	20, 25, 30, 35
Simulation area (m^2)	$100 \cdot 100$, $150 \cdot 150$, $200 \cdot 200$, $250 \cdot 250$	$200 \cdot 200$
Number of nodes	100, 225, 400, 625	400

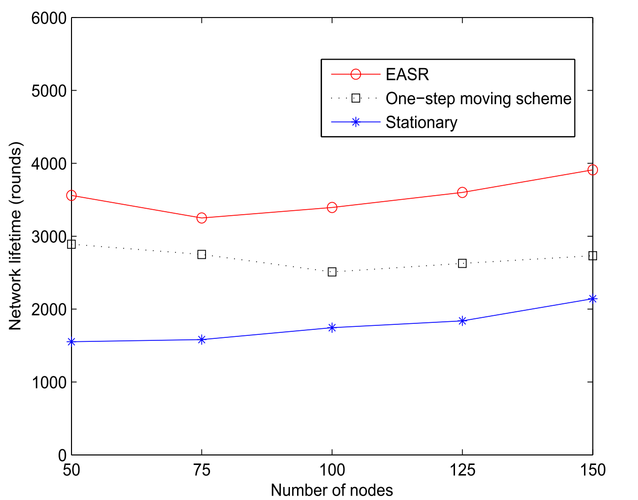

Fig. 16. The network lifetime comparisons in simulation scenario 1 with a varying number of sensor nodes.

two schemes (the One-Step Moving scheme and the stationary sink scheme) for any instance of the number of sensor nodes. As expected the stationary sink scheme received the worst network lifetime performance. The results also show that the stationary sink scheme had the worst performance results in simulation scenario 1 in any instance of the number of sensor nodes. Since the sink in the stationary sink scheme stays in the same position, the neighbors of the sink (the hot-spots) are always the same set of sensor nodes. Consequently they will quickly drain out their battery energy.

The performance results for network lifetime comparisons when the initial battery energy varied (simulation scenario 2) are given in Fig. 17. the EASR also outperformed the other schemes as the initial battery energy varied. And as the initial battery energy increased, the gap in the performance results increased between the EASR method and the other two compared schemes. In this figure, the stationary sink scheme also has the worst performance results. Figs. 18 and 19 show the simulation results for simulation scenarios 3 and 4

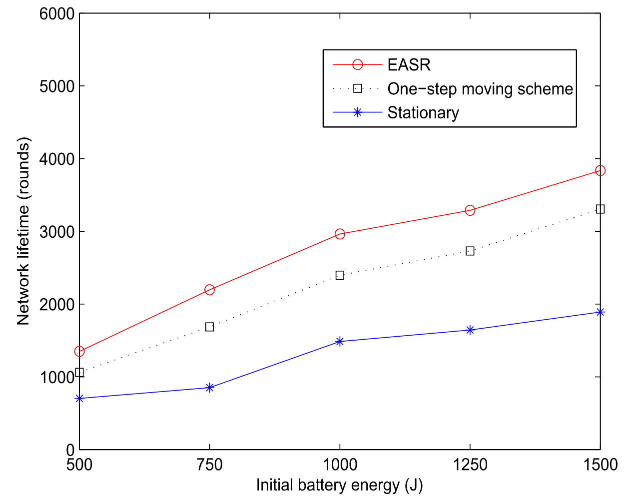

Fig. 17. The network lifetime comparisons in simulation scenario 2 with varying initial battery energy.

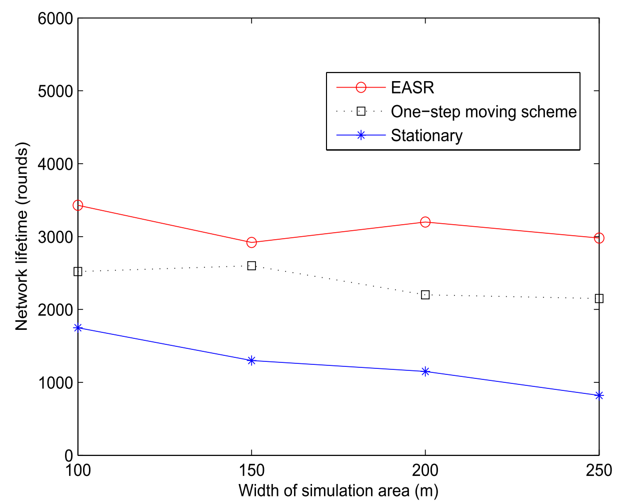

Fig. 18. The network lifetime comparisons in simulation scenario 3 with varying size of simulation area.

when the size of the simulation area and the transmission range vary, respectively. Note that, for each instance of size of simulation area, the number of nodes varies accordingly. For example, the instance of simulation area $100 \cdot 100$ m^2 (and $150 \cdot 150$ m^2), the number of sensor nodes deployed in this area is equal to 100 (and 225) (see the settings in TABLE II). Figs. 18 and 19 also show similar performance results as in simulation scenarios 1 and 2. Moreover, as shown in Fig. 19, the network lifetime increased as the transmission range increased for the EASR method and the other two compared methods. Since a transmission range is setting to be larger, the routing path length will be decreased and the number of neighbors with respect to the sink will also be increased. The amount of residual battery energy in the hot spots for performing the message relaying task to the sink will be increased, which might then increase the network lifetime of a WSN.

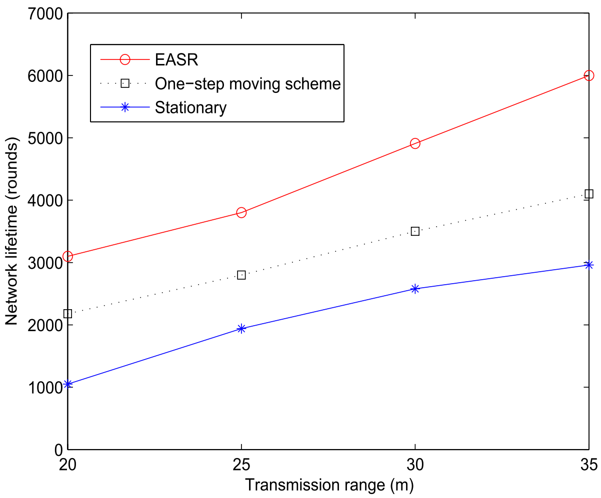

Fig. 19. The network lifetime comparisons in simulation scenario 4 with varying transmission range.

V. Conclusion

The depleting speeds of battery energy of sensor nodes will significantly affect the network lifetime of a WSN. Most researchers have aimed to design energy-aware routings to conserve the usage of the battery energy to prolong network lifetimes. A relocatable sink is another approach for prolonging network lifetime by avoiding staying at a certain location for too long which may harm the lifetime of nearby sensor nodes. This approach can not only relieve the burden of the hot-spot, but can also integrate the energy-aware routing to enhance the performance of the prolonging network lifetime. In this paper, we have proposed an energy-aware sink relocation method (EASR), which adopts the energy-aware routing MCP as the underlying routing method for message relaying. Theoretical analysis is given in this paper to demonstrate that EASR can prolong the network lifetime of a WSN. In addition, the simulation results show that the EASR method outperformed the other compared methods in the network lifetime comparisons under 4 different simulation scenarios.

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