On-Demand Node Reclamation and Replacement for Guaranteed Area Coverage in Long-lived Sensor Networks

Bin Tong*, Zi Li*, Guiling Wang**, and Wensheng Zhang*
*Department of Computer Science, Iowa State University
**Department of Computer Science, New Jersey Institute of Technology
Emails: {tongbin,wzhang,zili}@cs.iastate.edu, gwang@njit.edu

***Abstract*—To achieve required sensing coverage for a very long period of time is an important and challenging problem in sensor network design. Recently, Tong et al. have proposed a *node replacement and reclamation (NRR) strategy*, and designed an *adaptive rendezvous-based two-tier scheduling (ARTS) scheme*. However, the ARTS scheme only considers point coverage but not area coverage, which is required in many applications. To address this limitation, we propose in this paper a new implementing scheme for the NRR strategy based on a novel *staircase-based scheduling model*. Extensive simulations have been conducted to verify that the proposed scheme is effective and efficient.**

Key Words: Sensor Networks, Reclamation and Replacement, Duty-cycle Scheduling.

I. INTRODUCTION

In a wireless sensor network (WSN), sensor nodes are powered by batteries that can operate for only a short period of time, resulting in limited network lifetime if batteries are not replaced. The limited lifetime may disable its application in long-term tasks such as structural health monitoring for bridges and tunnels, border surveillance, road condition monitoring, and so on. Hence, many energy conservation schemes [1] were proposed to battle the constraint. These schemes can slow down the rate of energy consumption, but cannot compensate energy consumed. Fully addressing the problem requires energy to be replenishable to sensor nodes. One approach is to harvest energy from various environmental sources [2]–[6] such as the sunlight. The amount of energy that a solar cell can harvest is proportional to its surface area, but it is infeasible to equip a tiny sensor node with a large-size solar cell. The amount of available solar energy also depends on uncontrollable conditions such as cloudiness of the sky. Therefore, it is likely that the energy harvested is limited and unable to satisfy the needs of sensor nodes. Another approach is to incrementally deploy new sensor nodes to take over sensor nodes running out of energy. However, this approach is costly because sensor node hardware cannot be reused, and more importantly, it causes pollution to the environment because dead batteries and hardware are left in the environment. Therefore, seeking an effective and efficient way to guarantee long-term energy supply has persisted as a big challenge.

Recently, Tong *et al.* [7] proposed a *node reclamation and replacement (NRR)* strategy. With this strategy, a robot or human labor called *mobile repairman (MR)* periodically reclaims sensor nodes of low or no energy supply, replaces them with fully-charged ones, and brings the reclaimed sensor nodes back to a place called *energy station (ES)* for recharging. An *adaptive rendezvous-based two-tier scheduling (ARTS) scheme* [7] has also been designed to realize the NRR strategy. However, the ARTS scheme only considers point coverage [8], [9]. That is, it is assumed that sensor nodes are deployed to monitor points of interest scattered in a network field, while in many application scenarios such as border surveillance, guaranteeing area coverage [10]–[12] is desired.

To address the limitation of the ARTS scheme, we propose in this paper another implementing scheme of the NRR strategy to achieve guaranteed area coverage in long-lived sensor networks. Our proposed scheme consists of three tightly coupled components: (i) the protocol for sensors to coordinate their duty-cycle scheduling locally, (ii) the protocol for sensors and the ES to communicate with each other, and (iii) the algorithm for the ES to determine how to perform node reclamation and replacement on demand. These three components work together to achieve the following objectives: (a) required area coverage is guaranteed without disruption in the field monitored by the sensor network; (b) energy is replenished to the sensor network in an on-demand fashion to ensure infinite lifetime of the network and energy efficiency. The major contributions of this paper are as follows:

- To the best of our knowledge, this is the first effort that defines and addresses the problem of ensuring area coverage for an infinite period of time in sensor networks, under the node reclamation and replacement framework.
- We design a novel *staircase-based scheduling model* to address the important and challenging problem of achieving infinite network lifetime with limited number of backup sensor nodes. We have also found interesting results such as the minimum/maximum number of backup nodes that are needed to achieve infinite network lifetime. These results can help users of the proposed scheme to choose appropriate system parameters.
- Extensive simulations have been conducted to verify the effectiveness and efficiency of the scheme, as well as the validity of the findings we have discovered in theory.

The rest of the paper is organized as follows: Section II describes the system model. An overview of the proposed scheme is presented in Section III, which is followed by the detailed description in Section IV. Section V discusses some fundamental and practical issues. Section VI reports simulation results. Section VII summarizes related work, and finally Section VIII concludes the paper.

II. SYSTEM MODEL

We consider a network of n sensors, denoted as $s_1, s_2, s_3, \cdots, s_n$, is deployed to a continuous field for long-term monitoring. The monitored field is divided into m small areas, denoted as $a_1, a_2, a_3, \cdots, a_m$, such that, within any area a_i, the required sensing coverage level is the same at any point of the area.

As shown in Fig. 1, the whole NRR system is composed of an *energy station (ES)*, a *mobile repairman (MR)*, and a sensor network. The ES stores a certain number (denoted as

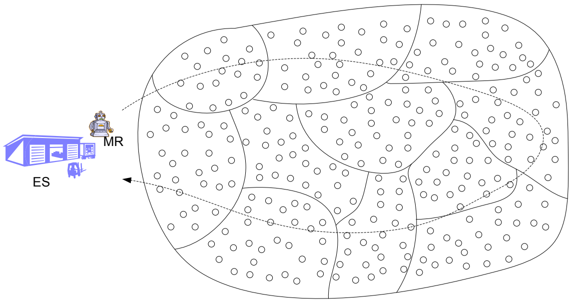

Fig. 1. System architecture

x) of backup sensors, and can recharge energy to sensors. The MR can be a human technician or a mobile robot. The MR can traverse the sensor network, reclaiming sensors of no or low energy, replacing them with fully-charged ones, and bringing the reclaimed ones back to the ES for recharging. Other assumptions of the system are as follows:

- All sensors are time synchronized. Time is divided into phases. A phase is a basic scheduling unit for duty-cycle scheduling; i.e., a sensor will not change its mode (active or sleeping) during a phase.
- A sensor has two modes: *active* and *sleeping*. For every phase, if a sensor is in the active mode, its energy is reduced by a fixed amount; if it is in the sleeping mode, its energy is unchanged. Let the energy of a fully-charged sensor be e. If a sensor is in the active mode all the time, its lifetime is denoted as T.
- For each area, the required sensing coverage level varies from N_{min} to N_{max}, subject to certain (e.g., Gaussian) distribution.
- Each area is deployed with $N_{max} + N_{back}$ (N_{back} is an integer greater than or equal to 1) *disjoint* sets of sensors, where each set of sensors can completely cover the area. That is, every point in the area can be covered by at least one sensor in each of the sets. We call these sets *coverage sets*. The reason for having more than N_{max} sets of sensors is to avoid service disruption at the time of node reclamation and replacement (Note: node reclamation and replacement cannot be completed in non-negligible time; hence, reclamation and replacement will inevitably disrupt the working of nodes that are reclaimed or newly placed).
- The MR has orientation and localization ability such that it can travel to designated locales and perform sensor replacement task. In this paper, we assume that the MR is able to carry x sensors a time. This can be relaxed to the case that the capacity of MR is smaller, and the trip scheduling algorithm studied in [7] may be applied to address this problem.
- Charging a sensor at the ES takes *non-negligible* time, which is denoted as τ. Note that, sensors can be recharged in parallel, we assume that it is possible to recharge all x backup sensors managed by the ES at the same time.

Design Goal. In this paper, we aim to design a collaborative scheduling scheme for sensors and the node reclamation and replacement algorithm for the ES/MR, such that (i) the sensor network can maintain the required area coverage for an infinite period of time, and (ii) the number of travels the MR should take is as small as possible (i.e., the average interval between two consecutive replacement trips is as large as possible).

III. OVERVIEW OF THE PROPOSED SCHEME

A. Key Ideas

To achieve guaranteed area coverage for an infinite period of time, two necessary tasks should be performed: firstly, sensors should collaboratively schedule their duty-cycles to achieve required area coverage; secondly, sensors and the ES/MR should coordinate to replenish energy into the network through node reclamation and replacement.

If the ES have unlimited number of backup sensors to use and the reclamation/replacement can be finished instantly, the above two tasks can be achieved easily. For example, any existing collaboratively duty-cycle scheduling schemes [13] can be applied for the first task; as for the second task, whenever an area is short of alive sensors, a request is sent to the ES, which then dispatches the MR to reclaim and replace sensors for the area. In reality, however, the backup sensors owned by the ES are limited and should be not too large for economic reasons, and the recharging take non-negligible time. Using the above naive approach, it may happen that, at some time instance, 1000 sensors should be replaced while the ES has only 500 backup sensors.

To address the above problem, the duty-cycle scheduling of sensors and the node reclamation/replacement activities should be carefully planned. In our design, we propose a *staircase scheduling model* for this purpose. The key ideas are as follows:

Coverage Set-level Scheduling. In each area, sensors are grouped into disjoint coverage sets, where nodes in each single coverage set can together cover any points in the area. Sensors are scheduled in the unit of coverage sets.

Intra-group Staircase. In each area, coverage sets are scheduled in a thoughtful way that, the required area coverage is guaranteed and meanwhile, the remaining energy levels of different sets are kept different, which form a *staircase* among the sets. Hence, different sets can be reclaimed and replaced at different time instances. As to be elaborated later, this facilitates the ES/MR to temporally reuse limited number of backup nodes to maintain lifetime.

Inter-group Staircase. Intra-group staircase may not be sufficient. It is likely that each of multiple areas needs to replace one of their coverage sets at the same time instance, and the demanded number of backup sensors could exceed what can be offered by the ES. To avoid this inter-group congestion of demands, our delicately designed scheduling strategy ensures that different areas issue demands at different time instances. This way, inter-group staircase is formed to further scatter demands and thus provide more flexibility to the ES/MR to plan the reclamation/replacement activities.

Redundancy for Flexibility. If the replacement requests issued by every area should be satisfied immediately by the ES/MR, the flexibility for performing reclamation/replacement activities will be strictly limited. At least, the number of trips taken by the MR may be too large, which may incur high system maintenance overhead. To address this issue, redundant nodes are deployed to areas to form backup coverage sets. With these backup sets, replacement requests can be satisfied with some delay, which allows the ES/MR to use one trip to satisfy multiple requests to reduce the maintenance cost.

B. Framework

Based on the above key ideas, the framework of our scheme is summarized as follows:

Duty-Cycle Scheduling. In our scheme, sensors in each area a_i are grouped into $N_{max} + N_{back}$ disjoint coverage sets, denoted as $cs_1, cs_2, \cdots, cs_{(N_{max}+N_{back})}$, where nodes in each coverage set can together sense every point in the area. The sensors in the same coverage set are scheduled together as an integral entity. Hence, sensors in the same coverage set have similar remaining energy at any time; to simplify scheduling, we assume all sensors in the same coverage set have the same remaining energy level. All coverage sets fall into two categories: N_{max} *primary* sets and N_{back} *backup* sets. At any phase, only primary sets can be scheduled, and a coverage set can change its role from primary to backup and vice versa. Each sensor knows which coverage set it belongs to, and also maintains the information of the remaining energy levels of sensors in other coverage sets. Therefore, every sensor in each area has a consistent view regarding the remaining energy levels of sensors in the same area.

In each area, a *head* is elected among all sensors through a certain collaborative selection algorithm [14], and the role is rotated among the nodes to balance energy consumption. At the beginning of each phase, the head broadcasts the coverage requirement for the current phase, i.e., the number of coverage sets (called *coverage number*) that shall be active. How to determine the coverage number is application-dependent and out of the scope of this paper. A possible approach is, the coverage number is determined based on the observations by active sensors in the last phase; if some event was detected in the last phase, the coverage number may be increased and vice versa. At the beginning of a phase, all sensors will wake up and listen to the broadcast of the coverage number. Upon receipt of the coverage number, each sensor runs our proposed duty-cycle scheduling algorithm independently to determine whether it should be active or not. Since all sensors in an area have the consistent view about the remaining energy level of all nodes in the same area, they will arrive at the same scheduling decision.

Interactions between Area Heads and the ES. Our duty-cycle scheduling algorithm ensures that, different primary sets will use up their energy at different time instances. Shortly before a primary set (say, cs_i) of sensors uses up its energy, it hands over its duty to a backup set (say, cs_j), which has full energy. After the handoff, cs_i becomes a backup set waiting to be reclaimed and replaced, while cs_j becomes a primary set. Meanwhile, the head of the area sends a *ready* message to the ES with the number of sensors in cs_i, which is the number of sensors that need to be reclaimed and replaced. Specifically, the ready message has the following format:

$$ready\langle a, cs_i, c\rangle,$$

where a is the ID of the area, cs_i is the ID of the coverage set needing to be reclaimed and replaced, and c is the total number of sensors in the cs_i.

If a primary set is about to use up its energy, and there is no backup set with fully-charged nodes to which the primary set can hand over its duty to, the head of the area sends out a *deadline* message to the ES. Specifically, the deadline message has the following format:

$$deadline\langle a\rangle,$$

where a is the ID of the area.

Node Reclamation and Replacement. Alg. 1 formally describes how the ES responds to the above ready and deadline messages. Specifically, when the ES receives a ready message, it accumulates the total number of sensors that are ready to be replaced. The ES will dispatch the MR when either of the following conditions is true: (i) It receives a deadline message; or (ii) the total number of sensors that are ready to be replaced exceeds x.

Algorithm 1 Reclamation and Replacement Scheduling: for the ES

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Notations:
    $x$: number of backup sensors
    $R$: set of ready messages that have not been served
    $t$: total number of sensors that are ready to be replaced
Initialization:
$R \leftarrow \phi$
$t \leftarrow 0$
Upon receipt of a ready message: $ready\langle a, cs, c\rangle$
$R \leftarrow R \cup ready$
$t \leftarrow t + c$
if $t >= x$ then
    Dispatch the MR to serve the earliest $x$ replacement requests.
    $t \leftarrow t - x$
    $R \leftarrow R - \{$served requests$\}$
Upon receipt of a deadline message: $deadline\langle a\rangle$
Dispatch the MR to serve all pending replacement reqeusts
$R \leftarrow \phi$
$t \leftarrow 0$
```

IV. DETAILED DESCRIPTION OF THE SCHEME

The duty-cycle scheduling scheme is performed at each sensor in each area at the beginning of each phase. The input to the duty-cycle scheduling scheme is (i) the estimated remaining energy level of every sensor in all coverage sets and (ii) the coverage number for the current phase. The output of the scheme is the coverage sets that should be active in the current phase. To ease understanding, we first describe how the scheduling scheme works when the coverage number of every area is fixed (i.e., N_{max}), which is followed by the general case where the coverage number of every area is variable ranging from N_{min} to N_{max}.

A. A Special Case: Fixed Coverage Requirement

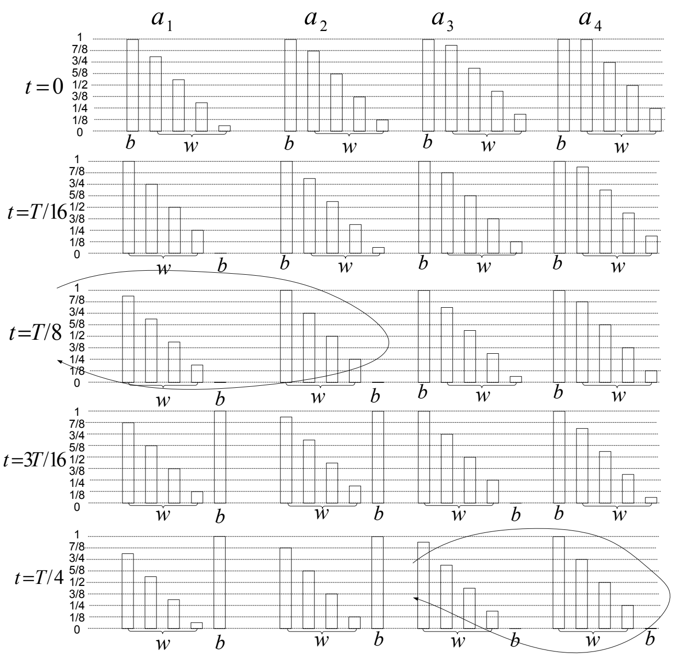

Fig. 2. Example 1: duty-cycle scheduling. Each bar represents a coverage set. $N_{max} = 4$, $N_{back} = 1$, $m = 4$, and $x = 32$. Each coverage set in every area has 16 sensors. "w" means primary set, and "b" means backup set.

Suppose for each area a_i, the number of sensors in each coverage set of area $a_i, 1 \leq i \leq m$, is denoted as c_i. Since areas are divided based on coverage requirement, c_i could be different for different areas. For each area $a_i, 1 \leq i \leq m$, we need to schedule all N_{max} primary coverage sets at any phase.

For all the N_{max} primary coverage sets, we let their remaining energy per node form a "staircase", and the height of each stair is

$$\frac{e}{N_{max}},$$

where e is the amount of full energy of a sensor. The formation procedure of this staircase is discussed later.

Fig. 2 shows an example where the monitored field consists of four areas. Each row in Fig. 2 shows the snapshot of remaining energy of each coverage set in each area at different time points. As can be seen, out of five coverage sets in each area, one is in the backup role, and the other four are in the primary role. The remaining energy per node of the four primary coverage sets forms a staircase with a stair height of $e/4$.

In our scheme, we define an order in which areas are visited by the MR to reclaim and replace sensors in these areas. For any two areas that are to be visited consecutively, their staircases have a phase difference δ, where δ and the height of a stair have the following relation:

$$\frac{e}{N_{max}} = m\delta, \tag{1}$$

where m is the number of areas. In Fig. 2, areas are sorted as a_1, a_2, a_3, a_4. As can be seen, at time point 0, the staircase of primary coverage sets in a_2 is $e/16$ higher than that of the primary coverage sets in a_1, the staircase of the primary coverage sets in a_3 is also $e/16$ higher than that of the primary coverage sets in a_2, and so on. This phase difference remains as time evolves.

Since the coverage requirement is always N_{max}, all the four primary coverage sets will be active at any time. When the primary coverage set with the minimum energy drains of its energy, it will (i) shift its duty to a backup coverage set, which has full energy; (ii) becomes a backup set. Meanwhile, the head of the area will send a ready message to the ES, and the full energy backup coverage set will become a primary coverage set.

In Fig. 2, at time $t = T/16$, the primary coverage set with the minimum energy in a_1 drains of its energy, and shifts its duty to the only backup coverage set. A ready message is also sent to the ES. Since at this time, the total number of nodes that are ready to be replaced is 16, which is less than $x = 32$, the MR will wait. At time $t = T/8$, the primary coverage set with the minimum energy in a_2 drains of its energy, and shifts its duty to the backup coverage set. A ready message is also sent to the ES. At this time, the total number of nodes that are ready to be replaced equals to x. Thus, the MR makes a replacement tour, replacing nodes in the backup sets of a_1 and a_2. Similarly, the MR makes another replacement tour at $t = T/4$, replacing nodes in the backup coverage sets of a_3 and a_4.

One noteworthy fact is that, in this example, recharging x sensors should be completed in $T/8$. We have derived a relation between recharging time and the minimum number of backup sensors needed, which is to be discussed later.

Staircase Formation In the above, we assume that the staircase structure is already formed. However, when a sensor network starts operating, all sensors in the sensing field have full energy. To form the staircase structure, we propose the following method. Without loss of generality, we assume the pre-defined visiting order to the areas is $\langle a_1, a_2, \cdots, a_m \rangle$. When a primary coverage set in a_1 consumes δ energy [1], it shifts its duty to a backup coverage set, and becomes a backup coverage set itself. The head of area a_1 also sends a ready message to the ES. Similarly, when a primary coverage set in a_2 consumes 2δ energy, it shifts its duty to a backup coverage set, and becomes a backup coverage set itself. Besides, the head of area a_2 sends a ready message to the ES. In general, a primary coverage set in a_i will make the role transition and trigger ready message reporting after it consumes $i\delta$ energy.

The next time for role transition and ready message reporting in a_1 is after a primary coverage set with the minimum energy has consumed $m\delta$ energy after the first role transition. The third time for role transition and ready message reporting in a_1 is after a primary coverage set with the minimum energy has consumed $m\delta$ energy after the second role transition; and so on. Other areas will follow the same rule to conduct their role transitions and ready message reporting. After time T, the staircase structure will be naturally formed. Fig. 3 shows an example of staircase formation of area a_1 in Fig. 2. Note that, the staircase shown at $(t = T)$ is the same as that at $(t = 0)$ in Fig. 2.

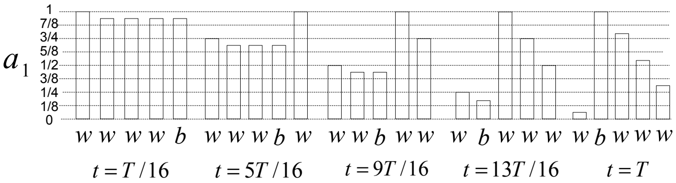

Fig. 3. Example 2: initial staircase formation of area a_1 in Fig. 2. $\delta = T/16$.

B. General Case: Variable Coverage Requirement

In this section, we consider the general case that the required coverage number is not always N_{max}, but varies in range $[N_{min}, N_{max}]$.

Given an area $a_i, 1 \leq i \leq m$, we let the remaining energy per node of its N_{max} primary coverage sets, denoted as $w_1, w_2, \cdots, w_{N_{max}}$, form a staircase as described above. Assume $e_i, 1 \leq i \leq N_{max}$ represents the remaining energy of coverage set w_i. Without loss of generality, we have $e_1 < e_2 < e_3 < \cdots < e_{N_{max}}$, where the difference between any two consecutive terms is $m\delta$. The duty-cycle scheduling is performed phase by phase.

Assuming the coverage number for the first phase is q_0, $N_{min} \leq q_0 \leq N_{max}$, we will need to schedule q_0 primary coverage sets. In our scheme, we schedule primary coverage sets $\{w_1, w_2, w_3, \cdots, w_{q_0}\}$ for the first phase. If the coverage number for the next phase is $q_1, N_{min} \leq q_1 \leq N_{max}$, we will need to schedule q_1 primary coverage sets. In this case, we will schedule coverage sets $w_{(q_0+1) \mod N_{max}}, w_{(q_0+2) \mod N_{max}}, \cdots, w_{(q_0+q_1) \mod N_{max}}$. In other words, we adopt a round-robin scheduling policy while maintaining the staircase structure.

In this case, whenever each area a_i uses up its primary coverage set with the minimum energy, its head sends a ready message to the ES if there are backup coverage sets with full energy. If all the backup coverage sets have empty energy before the primary coverage set with the minimum energy

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[1] Since all primary coverage sets will have the same remaining energy at that time, we randomly pick one.

is about to use up its energy, the head will send a deadline message to the ES.

The formal duty-cycle scheduling algorithm for the variable coverage number case is described in Alg. 2.

Algorithm 2 Duty-Cycle Scheduling for the variable coverage requirement case: for sensors in primary coverage set $w_i, 1 \leq i \leq N_{max}$

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Notations:
    $q$: coverage number in phase $p$
    $b_j, 1 \leq j \leq N_{back}$: $N_{back}$ backup coverage sets
    var $start$; // start position of primary coverage sets for phase $p$.
if $w_i \in \{w_{start}, w_{((start+1) \mod N_{max})}, \cdots, w_{((start+q-1) \mod N_{max})}\}$ then
    Schedule coverage set $w_i$.
    if $w_i$ drains of its energy then
        Randomly choose a backup coverage set with full energy, $b_j$.
        Coverage set $w_i$ changes its role to backup.
        Coverage set $b_j$ changes its role to primary.
$start \leftarrow (start + q) \mod N_{max}$
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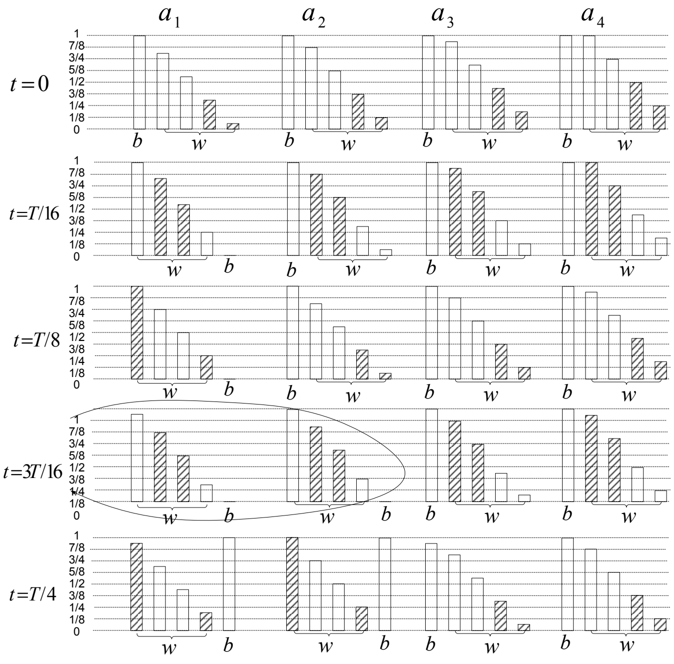


Fig. 4. Example 3: duty-cycle scheduling. Each bar represents a coverage set. Shaded bars are scheduled in the current phase. $N_{max} = 4$, $N_{back} = 1$, $m = 4$, and $x = 32$. Each coverage set in every area has 16 sensors. Phase length is $T/16$.

Fig. 4 shows an example. In this example, the length of a phase is $T/16$, and the coverage number is two for the first four phases for all areas. As can be seen, in the first phase, the two primary coverage sets with the minimum remaining energy in all areas are scheduled. In the second phase, the next two primary coverage sets in all areas are scheduled. This process is carried on.

At time $t = T/16$, the head of area a_1 sends out a ready message to the ES. The MR will not make a replacement tour since the number of sensors that are ready to be replaced, 16, is less than $x = 32$. At time $t = 3T/16$, the head of area a_2 sends another ready message. At this time, the number of sensors that are ready to be replaced reaches x, and thus the MR conducts a replacement.

Staircase Formation. The staircase formation procedure for the variable coverage number case is the same as that for the fixed coverage requirement case.

V. DISCUSSIONS

A. Lower Bound of Required Number of Backup Nodes

Since charging batteries takes non-negligible time, the energy replenishment rate is affected by the number of backup nodes owned by the ES. Assuming the number of backup nodes is x, the time to recharge a sensor is τ, and full energy of a sensor is e, the energy replenishment rate is

$$xe/\tau.$$

This rate should be large enough to compensate energy consumption of the network even in the worst case scenario. Specifically, the worst case energy consumption rate occurs when the coverage number in each area is N_{max}.

Consider area $a_i, 1 \leq i \leq m$, in which each coverage set has c_i sensors. N_{max} coverage sets will each consume e/N_{max} energy in T/N_{max} time, where T is a sensor's lifetime. Thus the total energy consumption of area a_i in T/N_{max} time is

$$c_i N_{max} \frac{e}{N_{max}} = c_i e$$

It follows that the energy consumption rate in area a_i is $c_i e N_{max}/T$.

The total energy consumption rate over all areas is

$$\frac{e}{T} \sum_{i=1}^{m} c_i N_{max}$$

We have

$$\begin{aligned} \frac{xe}{\tau} &\geq \frac{e}{T} N_{max} \sum_{i=1}^{m} c_i \\ x &\geq \frac{\tau}{T} N_{max} \sum_{i=1}^{m} c_i \qquad (2) \end{aligned}$$

B. Upper Bound of Number of Backup Nodes

In the proposed scheme, the MR only replaces sensors in backup coverage sets for each area. The reason is that replacement will disrupt sensor nodes' operation. By not replacing the N_{max} primary coverage sets, service disruption is avoided.

As a result, at one time, the maximum number of sensors that are ready to be replaced in area a_i is $N_{back} c_i$, and the total number of sensors that are ready to be replaced over all areas is

$$N_{back} \sum_{i=1}^{m} c_i \qquad (3)$$

In general, this is the upper bound for x in the sense that if $x > N_{back} \sum_{i=1}^{m} c_i$, the surplus backup sensors will never be used.

However, there is an exception when the lower bound calculated by Eq. (2) is greater than the upper bound calculated by Eq. (3). This case is discussed in the following.

C. Impact of Node Recharging Time

If sensor recharging time at the ES is very long, it is possible that the lower bound of x calculated by Eq. (2) is greater than the upper bound calculated by Eq. (3). Here we face a dilemma: On one hand, x should be greater than the calculated lower bound in order to guarantee the coverage requirement over an infinite period of time; on the other hand, if x is greater than the calculated upper bound, the surplus sensors will not be used. We propose the following method to address this issue.

Assume the lower bound of x calculated by Eq. (2) is denoted as l, and the upper bound calculated by Eq. (3) is denoted as h. Given sensor recharging time τ, we list its divisors by natural numbers $2, 3\cdots$, and for each divisor, we calculate a lower bound l' using Eq. (2). This process stops $l' < h$. Assume at this time the divisor of τ is $\tau/k, k \geq 2$.

If we have $kh \geq x \geq kl'$, then the x backup sensors can be divided into k batches. All sensors in a batch will start being recharged at the ES at the same time. Further, we order the k batches into a sequence, and the start times for any two consecutive batches in the sequence being recharged differ by τ/k. In other words, the system generates x/k, $h \geq x/k \geq l'$, fully charged sensors every τ/k. This way, the proposed scheme works as the regular case.

D. Some Practical Issues

Next, we discuss some practical issues in implementing the proposed scheme.

First, sensor nodes may fail at any time. Our scheme can tolerate sensor failures, i.e., failed sensors will be replaced by the MR. We employ the following method to detect sensor failures. At the time for scheduling (i.e., at the beginning of a phase), if a primary coverage set w is chosen to be active in the phase, all sensors in the coverage set will send a message to the head of the area. If the head does not receive the message from a sensor u for more than a threshold of times, it considers u has failed, and then sends a *failure* message to the ES. The MR will replace the failed sensor in its next replacement trip.

Second, our scheme requires communication between active sensors and the head of each area in every phase. Since the size of an area is typically small, the imbalance in energy consumption among sensor nodes for forwarding data packets is limited. Further, we factor the maximum energy consumption for packet forwarding into total energy consumption at each sensor.

Third, the head of each area will report ready and deadline messages, which may travel a long route. However, reporting of these messages is infrequent since they are only sent out when the area have consumed considerable amount of energy, which is on the magnitude of sensor batteries's lifetime.

TABLE I
GENERAL EXPERIMENTAL SETTINGS

field size	$500m * 500m$
# of areas	80
sensing range	$20m$
transmission range	$40m$
N_{min}	1
N_{max}	4
N_{back}	$\{1, 2, 3\}$
recharging time	6 hours
sensor's lifetime time	240 hours (5 days)
# of sensors per coverage set	$Gau(16, 3)$
sensor's full energy	1440 units
phase length	10 minutes
energy consumption rate	0.1 unit/minute
cut-off time	4800 hours (200 days)

VI. PERFORMANCE EVALUATION

We built a custom simulator using C++ to evaluate the performance of the proposed scheme.

A. Experimental Settings, Metrics and Methodology

Table I shows system parameters we used in the simulation. We consider a sensor network composed of 80 areas. Each area has $(N_{max} + N_{back})$ disjoint coverage sets, and each of which is able to cover the whole area. The number of sensors in each coverage set is a random number, which complies to a Gaussian distribution, $Gau(16, 3)$, with mean of 16.

In the experiments, we normalize the full energy level of a sensor to 1440 units and the energy consumption rate is 0.1 unit/minute if the sensor is active. Thus, each sensor's lifetime T is 240 hours, i.e., 5 days. The length of a phase is set to 10 minutes. Coverage numbers for each area vary between N_{min} and N_{max}. N_{min} is set to 1, and N_{max} is set to 4 in all experiments.

In reality, coverage number is determined by the application, as well as the real-time frequency and distribution of events. In our simulation, coverage number complies to a truncated Gaussian distribution, which is $Gau(\mu = N_{min}, \sigma = 2)$ truncated to the range $[N_{min}, N_{max}]$.

The performance metrics include:

- *Average replacement interval*: Average time between two consecutive replacement tours made by the MR.
- *Average utilization of the MR*: The MR may not carry x sensors in each replacement tour due to the replacement deadlines set by each area. Average utilization of the MR is the average ratio of the number of backup sensors actually carried by the MR to x.
- *Distribution of replacement intervals*: To ease reclamation/replacement planning, a distribution of replacement intervals with smaller variance is preferred in practice.

We consider the following sets of scenarios: (i) All areas have the same coverage number at any time, and (ii) All areas subject to the same distribution of coverage numbers, but coverage numbers in all areas are independent of each other. For each experiment, our proposed scheme is executed for a long time period, starting at 0 and ending at a *cut-off* time. The cutoff time is set to 4800 hours, i.e, 200 days, for all experiments. Furthermore, we run each simulation for 50 times for the metrics of average replacement interval and average utilization of the MR, and 500 times for the metric of distribution of replacement intervals, and take average for each of the metrics.

B. Scenario I: Same Coverage Number for All Areas

In this experiment, coverage number is the same for all areas at any phase. The number of backup coverage sets, N_{back}, varies among $\{1, 2, 3\}$. The results are shown in Fig. 5. Fig. 5(a) and Fig. 5(b) show the trend of average replacement interval and utilization of the MR when coverage number complies to the truncated Gaussian distribution. As can be seen, given the number of backup coverage sets, average replacement interval increases as the number of backup sensors, x, increases in an approximately linear fashion. At the same time, the utilization of the MR keeps at 1. However, when x reaches a certain value, the average replacement interval levels off, and at the same time, the utilization of the MR starts to drop.

For example, given one backup coverage set for each area, when x exceeds 1300, the average replacement interval stops increasing, and the utility of the MR drops to 0.95.

The reason for this phenomenon is explained as follows. Since all areas have the same coverage number, their primary coverage sets consume their energy at the same rate. Further, in our scheme, the remaining energy of primary coverage sets in any two consecutive areas according to the pre-defined visiting order has a phase difference δ. Therefore, the time instances for the heads in all areas to send ready messages are evenly distributed as time evolves.

when x is small, the time instances when the number of sensors that are ready to be replaced exceeds x are always ahead of arrival of any deadline message. Thus, the MR will replace x sensors in each replacement tour, which results in a full MR utilization. Further, given the total amount of energy consumption of the network until the cutoff time, the total amount of energy that is needed to be replenished into the network is fixed. As a result, average replenish interval increases with x in a linear fashion.

On the other hand, when x exceeds the upper bound of x calculated by Eq. (3), which is between 1200 and 1300 in this experiment, a deadline message will arrive before the number of sensors that are ready to be replaced reaches x. Therefore, replacement interval stops to increase at this point. Furthermore, since the number of backup sensors that are actually used stays at the upper bound value, as x increases, the utilization of the MR decreases in a reciprocal fashion.

The results show that given a fixed number, N_{back}, of backup coverage sets, we cannot raise average replacement interval over a certain value by simple increasing x. Instead, N_{back} will need to be increased.

Fig. 5(c) shows histograms of replacement intervals for three different parameter sets. In Fig. 5(c), the first number in a pair of parentheses is the number of backup coverage sets, and the second number is x. For example, "(1,1000)" means one backup coverage set and 1000 backup sensors. Note that for all the three parameter sets, the utilization of the MR is 1. As can be seen in Fig. 5(c), replacement intervals cluster in a small range. For parameter set (1,1000), the mean of replacement intervals is 98.53, and the standard deviation is 2.35.

C. Scenario II: Same Coverage Number Distribution for All Areas

In this experiment, all areas have the same value of $N_{max} = 4$, and their coverage numbers comply to the same probability distribution. However, coverage numbers of different areas are independent of each other. In addition, we assume in each area, coverage numbers at different phases are independent of each other.

Fig. 6(a) and Fig. 6(b) show very similar patterns as in Fig. 5(a) and Fig. 5(b), respectively. This can be explained as follows.

Since coverage number is a random variable between N_{min} and N_{max}, and coverage numbers at different phases are independent of each other, the summation of coverage numbers over a large number phases can be approximated with a Gaussian distribution by the Central Limit Theorem. According to our experiment settings in this experiment, it takes 360 phases for a sensor to consume energy to the amount of the stair height (i.e., $\frac{e}{N_{max}}$). Since all area's coverage number complies to the same distribution, their summation of coverage numbers over a large number of phases can be approximated with the same Gaussian distribution with the same mean. Thus, all areas consume energy at approximately the same average rate.

Furthermore, our scheme maintains a phase difference δ among the staircases in different areas. Thus, the time instances for all areas to send out ready message are *approximately* evenly distributed as time evolves. Therefore, both average replacement interval and utility of the MR follow the similar pattern as in Fig. 5.

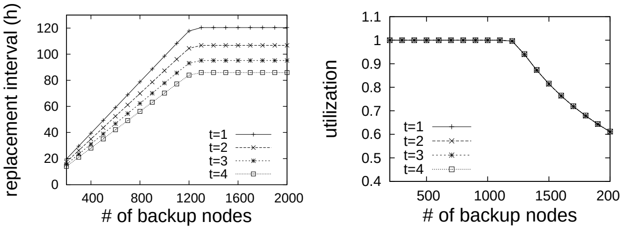
One notable difference between Fig. 6 and Fig. 5 is in the histograms of replacement intervals. The histograms in Fig. 5(c) are taller and narrower than the corresponding ones in Fig. 6(c), which implies smaller standard deviations. This is because the independence of coverage numbers of the areas brings more variance in terms of the interval between two consecutive time instances when the number of sensors that are ready to be replaced reaches x.

D. Variable Distribution of Coverage Numbers

In this experiment, all areas have the same values of parameters N_{min} and N_{max}, and their coverage numbers comply to the same truncated Gaussian distribution and are independent of each other. In the prior experiments, we always truncate $Gau(\mu = N_{min}, \sigma = 2)$ to the range $[N_{min}, N_{max}]$ to get truncated Gaussian coverage numbers. In this experiment, we set $N_{min} = 1$, $N_{max} = 4$, and truncate $Gau(\mu = t, \sigma = 2)$ to the range $[N_{min}, N_{max}]$, where t varies in $\{N_{min}, N_{min} + 1, \cdots, N_{max}\}$, i.e., $\{1, 2, 3, 4\}$. We only consider one backup coverage set in this experiment.

Fig. 7 shows the trend of average replacement interval and utilization of the MR when t varies.

As can be seen, when t is larger, average replacement interval is smaller. This is because larger t implies higher energy consumption rate of the network, and thus the MR needs to replace sensors more frequently. On the other hand, the value of x where average replacement interval levels off and the utilization of the MR starts to drop is the same for all the values of t. This is because the distribution of coverage numbers does not affect the upper bound of x according to Eq. (3).



(a) Average replacement interval (b) Average utilization of the MR

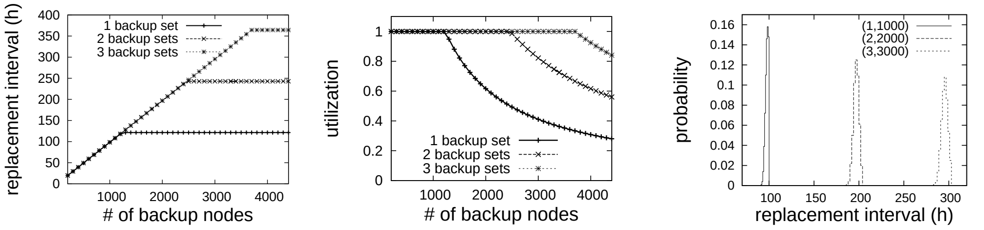
Fig. 7. Variable Gaussian distribution

VII. RELATED WORK

Recent studies [15], [16] have explored mobility to mitigate the energy issues. These schemes work in a "preventive" way and try to relieve sensor nodes from some responsibilities by leveraging mobile nodes. However, when a certain number of sensor nodes are drained of energy, the network cannot heal itself and thus cannot operate for a long time, which is required by long-term surveillance applications.

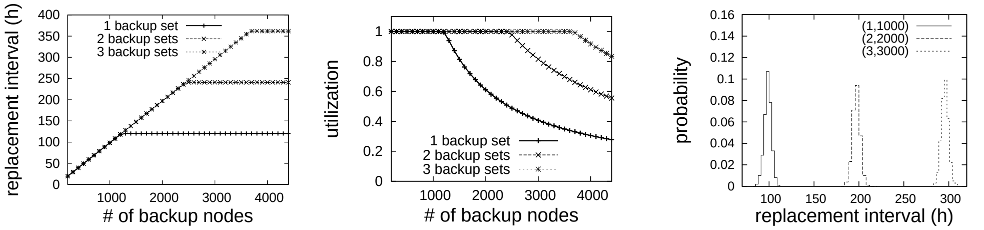
To enable self-healing of a sensor network and for other purposes, Wang et al. [17] introduce mobile sensors to replace sensors died of energy depletion. In a long-time surveillance application, eventually, all the sensor nodes need to be replaced by the mobile nodes, which increases the network cost. Schemes [18], [19] that propose to employ unmanned aerial vehicles or robots to repair networks have the following drawbacks: i) Infinite number of backup sensors is assumed. ii) Intensive communication between sensors and base station(s), and sensors and robots, is required.

Another approach to address the energy issues is to take advantage of ambient energy [3], [5], [6] in the environment, e.g., solar energy. As mentioned in Section I, practical solutions are still under investigation.



(a) Average replacement interval (b) Average utilization of the MR (c) Histogram of replacement intervals

Fig. 5. Scenario I: Same Coverage Number for All Areas



(a) Average replacement interval (b) Average utilization of the MR (c) Histogram of replacement intervals

Fig. 6. Scenario II: Same Coverage Number Distribution for All Areas

VIII. CONCLUSION

In this paper, we proposed an on-demand node reclamation and replacement scheme for long-term surveillance sensor networks based on the area coverage model. Our scheme periodically replaces sensors drained of energy given a fixed number of backup sensor nodes, and guarantees that the coverage requirement of the network is satisfied over an infinite period of time. The simulation results show our scheme are both effective and efficient.

IX. ACKNOWLEDGMENTS

This work was partially supported by the National Science Foundation under Grands CNS-0831874, CNS-0831906, CNS-0834585, and CNS-0834593.

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