# Node-Replacement Policies to Maintain Threshold-Coverage in Wireless Sensor Networks

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***Abstract*— With the rapid deployment of wireless sensor networks, there are several new sensing applications with specific requirements. Specifically, target tracking applications are fundamentally concerned with the area of coverage across a sensing site in order to accurately track the target. We consider the problem of maintaining a minimum threshold-coverage in a wireless sensor network, while maximizing network lifetime and minimizing additional resources. We assume that the network has failed when the sensing coverage falls below the minimum threshold-coverage. We develop three novel node-replacement policies to maintain threshold-coverage in wireless sensor networks. These policies assess the candidature of each failed sensor node for replacement. Based on different performance criteria, every time a sensor node fails in the network, our replacement policies either replace with a new sensor or ignore the failure event. The node-replacement policies replace a failed node according to a node weight. The node weight is assigned based on one of the following parameters: *cumulative reduction of sensing coverage*, *amount of energy increase per node*, and *local reduction of sensing coverage*. We also implement a *first-fail-first-replace policy* and a *no-replacement policy* to compare the performance results. We evaluate the different node-replacement polices through extensive simulations. Our results show that given a fixed number of replacement sensor nodes, the node-replacement policies significantly increase the network lifetime and the quality of coverage, while keeping the sensing-coverage about a pre-set threshold.**

**Keywords:** wireless sensor networks and sensing coverage.

## I. INTRODUCTION

The next-generation networks are envisioned to be deployed as an infrastructure of devices that are available anywhere and any time, autonomous, survivable against multiple faults and attacks, and highly secure for communication. Recent advances in wireless communications and electronics have enabled the development of low-cost, low-power, small-size, and multi-functional sensor nodes. These sensors consist of a microprocessor capable of handling a few million instructions per second, limited storage in the order of a few kilobyte of RAM, a short-range radio transmitter, a small power source (often a battery), and a couple of sensors and/or actuators to interact with the environment [1]. Such tiny sensor nodes that are deployed in an ad hoc fashion and that cooperate on sensing a physical phenomenon, have led to the emergence and deployment of wireless sensor networks. Sensor networks hold the promise of revolutionizing sensing in a wide range of application domains because of their reliability, accuracy, flexibility, cost-effectiveness, and ease of deployment. Sensor networks are envisioned to invade the world for data acquisition like the way the Internet has taken over the world for data dissemination.

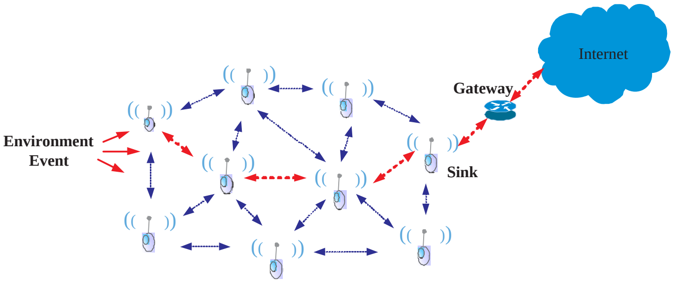


Fig. 1. Wireless sensor network.

A typical wireless sensor network, shown in Fig.1, consists of one sink node and many sensor nodes scattered across a sensing site. Each of these scattered sensor nodes is capable to collect the data and to forward the data back to the sink through a multi-hop architecture. The data may be delivered to the user at the remote site through the Internet connection. A gateway usually resides between the sink and the Internet and provides the interface between them.

Sensing coverage is a fundamental concept in sensor networks that characterizes the monitoring quality provided by a sensor network in a designated region. Coverage of a sensor network represents the quality of service (QoS) that it can provide and serves as a basis for applications such as physical phenomenon or target detection, classification and tracking [2]. Some typical applications include: battlefield surveillance, biological detection, atmosphere and ocean environment monitoring [3], [4], habitat tracking, forest fire detection, radar and sonar coverage, inventory tracking, and infrastructure security [5]. Due to a variety of sensors and the diversity of sensor network applications, coverage is subject to a wide range of interpretation; for example, spatial vs. temporal. Sensing coverage depends on the density and sensing characteristics of the sensors. One of the main objectives of the coverage problem is to prolong network lifetime.

There are several important tracking and monitoring applications that require a minimum threshold-coverage in order to be successful. The minimum coverage-threshold can range from full-coverage (100%) to fractional-coverage. In this paper, we aim to develop efficient node-replacement policies so that given a threshold-coverage requirement and a fixed amount of additional resources (replacement sensors), we maximize the network lifetime. Our policies work independent of the actual-value of threshold-coverage. We have also assumed a flat sensor network architecture without data-fusion support.

The rest of the paper is organized as follows. Section II provides a detailed overview of the problem. Section III describes the proposed node-replacement policies to maintain threshold-coverage in wireless sensor networks. Section IV presents our simulation results, and Section V concludes the paper.

## II. PROBLEM DESCRIPTION

Network life and sensing coverage are two fundamental issues in wireless sensor networks. There are several limitations that have to be considered while working with wireless sensor networks. If the network is initially deployed in an ad hoc manner, the nodal density (connectivity) of each sensor may vary significantly, and the overlap area of sensing coverage with each neighboring node may also vary significantly.

Every node in a wireless sensor network forward data to the base station based on an *information-dissemination routing tree*. Based on the position of each sensor on the routing tree, each sensor may be responsible for forwarding a highly variable number of packets through it. Sensors that are close to the base station on the routing tree will be forwarding a large number of packets per unit time compared to the sensors at the leaf of the routing tree.

Applications that cover a large sensing site with a very large-scale sensor network, may develop network partitions due to the loss of an entire (possibly-large) sub-tree. Network partitions result in a dramatic reduction of network coverage and may seriously hamper the functioning of the sensing application. There may be several nodes in the network that could be *articulation points*, i.e., failure of this node results in a disconnected network. If Node $v$ is an articulation point, then there exist distinct vertices Node $w$ and Node $x$ such that Node $v$ is in every path from Node $w$ to Node $x$. Sensor nodes that have high-connectivity and are possible articulation points may be critical in maintaining the sensing coverage about a certain threshold. Certain nodes at the lower-levels of the routing-tree do not forward much of the traffic. The failure of such nodes does not significantly affect the sensing coverage of the network. On the other hand, if nodes toward the root of the routing tree fail, they significantly affect the sensing coverage of the network. We propose several node-replacement polices that determine if a failed node in the network is important enough to be replaced. Node replacement is done in such a way that we increase the network life and maintain the sensing coverage above a pre-defined threshold.

The actual process for physically replacing a failed node is an interesting problem and is outside the scope of this paper. One simple approach is to use mobile backup sensor nodes that relocate to the position of the failed node. Alternately, we could redeploy identical static sensor nodes at the same location as the failed sensor node.

## III. NODE-REPLACEMENT POLICIES

In this section, we proposed several node-replacement policies that help determine the importance of each failed node on the sensing coverage and the lifetime of the entire network. Each policy calculates the weight of the failed node based on a specific parameter. If the weight of a failed node is greater than the policy threshold, we replace the node. If not, we ignore and continue. The following parameters are used to compute the weight of each failed node.

- Cumulative reduction in area of sensing coverage due to the failed node.
- Energy increase per node, i.e., increase in total energy-expended to transmit packets to the base station due to the failed node.
- Local reduction in area of sensing coverage due to the failed node.

### A. Cumulative Reduction of Sensing Coverage

In this policy, we calculate the *cumulative reduction of sensing coverage* due to a failed node. Every time a node fails, we compute the weight $CR$ for the failed node. If $CR$ is above a pre-determined threshold, then the failed node is replaced with another backup node. Otherwise, the network ignores the node failure and recomputes alternate routes to the base station for the other sensors connected through the failed sensor node.

If a failed node happens to be an articulation point, then the $CR$ is given by the sum of the coverage area of the failed node plus the cumulative coverage area of all the nodes in the disconnected sub-network. Let us consider the example in Fig. 2 to better understand this policy. Assume that we have randomly deployed twelve sensor nodes with a single base station (solid black circle). The circle around each node indicates the transmission and sensing range of each node. Fig. 2(a) depicts the initial coverage of the network. The actual sensing coverage is the cumulative sensing coverage of all the nodes (Node 1 through Node 12) after removing the overlapping area. Assuming that Node 10 fails, Fig. 2(b) depicts the updated sensing coverage of the network i.e., cumulative coverage area of all the nodes, Node 1 through Node 9. The failure of Node 10 will not only result in the reduction of coverage area due to Node 10, but also disconnects Node 11 and Node 12 from the base station. Hence, the cumulative reduction of sensing coverage is given by,
$CR = A_{10} + A_{11} + A_{12} - A_{10} \cap A_{11} - A_{11} \cap A_{12} - A_{10} \cap A_{12} + A_{10} \cap A_{11} \cap A_{12}$, where $A_i$ is the sensing coverage area of Node $i$. In order to find the cumulative reduction of sensing coverage in general, we have: $CR = \sum_{i=1}^{n} A_i - \sum_{i<j} A_i \cap A_j + \sum_{i<j<k} A_i \cap A_j \cap A_k \mp \cdots \pm \bigcap_{i=1}^{n} A_i$ [6].

### B. Energy Increase per Node

In the *energy increase per node* policy, we compute the increase in total energy-expended to transmit packets to the base station due to the failed node. If the node is on the shortest-path of another node, its failure will affect the total energy-expended by other nodes along the path for sending packets to the base station. When a sensor node fails, if it is on the shortest-path of another node, the recalculated alternate path will expend more energy than the original shortest path. Path recalculation has to be implemented for all nodes to the base-station routes that used the failed node on their primary path. Hence, all the recalculated paths will expend more energy compared to using the primary paths through the failed node. We compute node weight, $EI$, the average energy increase per node due to a node failure. If $EI$ is above a pre-determined

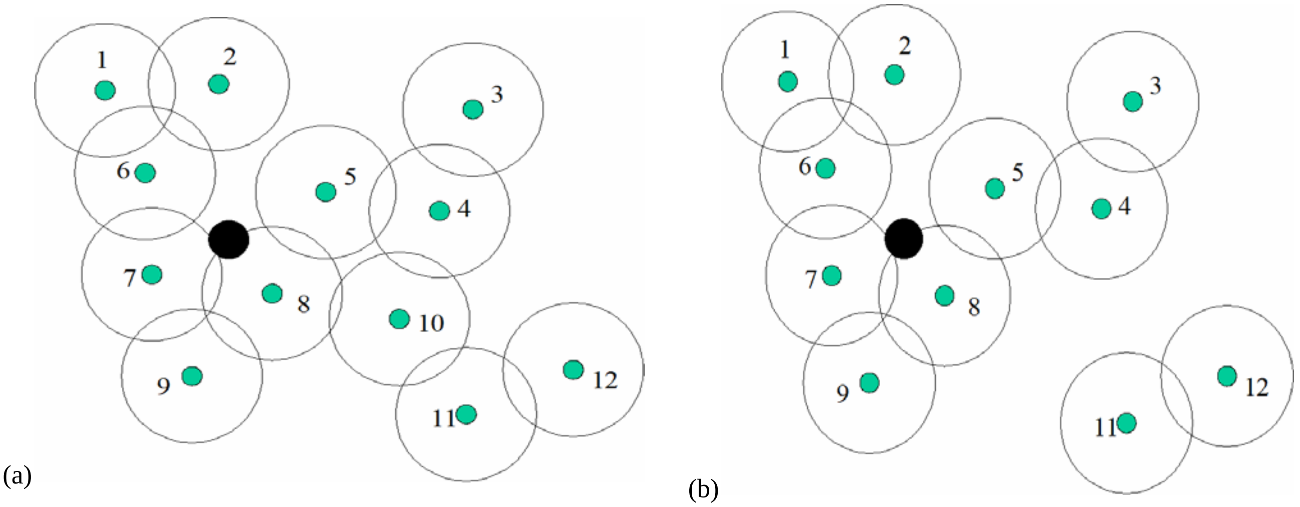


Fig. 2. Sensing coverage area (a) before and (b) after failure of Node 10.

threshold, then the failed node is replaced with another backup node. Otherwise, the network ignores the node failure and recomputes alternate routes to the base station for the other sensor connected through the failed sensor.

Let us consider the 12-node wireless sensor network in Fig. 3 to better understand this policy. Fig. 3(a) depicts the shortest-path from Node 8 to base-station being $N_8->N_6->N_5->BS$. Let $E_1^8$ be the total energy-expended on this shortest-path, where energy is calculated as the distance square between the source node and the destination node. If we consider all the routes in the network, let $E_{NET}$ be the total energy-expended by the network. In Fig. 3(b), after the failure of Node 5 the path from Node 8 to the base station changes to $N_8->N_7->N_9->BS$. Thus the new path expends an energy of $E_2^8$, where $E_2^8 \geq E_1^8$. Total energy-expended by the network (on all routes) after Node 5's failure is given by, $E'_{NET} = E_{NET} + \sum_{i=1}^{N-1}(E_2^i - E_1^i)$. The average energy-expended per node before Node 5's failure be $E_{Node} = \frac{E_{NET}}{N}$, and the average energy-expended per node after Node 5's failure be $E'_{Node} = \frac{E'_{NET}}{N-1}$, where $N$ is the number of nodes. We clearly observe that the average energy-expended per node increases after a node failure, $E'_{Node} > E_{Node}$. $EI$ the total energy increase per node is given by, $EI = E'_{Node} - E_{Node}$.

### C. Local Reduction of Sensing Coverage

In *local reduction of sensing coverage* policy, the replacement decision is based on the amount of non-overlapping area of the failed node. In a randomly deployed network, there are nodes that overlap with neighboring nodes. When a node fails, the non-overlapping sensing coverage area is effectively lost.

Let us consider the example in Fig. 4 to better understand this policy. We calculate the node weight ($LR$) as follows: In Fig. 4(a) there are four nodes considered with fixed sensing range. The shaded area is the sensing area and the white area is the overlap of the sensing area. In Fig. 4(b), we depict the residual coverage area after the failure of a node. The black shaded area is the loss of non-overlapping sensing coverage. This policy is similar to the cumulative reduction of sensing coverage policy, except that the parameter is a local to the failed node.

### D. Hybrid

We also propose a *Hybrid* policy wherein, the replacement decision is based on the all the above policies. The weight of a failed node is calculated by assigning different weights to the policies. $W = \alpha CR + \beta EI + \gamma LR$, where the weight of the cumulative reduction of sensing coverage is $\alpha$, the weight of the energy increase per node of the network is $\beta$, and the weight of the local reduction of sensing coverage a node is $\gamma = 1-(\alpha+\beta)$. Note that $CR$, $EI$, and $LR$ are first normalized to the same range (0-10). If $W \geq 5$, we replace the failed node.

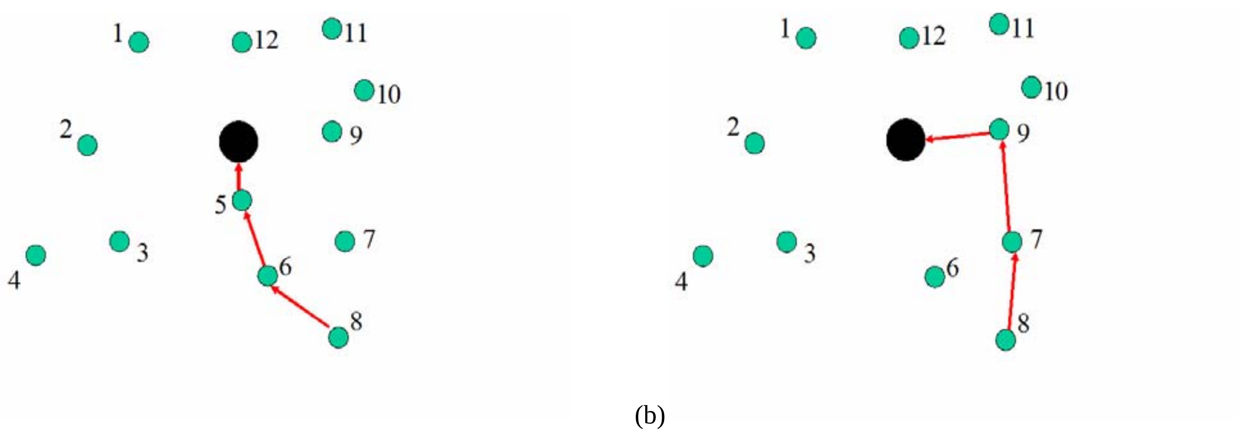
## IV. SIMULATION RESULTS

In order to evaluate the effectiveness of the proposed node-replacement policies we develop a discrete-event simulator. All the performance results are obtained using a Matlab-based simulator.

### A. Simulation Model

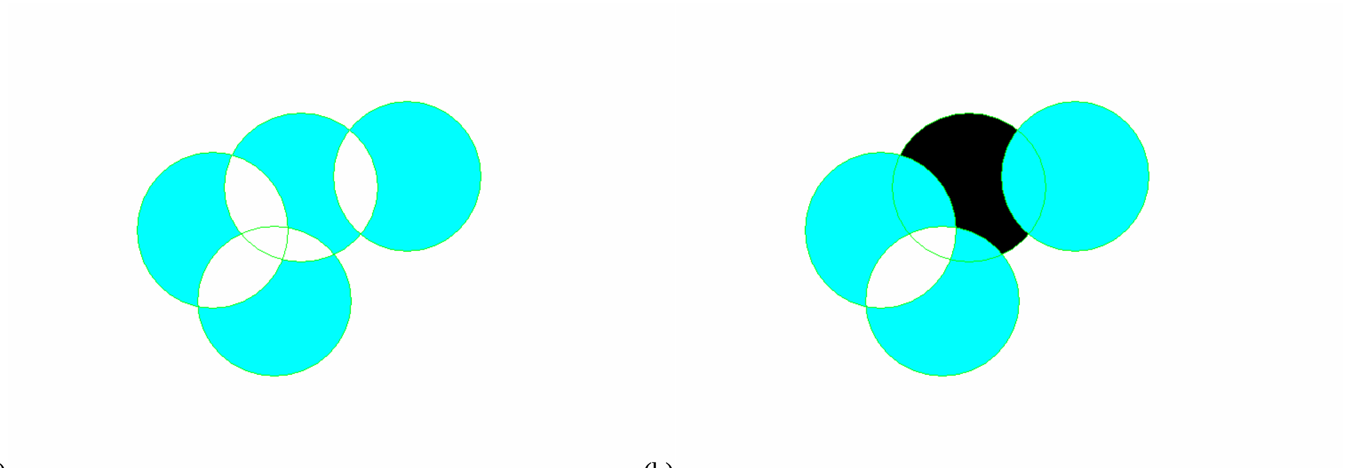
The following are the important parameters of our simulation model:

- Sensing site = 300 m x 300 m.
- $N$: number of sensor nodes randomly deployed, $N$ ranges from 100 to 180.
- $M$: number of replacement nodes, $M = 10$.
- Base station is placed at the center of the sensing site.
- Sensing range = 20 m.
- Transmission range = 50 m.
- Transmission energy, $E = d^2$ J, where $d$ is the distance between the end points.
- Sensor node energy = 30 KJ.
- $C_i^N$: initial sensing coverage of a network with $N$ nodes using random deployment.
- $C_t^N$: sensing coverage-threshold of a network with $N$ nodes.
- $C^N$: current sensing coverage of a network with $N$ nodes.



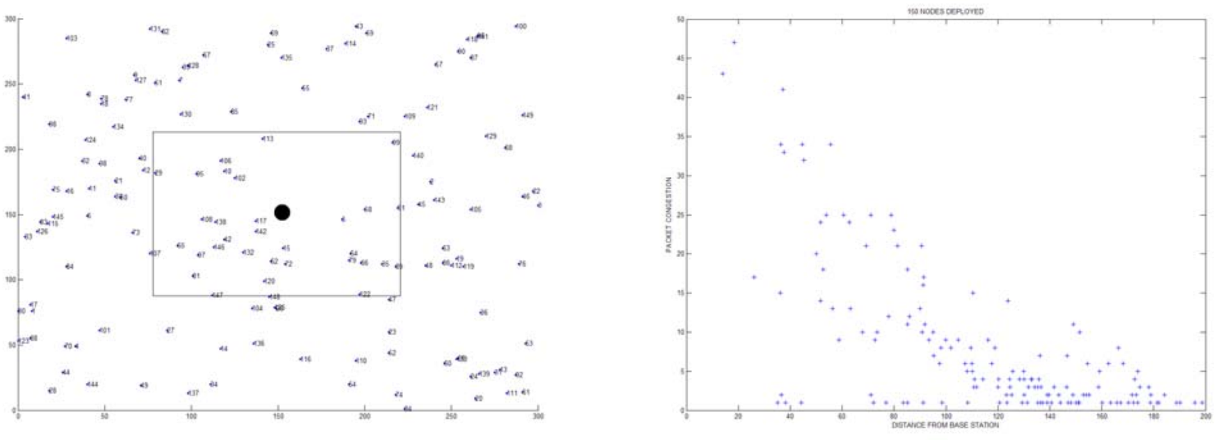
(a) (b)

Fig. 3. Routing path (a) before ($E_1^8 = N_8 - > N_6 - > N_5 - > BS$) and (b) after ($E_2^8 = N_8 - > N_7 - > N_9 - > BS$) failure of Node 5.



(a) (b)

Fig. 4. Sensing coverage overlapping and non-overlapping regions a) before and (b) after node failure.



(a) (b)

Fig. 5. a) sample 150-node randomly deployed network topology. (b) Number of flows through each node (flow degree) versus node's distance from base station.

The network is considered to be dead (due to application failure), when sensing coverage is below $C_t^N$. We also assume that a distress signal (SOS) is transmitted by every node before (planned) failure such that, there is sufficient time to execute the replacement algorithm and if needed replace the failing node by a backup node with minimal communication disruptions. We have observed that the initial coverage with a random deployment of 100 nodes gives us a sensing coverage of $C_i^{100} = 79\%$. We set our minimum coverage-threshold, $C_t^{100} = 69\%$, that is 10% less than the initial sensing coverage. In our simulation, we use the same threshold-coverage for all network configurations. Figure 5(a) depicts a randomly deployed network with 150 nodes in a sensing site of 300 m X 300 m, with the base station positioned at the center of the sensing area. In Fig. 5(b) we have plotted the number of flows through each node (flow degree) versus the distance of the node from the base station. We observe that as the distance between a node and the base station increases, the flow degree of that node decreases.

In order to compare the performance of the different node-replacement policies, we evaluate them with respect to the *network lifetime* and *quality of coverage*.

- Network lifetime is defined as the duration of time from the initial deployment until when the sensing coverage of the network falls below the threshold-coverage $C_t^N$.
- Quality of coverage (QoC) is defined as the total are under the lifetime plot when the sensing coverage of th network, $C^N \geq C_t^N$. Larger the total area during th lifetime of the network, better the QoC.

### B. *No-Replacement Policy Results*

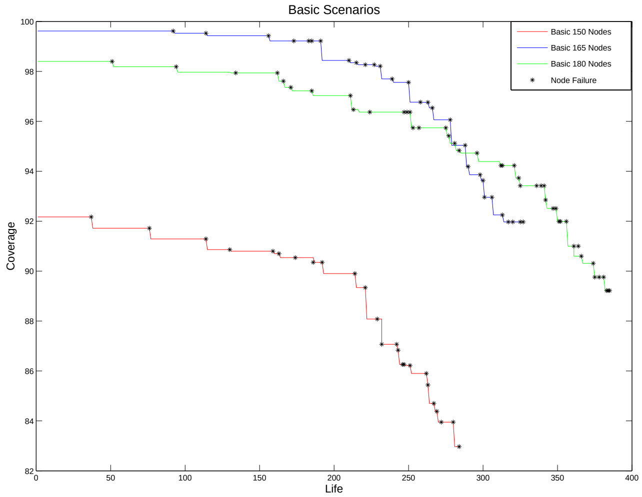


Fig. 6. Sensing coverage versus network lifetime using no-replacement policy.

In order to better understand the network behavior, we first simulate wireless sensor network with the baseline *no-replacement* policy. In Fig. 6 we plot the network lifetime versus sensing coverage with different number of initially deployed nodes. We consider three network topologies (150, 165, and 180 nodes) and observe how the sensing coverage reduces with time while keeping it above the threshold sensing coverage ($C_t^N = 69\%$). In each of the plots we indicate the actual time instant when a node in a network fails ($*$ symbol). Let us first consider the performance of the 165-node network. From the plot (blue line) we can see that on deployment the sensing coverage of the network $C_i^{165} = 98.5\%$. We observe that at network life of 380 seconds with a sensing coverage of $C^{165} = 88.5\%$, the base station is on the verge of being disconnected from the outer (boundary) sensor nodes. The failure of the next node drops the sensing coverage of the network below the threshold ($C_t^{165} = 69\%$). At this point, we consider our network to have failed. In the 165-node network, 29 nodes fail during the simulation. If we consider both the 150-node and 180-node topologies, the initial coverage on deployment are $C_i^{150} = 92\%$ and $C_i^{180} = 99.5\%$, respectively. Both the topologies experience similar performance as the 165-node topology. The 150-node topology fails at network life of 282 seconds, when the sensing coverage drops below the threshold from $C^{150} = 82.5\%$ due to the failure of 25 nodes. While, the 180-node topology fails at network life of 330 seconds, when the sensing coverage drops below the threshold from $C^{180} = 92\%$ due to the failure of 44 nodes.

### C. *Node-Replacement Policy Results*

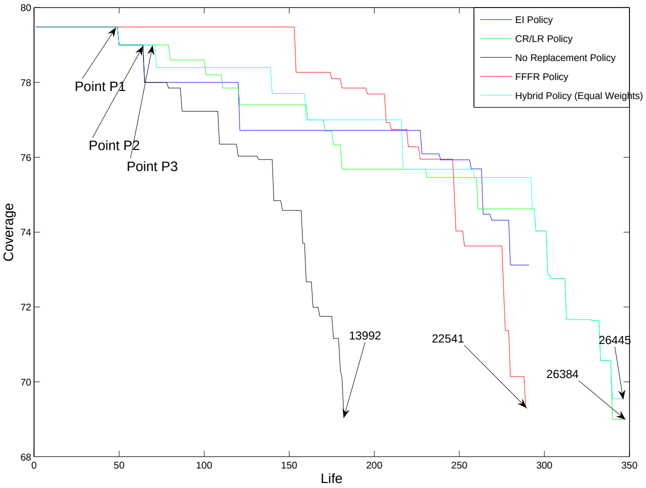


Fig. 7. Sensing coverage and quality of coverage versus network life.

We now discuss the performance results of the different node-replacement policies. In order to compare the effectiveness of our proposed policies, we compare them with a simple first-fail-first-replace (FFFR) policy. We consider a 100-node sensor network with 10 replacement nodes. The same underlying assumptions mentioned in the beginning of the section apply to this case as well. In FFFR, the 10 replacement nodes replace the first 10 sensor nodes that fail.

Figure 7 plots the network lifetime and the QoC for all the six policies while keeping the network sensing coverage above the threshold-coverage, $C_t^{100} = 69\%$. Note that for the Hybrid policy, we assign equal weights for $\alpha$, $\beta$, and $\gamma$. We observe that the FFFR policy performs better than the no-replacement policy. We also observe that the proposed policies outperform the simple FFFR policy. Specifically, we observe that the Hybrid policy improves the network lifetime by up to 90% compared to the no-replacement policy and up to 23% compared to the FFFR policy.

In Fig. 7, at Point $P1$ the first node in the network fails and a decision has to be made either to replace a failing node or to ignore and continue. The FFFR policy replaces the first 10 failed nodes in the network and hence replaces the first failed node at Point $P1$. All the proposed policies compute their respective weights and determine that the sensing coverage lost due to the first node is not above their respective threshold. Hence, none of the policies replace the failed node. At Point $P2$, we observe that the loss of sensing coverage is significant. All the policies that consider coverage reduction, namely, Hybrid, CR, and LR, replace the failed node with one of the replacement nodes. We find that the total energy increase per node is not significantly higher than before the failure of the second node and hence the EI policy chooses not to replace the failed node. At Point $P3$, the Hybrid, CR, and LR policies have to decide weather to replace or not. The reduction in sensing coverage is high enough to push the weight of the CR and LR policies above their respective threshold values, leading to replacement of the failed node. The Hybrid policy on the other hand is also dependent on the energy increase per node in addition to CR and LR policies. Also the energy increase per node is lower than the threshold leading to no-replacement of the failed node. In this randomly deployed 100-node network, we observe that the performance of both the CR policy and the LR policy is identical. This may not necessarily be true for other randomly generated network instances. We have also indicated the QoC value at the end of each plot. The QoC of the sensing coverage-based policies seem to be the highest as expected. We can clearly conclude that the Hybrid policy not only provides the best network lifetime but also provides the best quality of coverage during the operation of the network.

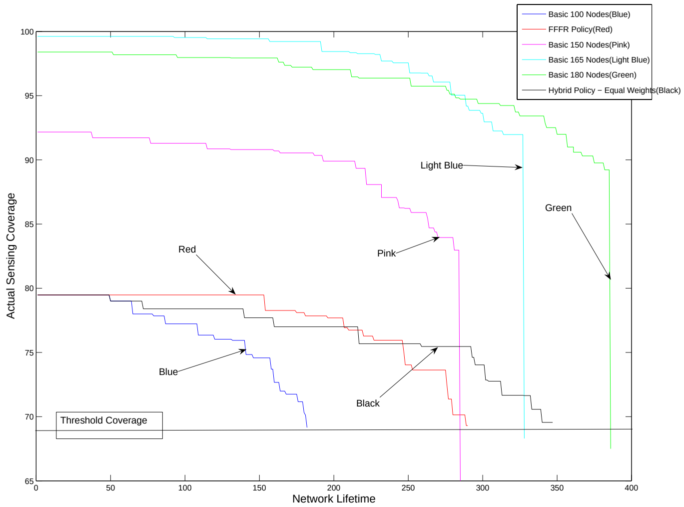


Fig. 8. Sensing coverage versus network life.

In order to emphasize the importance of implementing node-replacement policies, we compare the performance of the Hybrid policy (best policy) with different randomly generated static network topologies. If a network does not support node-replacement policies, a simple approach to improve the network lifetime while keeping the sensing coverage above a minimum threshold is to have higher number of static nodes at network deployment. Therefore, we generate four randomly generated networks with 100, 150, 165, and 180 static nodes. Fig. 8 plots the sensing coverage versus the network lifetime for all these scenarios (including FFFR policy). As before, we assume that $C_t^N = 69\%$ and $M = 10$. We observe that the static no-replacement network with 100, 150, 165, and 180 nodes result in a network lifetime of 180, 280, 330, and 380 seconds, respectively. By using 10 replacement nodes with a 100-node network, we increase the network lifetime to 282 seconds with FFFR policy and to 347 seconds with the Hybrid policy. By adopting the Hybrid policy with 10 replacement nodes, we can improve the network lifetime of a 100-node network to the equivalent performance of a 165-node or a 180-node static network.

## V. CONCLUSION

There are several important wireless sensor applications such as target tracking, that require a minimum threshold-coverage in order to operate effectively. In this paper, we propose several node-replacement policies to improve the network lifetime and the quality of coverage while maintaining a threshold-coverage. By utilizing a minimal number of additional replacement nodes ($< 10\%$), we shown that the proposed node-replacement policies improve the network lifetime and the quality of coverage by approximately 90% each, compared to the no-replacement policy. We have also observed that by effectively utilizing 10 replacement nodes with a 100-node network, we can achieve the equivalent performance of a 180-node static network. We have not addressed the problem of physically replacing the failed nodes in a deployed network. We conclude that node-replacement policies are beneficial, if the cost of replacing 10-nodes is lower than the cost approximately 80 static nodes.

An interesting area of future work is to divide the sensing site in to multiple sectors and to implement distributed node-replacement policies to keep the sensing coverage of each sector above the minimum threshold-coverage.

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