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A node failure and battery-aware coverage protocol for wireless sensor networks☆

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ABSTRACT

A typical wireless sensor network (WSN) is used to monitor or sense an area for events. Sensing-area coverage of a WSN is the collective sensing area of all the active nodes in the WSN. However, there might be a possibility of multiple active nodes monitoring the same area. This would result in energy wastage. Further, the sudden failure of nodes may result in *coverage gaps* within the sensing area. We propose *Optimized Discharge-Curve-based Coverage Protocol* (ODCP) to handle these problems. ODCP determines optimal sleep schedules for redundant nodes using their neighboring active nodes' battery discharge rate, failure probability, and coverage overlap information. ODCP is simulated extensively using various scenarios of WSNs. The simulation results show that ODCP provides energy-efficient coverage as compared to other existing coverage protocols.

1. Introduction

A typical Wireless Sensor Network (WSN) [1] is an ad-hoc network composed of small sensor nodes that cooperatively monitor or cover a region. Each node in the WSN has a sensing range (R_s) and a communication range (R_c). Sensing area coverage of a sensor node is the region within its sensing range [1]. Further, radio coverage of a sensor node is the area within its communication range [1]. *Total sensing area coverage* [1] is the collective sensing area coverage of all the ACTIVE (actively monitoring) sensor nodes in the WSN. A sufficient number of nodes are required to monitor a region entirely. However, some sensor nodes may have overlapping sensing areas (coverage redundancy), if node deployment is random. Energy is wasted due to this coverage redundancy. Redundant sensor nodes can switch to sleep state, if the sensing coverage does not reduce significantly. We define *optimal coverage* as the maximum possible total sensing area coverage with lowest possible coverage redundancy. The focus of our work is to ensure optimal coverage.

Existing coverage optimization techniques or algorithms use clustering [2–6] or non-clustering approaches [7–12]. Examples of clustering techniques are – Energy and Coverage-aware Distributed Clustering Protocol (ECDC) [2], Area of Interest (AOI) [3], Coverage and Energy Strategy for wireless Sensor networks (CESS) [4], Coverage, Connectivity and Communication protocol (C3) [5] and Coverage-Aware Clustering Protocol (CACP) [6]. Examples of non-clustering techniques are– Distributed Coverage Calculation Algorithm (DCCA), Probing Environment and Adaptive Sleeping (PEAS) [10], Probing Environment and Collaborating Adaptive Sleeping (PECAS) [11], Random Backoff Sleep Protocol (RBSP) [8] and Discharge Curve Backoff Sleep

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Protocol (DCBSP) [9]. The inactive (SLEEPing) nodes in these techniques have sleep schedules that are not synchronized with the energy depletion of the neighboring ACTIVE nodes. Thus, the SLEEPing nodes would waste energy in unnecessary wake-ups.

Sleep schedules in RBSP are based on the residual energy of neighboring ACTIVE nodes. In the case of DCBSP, it is based on actual battery discharge curve. However, in DCBSP, failure probability and coverage redundancy of ACTIVE nodes have not been addressed. The cause for node failure could be physical damage during deployment, hardware failure due to malfunction, or environmental conditions. To address these challenges, we propose a new protocol, *Optimized Discharge-Curve-based Coverage Protocol* (ODCP). ODCP computes sleep schedules, for *optimized coverage*, using neighboring ACTIVE node's *battery discharge curve, node failure probability* [13], and *coverage redundancy*. Our experimental evaluations show that ODCP leads to increased sensing area coverage and network lifetime, as compared to other protocols.

The rest of the paper is organized as follows: Section 2 reviews some of the optimal-coverage algorithms used in WSNs. Section 3 highlights our contributions and assumptions. Section 4 presents the first phase of ODCP, that is, node wake-up time computation. Section 5 presents the second phase of ODCP, that is, coverage redundancy computation. Section 6 discusses simulation results and energy overhead analysis. Section 7 presents concluding remarks and future work.

2. Related work

In this section, we discuss some of the optimal-coverage algorithms for wireless sensor networks. We broadly classify these coverage algorithms into *clustering* algorithms and *non-clustering* algorithms. First, we discuss clustering algorithms for optimal coverage. Misra et al. have proposed *Area of Interest* (AOI) [3] algorithm. This algorithm divides the WSN into node clusters. Cluster heads divide each cluster into disjoint subsets of nodes while maximizing the coverage of each subset. Multiple subsets within a cluster may monitor the same area of interest. A cluster head defines the ACTIVE state duration for each of its subsets. After the timeout, a new subset in the cluster becomes ACTIVE. In this technique, since node subsets are used to monitor an *Area of Interest*, some areas within a cluster may remain uncovered. Xin et al. have presented Energy and Coverage-aware Distributed Clustering Protocol (ECDC) [2]. ECDC schedules sensor nodes to work as a cluster head or cluster member (normal node). ECDC is based on LEACH [14] protocol with additional checks on a node's area or point coverage, and residual energy. In ECDC, the sensor nodes that are closer to the cluster head suffer from *cascading effect* [15]. Due to this, batteries of the nodes closest to the cluster head drain faster as these nodes are used on multiple paths, for data forwarding.

Le et al. have proposed Coverage and Energy Strategy for Wireless Sensor Networks (CESS) [4]. In CESS, each ACTIVE node maintains network connectivity and reduces coverage voids by performing coverage redundancy calculations based on *perimeter, center* and *distance* tests. However, these calculations may not eliminate coverage redundancy, which would lead to energy wastage. In CESS, the batteries of some of the ACTIVE nodes may drain quickly, if they are used for coverage as well as connectivity. Akhlaq et al. have proposed Coverage, Connectivity and Communication (C3) [5] protocol. C3 uses *Received Signal Strength Indicator* (RSSI) [16] to divide the network into *virtual rings*. Each virtual ring consists of clusters, with cluster heads. *Triangular tessellation* is used to identify coverage redundant nodes by dings, which are virtual rings inside a cluster. However, in the case of random deployment, nodes may not be present at the vertices of triangular tessellation. This could result in coverage voids (gaps). Further, energy may be wasted due to hierarchical multi-hop transmissions (Base Station-Ring-Ding).

Tezcan et al. have proposed Distributed Coverage Calculation Algorithm (DCCA) [17], which uses co-ordinate information to determine redundant sensor nodes. DCCA computes coverage redundancy using a logic similar to CESS [4]. However, it suffers from *cascading effect*, as described in the case of ECDC [2]. Qu and Georgakopoulo have developed Distributed Area Coverage Algorithm (DACA) [7] that adjusts each node's sensing range for maintaining full area coverage. DACA works in two stages. In stage one, if coverage voids are identified using a *Voronoi diagram*, then, in the second stage, the sensing radii of some nodes are adjusted to achieve full area coverage. Wang et al. have presented Coverage-Aware Clustering Protocol (CACP) [6] that selects cluster heads and ACTIVE nodes using a *coverage-aware cost metric*. The *coverage-aware cost metric* for a node is based on its relative residual energy level and coverage area overlap. Next, we discuss non-clustering algorithms for optimal coverage.

Ye et al. have presented Probing Environment and Adaptive Sleeping (PEAS) [10] that uses a probing mechanism to turn on a minimum number of ACTIVE nodes. In PEAS, ACTIVE nodes remain in the same state till energy depletion. PEAS is useful for a network where the node density is high. If the node density is not high enough then some of the probing nodes may enter ACTIVE state which would lead to a reduction in the network and node lifetime. PEAS does not provide a guarantee for sensing coverage. Gui et al. have proposed Probing Environment and Collaborating Adaptive Sleeping (PECAS) [11], which is an extension to PEAS [10]. In PECAS, ACTIVE nodes do not operate continuously till energy depletion. However, frequent node state switching could lead to energy wastage. More et al. have proposed Random Backoff Sleep Protocol (RBSP) [8], a location-unaware protocol, that determines a *sleeping window* from an ACTIVE node's residual energy level. A limitation of RBSP is the randomness in the *Backoff Sleep Time* derived from this *sleeping window*. Further, at lower residual energy levels the sleeping window is small that would cause frequent wake-ups of neighboring SLEEPing nodes. This results in energy wastage. More et al. have proposed Discharge Curve Backoff Sleep Protocol (DCBSP) [9] that uses a generic battery discharge curve to determine the *Backoff Sleep Time*. However, ACTIVE-node failure probability and coverage redundancy are not considered in DCBSP. Aliyu et al. have proposed Edge Based Centroid algorithm (EBC) [18] that enhances area