Coverage Preservation in Energy Harvesting Wireless Sensor Networks for Rare Events

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***Abstract*—Wireless sensor networks for rarely occurring geospatial events must minimally maintain constant sensing coverage to ensure detection wherever and whenever such events occur. This paper proposes an *Equitable Sleep Coverage Algorithm for Rare Geospatial Occurrences (ESCARGO)* for timely event notification where the network must also maintain connectivity at all times regardless of the significant energy cost of doing so. This non time-synchronized, fully distributed duty-cycling algorithm is shown to significantly extend the operational lifetime of battery powered rare event sensing networks with an optimised, low node density, non-random deployment scheme without compromising detection probability or notification delay. The algorithm is further shown to facilitate potentially indefinite coverage maintenance in sensor networks powered by small form factor solar panels without relying on charging efficiencies beyond the capabilities of existing technology.**

Keywords – Rare event detection, coverage, energy harvesting, wireless sensor networks.

I. Introduction

Time sensitive geospatial occurrences, rare events that are both ephemeral and transitory, pose a challenge to wireless sensor networks (WSNs) deployed for their detection. Maximising detection probability (likelihood the event is detected) and minimising detection delay (time taken for notification to reach a network sink) implies sufficient nodes must be active at all times to both maintain initial sensing coverage and provide a route to the network sink delayed only by transmission overhead. Energy saving pauses during transmission such as those implemented in MAC protocols featuring receiver initiated transceiver de-activation [1] or demand wake-up [2] could be regarded as having too great an impact on detection delay. In this study, detection delay is minimised by having an always on, always connected communication route to the network sink at the cost of significant energy consumption through idle listening.

Establishing and maintaining sensing coverage in WSNs for rare events can be regarded as ensuring every point in the sensing area is covered by at least one sensor node at all times whilst maintaining energy efficiency [3]. WSNs with a sufficiently dense overpopulation of sensing nodes can self-organise such that a given node is in a position to power down if a subset of its neighbours are willing to take temporary responsibility for its sensing area. In battery powered WSNs, this duty-cycling extends the operational lifetime of a subset of deployed nodes and in doing so can both extend the period during which the network maintains its initial coverage and the period during which there is at least some coverage [4].

When energy harvesting replaces battery power, duty-cycled nodes not only preserve their stored energy but also have the opportunity to replenish it more rapidly than when active. The design of solar energy harvesting systems for WSNs is non-trivial [5], yet if the energy harvested and stored is sufficient, networks have the opportunity to maintain initial sensing coverage for extended periods with the potential for indefinite operation. For solar energy harvesting, the physical dimensions, output voltage, maximum current and efficiency of installed solar panels determine the harvestable energy for a given incident radiation. Once harvested, energy is lost through inefficiencies in storage componentry yet recent low-power management systems demonstrate charging efficiencies in excess of 90% [6].

This paper proposes an Equitable Sleep Coverage Algorithm for Rare Geospatial Occurrences (ESCARGO) that addresses both coverage and connectivity requirements of rare event sensing. The efficacy of the proposed algorithm is assessed in optimally distributed networks of identical sensing nodes, evaluating its deployment in battery powered and energy harvesting networks. Further analysis is done to determine charging efficiency required to maintain rare event sensing coverage in connected networks powered by energy harvested using photovoltaic technology. Small form-factor solar cells are chosen to both minimise costs and match the dimensions of commercially available sensing nodes. Identical IEEE 802.15.4 compliant motes are powered by a custom energy harvesting model configured using data gained from experimental evaluation of the motes under typical usage scenarios, from vendor data sheets on the solar panels and average annual solar radiation data for the selected location. Areas for further investigation are outlined and related work is surveyed.

II. Related Work

A distributed algorithm ensuring coverage in energy harvesting WSNs has been proposed by Yang and Chin [7]. Their Maximum Energy Protection (MEP) protocol addresses the same Distributed Maximum Lifetime Coverage with Energy Harvesting (DMLC-EH) problem as the algorithm presented here. MEP is aimed at continuous sensing of discrete targets at known locations, this work is focused on event sensing where the location and timing of the event is not known in advance, continuous area sensing being required. By Yang and Chin's definition, this work is a *self-configuration* protocol, yet in the scenario targeted here the overhead of *global-reshuffle* algorithms posited in [7] is marginalised as the cost of sending co-ordination messages is minimal compared to the energy lost through the constant idle listening required for instantaneous propagation of event notification messages.

Maintenance of a less stringent Quality of Service (QoS) metric than presented here (preserving a minimum number of targets that can be covered by the network over a 24-hour period) has been achieved by adjusting sensing ranges to reduce energy consumption during periods of negligible or no energy harvesting [8]. This approach, whilst ensuring the network exhibits acceptable but degraded coverage, does not address the peculiar requirements of time critical rare event sensing where initial coverage and instantaneous connectivity must be maintained at all times.

The Role Alternating Coverage Preserving Coordinated Sleep Algorithm (RACP) [4] for battery powered WSNs specifically excludes connectivity consideration. Detectable events are assumed to occur in a finite set of known locations, with coverage of only these locations being required.

III. Coverage Preservation Algorithm

We assume a two dimensional rectangular distribution of location and sensing area aware nodes. Individual node sensing areas are assumed identical and exactly circular, and the node communication range is at least twice that of the sensing range to preserve network connectivity [9].

A. Overview

Nodes are in one of four states: *sponsored* where sensing responsibility is delegated to at least one other node, *sponsoring* where they are taking responsibility for the sensing area of one or more neighbouring nodes, *seeking* where they are actively attempting to find neighbouring nodes willing to sponsor them, and *passive* where they are un-sponsored, not seeking sponsorship, and are not sponsoring any of their neighbours. Fig. 1 shows the algorithm's state transition.

All nodes start simultaneously and enter the passive state, rapidly broadcasting periodic STATus (STAT) messages containing their position and cumulative run-time statistics. During this start-up period nodes listen for STAT messages from other nodes and determine who their sensing neighbours are. Two nodes are deemed to be sensing neighbours if they are separated by a distance less than or equal to their common sensing range.

A node is eligible to enter sponsored state if and only if it determines its sensing area is fully contained by the union set of some combination of its passive, seeking or sponsoring neighbours' sensing areas. Combinations of neighbouring nodes that could sponsor a given node are known as *sponsor groups*. Sponsor group membership is determined by geometric calculations taking into consideration the boundary of the sensing area as detailed in Section III-B. Nodes adjust their sponsor group lists each time a STAT from a previously unknown sensing neighbour is received. Nodes that deem themselves eligible for sponsorship cycle through their sponsor groups in a round-robin fashion, seeking sponsors starting with the group after the previous sponsor group. For each sponsor group selected, a Sponsor REQuest (SREQ) message is sent to each node in the group. Nodes in receipt of an SREQ add the requesting node to their sponsored list and return a Sponsorship ACKnowledgement (SACK) message. Once a node has agreed to be a sponsor it will no longer attempt to gain its own sponsors until it is notified by the nodes it is sponsoring that they no longer require assistance.

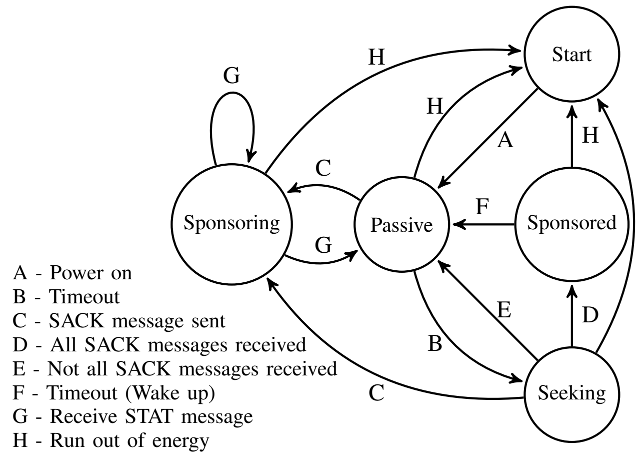


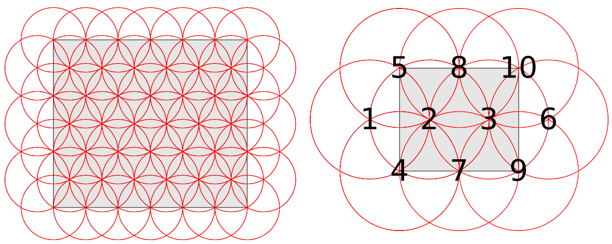
Fig. 1: ESCARGO State Transitions

When a seeking node wishing to be sponsored has received a SACK from each of the nodes it sent an SREQ to, it enters sponsored state for a predetermined period. In sponsored state, nodes enter a low energy mode where all sensors and the radio transceiver are powered down. If fewer SACKs are received than SREQs sent, the requesting node reverts to passive state and broadcasts a burst of STATs. Neighbouring nodes that had already agreed to be sponsors remove the requesting node from their sponsored lists on receipt of any of these STATs. On wake-up from a period of sponsorship, nodes similarly broadcast a small number of STATs and their sponsoring nodes adjust their sponsored lists accordingly.

SREQs contain the stored charge of the requesting node. Potential sponsor nodes will respond to the SREQ with a SACK if and only if the sponsoring node has more stored charge than the requester. Whilst waiting for SACKs, a seeking node that receives an SREQ from a node with less stored charge than itself will cease waiting for any remaining inbound SACKs, send a SACK of its own to the requesting node and enter sponsoring state.

B. Sleep Eligibility

When a node goes to sleep it takes no part in the sensing activities or communication links of the WSN until it wakes up again. To maintain sensing coverage in the WSN, the entire



(a) 52 nodes (b) 10 nodes

Fig. 2: Placement of nodes relative to shaded sensing area

sensing area a sleeping node was responsible for must be covered by one or more neighbouring nodes. Only when a node is confident its sensing area is covered by a set of awake neighbours does it become sleep eligible.

Wang *et al.* [9] performed geometric analysis of the relationship between connectivity and coverage in networks made up of nodes with uniform sensing and transmission ranges, they define the k-coverage eligibility rule. ESCARGO requires nodes exhibit at least 1-coverage eligibility.

IV. Node Placement

This paper focuses on an ideal, planned placement of nodes based on a repeating and overlapping pattern of three nodes. The three nodes' sensing area perimeters, being of equal length, intersect the vertices of an equilateral triangle of side $2 \times sqrt((2r)^2 - r^2)$ where r is the node sensing range, and intersect with each other at the midpoints of the triangle's sides. When a third node is added at the intersection of the three existing nodes sensing ranges, the new node is 1-coverage eligible with a single sponsor group made up of the original three nodes. Repeating this pattern using existing nodes as members of new groups leads to a uniform coverage where each node is at least 2-coverage eligible, having no less than two sponsor groups. Placements of 52 and 10 nodes are shown in Fig. 2a and Fig. 2b.

V. Sponsor Group Membership

Fig. 2b shows a placement of ten nodes over a small sensing area; only nodes 2 and 3 are within bounds, the remaining nodes being located outside the sensing area or on the boundary. In this configuration, all nodes have at least two sponsor groups as those on or beyond the sensing area boundary do not need their entire sensing area sponsored, just the subsection coincident with the network sensing area. Node 4 can be sponsored either by Node 2 alone, or by a combination of nodes 1 and 7.

VI. Energy Model

Energy available to sensing nodes is modelled as a linear charge store. As the nodes consume energy, charge is removed from the store; when harvesting energy during daylight hours, charge is added up to a maximum capacity. In practice, dual capacitor storage systems are required to facilitate simultaneous charge and discharge of the storage system [10]. When the charge held by a node is entirely depleted it shuts down and the energy model waits until the store achieves 10% of initial charge before waking the node up to resume its sensing responsibilities. The model does not consider practical storage issues such as supercapacitor leakage and self-discharge, or cycle exhaustion in rechargeable batteries. When nodes change state a message is sent to the energy model informing it of the current drawn by the previous state and how long the node spent in that state. State specific current draw figures for the simulation are: Sleep $1\mu A$[1], Idle Listen $18.4mA$, Receive $19.2mA$, Transmit $19.9mA$.

Historic average incident radiation data for 41° 19' 24" S, 174° 46' 12" E (Wellington, New Zealand) were obtained from public records and a solar panel selected from commonly available components with a form factor slightly larger than the 81.90mm $\times$ 32.50mm Advanticsys CM5000 motes used in the study. Charge available for storage in a given time period s seconds starting at time T is:

$$Q = \sum_{t=T}^{T+s} MIN \left\{ I_p, \left(\frac{\lambda_t \times l_p \times w_p \times \eta_p}{V_p} \right) \right\} \times \eta_c \qquad (1)$$

where λ_t is the incident radiation at time t, η_p and η_c are the efficiencies of the solar panel and charging circuit respectively, I_p and V_p are peak current and peak voltage of the solar panel of length l_p and width w_p respectively.

VII. Simulation Parameters

ESCARGO requires transmission range to be at least twice sensing range; radio range on the simulated Advanticsys CM5000 motes is restricted to 94.8m, sensing range is set to 40m. An initial charge of 4800mAh is given to each node; equivalent to two Duracell NiMH AA rechargeable batteries. All simulations start at 00:00 on January 1. Note that the solar radiation data are for the southern hemisphere, as such the simulations start in the height of summer. Specifications for the SZGD6161 soar panel used are: Efficiency 16.5%, Peak Voltage 2.2V, Peak Current $92mA$, Dim. $61mm \times 61mm$.

VIII. Results

In the ESCARGO simulation, changes in node state that could lead to an alteration in coverage trigger a recalculation via a scan line algorithm over the network sensing area. If a point within the scan is within sensing range of one or more nodes not in sponsored state, it is deemed to be covered. Nodes entering sponsored state do not impact coverage. Two metrics are of interest: coverage and stored charge.

A. Algorithm Efficacy

Using the 10 node planned placement (Fig. 2b) a full calendar year of operation was studied for four operational configurations: (1) Battery only - no synchronised sleep scheduling, no energy harvesting; (2) Battery power with ESCARGO; (3) Energy harvesting replaces battery but ESCARGO is disabled; and (4) ESCARGO with energy harvesting.

[1] From manufacturer's datasheet, all other values by direct measurement

On battery power alone, stored charge depletes entirely in around eleven days at which point all coverage is lost. Adding ESCARGO to battery power extends network lifetime significantly. However, original coverage is not maintained for the entire period. As nodes' stored charge become exhausted, they die and coverage is compromised. Original coverage is maintained until around day 17 when the first nodes die. Coverage is restored briefly as sponsored nodes return to passive state then tails off quickly as further nodes die.

TABLE I: Coverage Maintenance

Configuration	Days Maintained
Battery	11
ESCARGO & Battery	17
Energy Harvesting	152
ESCARGO & Energy Harvesting	Indefinite

During the first month of operation (the height of summer) adding ESCARGO to energy harvesting maintains a higher mean stored charge, but the practical benefits are negligible as more energy is available for harvesting than can be stored and used. During the winter months, when less energy is available, a harvesting only solution exhibits a sharp degradation in average stored charge as more energy is used each day than can be replenished. Combining ESCARGO with energy harvesting results in significantly improved mean stored charge.

When ESCARGO and energy harvesting are combined, no nodes die, a high proportion of nodes are asleep at any time and initial sensing coverage is maintained throughout the entire year. The number of days initial coverage is maintained for each configuration are shown in Table I.

B. Required Charging Efficiency

Khosropour *et al.* [6] propose a low power charging circuit with 90% efficiency and reference other similar systems with charging efficiencies of 67%, 70%, and 86%. Running simulations based on the planned 10-node network (Fig. 2b) and varying the charging efficiency η_c in Eqn (1) show a charging efficiency of 55% is sufficient to maintain mean stored charge close to 50% of original. Fig. 3 shows mean stored charge over a full year for charging efficiencies from 50% to 70%.

For planned placements, ESCARGO assures equitable discharge and re-charge for all nodes in the WSN, hence any charging efficiency that realises an non-zero average stored charge across all nodes will ensure 100% of original coverage is maintained. Fig. 3 shows a charging efficiency of 50% is insufficient to maintain sensing coverage throughout the year. The point were where coverage becomes compromised coincides with the point in Fig. 3 where average stored charge drops to zero.

IX. Conclusion and Future Work

A study of the proposed algorithm, ESCARGO, in a non-time-synchronized rare event monitoring WSN powered by energy harvested from small form-factor solar panels, indicates initial sensing coverage in low density planned node placements can be maintained indefinitely with charging efficiencies within the capability of existing power management systems. ESCARGO is also shown capable of extending the lifetime of the same WSN by more than 50% when nodes are battery-powered. ESCARGO is known to be effective in sufficiently dense random distributions; ongoing work includes an assessment of the node density required to provide each node with at least one sponsor group. Random distributions give rise to situations where a minority of nodes have a large number of sponsor groups, an analysis of how this impacts the nodes involved, both sponsors and sponsorship beneficiaries, will be undertaken.

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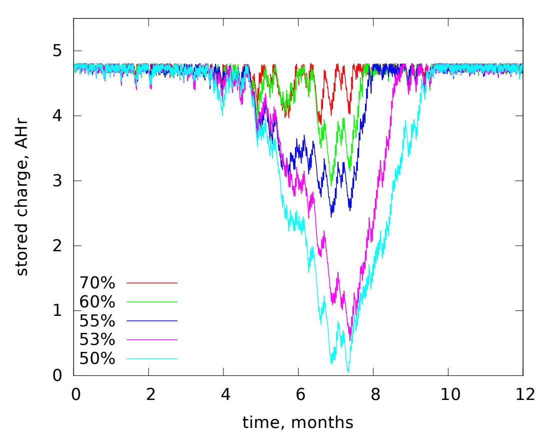

Fig. 3: Mean stored charge over time by charging efficiency