

Opportunistic Geographic Forwarding in Wireless Sensor Networks for Critical Rare Events

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Abstract—Wireless sensor networks for rarely occurring critical events must maintain sensing coverage and low latency network connectivity to ensure event detection and subsequent rapid propagation of notification messages. Existing geographic forwarding algorithms have proved successful in providing energy efficient network connectivity for arbitrary topologies where sensing coverage is not guaranteed. This paper proposes a location aware algorithm for *Swift Opportunistic Forwarding of Infrequent Events* (SOFIE) that takes advantage of geometric properties common to sensing networks providing perfect area coverage. The algorithm is shown to deliver more rapid message propagation than two established, general purpose geographic forwarding algorithm in optimally and randomly placed networks of varied sensing node density. Further, the algorithm is shown to maintain this advantage when deployed in a coverage preserving, duty-cycled sensing network where nodes may power down whilst the network is actively forwarding event notification messages.

Keywords – *Rare event detection, sensing coverage, opportunistic forwarding, wireless sensor networks.*

I. INTRODUCTION

Wireless sensor networks (WSNs) have been classified by their data delivery profile as being *continuous*, *event-driven*, *observer-initiated* (query-based), or a *hybrid*, the latter two falling outside the scope of this paper. In continuous sensing scenarios, data samples are taken periodically and between samples the transceiver or the entire node can be powered down. Increasing the gap between samples leads to an increase in network life. If multi-hop communication is required, nodes can synchronise their activity to ensure network connectivity and employ algorithms that minimise overuse of individual routing nodes. Similar techniques can be adopted for networks where data collection is initiated by base station requests.

Event sensing, with the assumption that events occur randomly, introduces additional complexity as a node that is not energised cannot sense the event and a node with a powered down transceiver cannot take part in forwarding notification messages. Critical events that are both ephemeral and transitory pose significant challenges to 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) [3] imply sufficient nodes need to be active at all times to both maintain sensing coverage and provide a low latency route to the network sink delayed only by transmission overhead.

This paper proposes an algorithm for Swift Opportunistic Forwarding of Infrequent Events (SOFIE) in event sensing WSNs exhibiting *perfect area coverage*, defined as a network where every point in the sensing field is within sensing range of at least one energised node. SOFIE takes advantage of the geometric properties of such networks and is shown to deliver a lower detection delay than two general purpose location aware forwarding algorithms. Minimisation of detection delay is prioritised over *all other considerations*, and detection is assumed to be guaranteed by the perfectly covered network.

II. RELATED WORK

For critical event sensing, routing protocols where the first post-event packet to reach the sink does not contain the sensed data can be regarded as sub-optimal, having too great an impact on detection delay.

Routing protocols in wireless networks can be classified as either *proactive* (constantly maintain route tables), *reactive* (determine routes only when needed) or a hybrid. In networks where network topology is constantly changing, either through node mobility or duty cycling, opportunistic, broadcast forwarding algorithms have been shown to provide better throughput than unicast routing protocols [1].

Position based routing uses an understanding of the location of network elements to inform routing decisions. Geographic (location-aware) forwarding has proved efficient when information on the network topology is unavailable, but nodes are aware of their own location and those of some or all of the other nodes in the network [5]. In the simplest case, the one addressed by SOFIE, nodes are aware only of their own location and those of the network sinks.

Existing opportunistic forwarding algorithms have a number of common themes: collision avoidance, energy conservation, and hole avoidance; yet no previous work has focused on the unique situation sensing critical rare events introduces, namely the need to minimize detection delay *at all costs*. Collision avoidance algorithms that do not de-activate forwarding nodes promise the least impact on latency; as such, CBF [4] and BOSS [7] are selected for comparison with SOFIE.

III. SWIFT OPPORTUNISTIC FORWARDING

We assume a two dimensional distribution of location aware wireless sensor nodes, each of which knows the location of all

network sinks, though for simplicity, in this paper we assume a single sink. Sufficient nodes are placed within the sensing field to ensure perfect area coverage. Node sensing ranges (R_s) and communication ranges (R_c) are assumed identical and exactly circular, with R_c being at least $2R_s$ to preserve network connectivity [8]. All nodes within sensing range of an event are assumed to simultaneously detect it.

A. General Approach

When a node detects an event, a notification is broadcast containing the following information where the size of all fields are situational:

- Sender ID (globally unique)
- Notification ID (unique within the sender)
- Sender Coordinates
- Forwarder Coordinates (= sender coordinates)
- Payload Length
- Payload (if any)

Nodes within R_c that successfully receive the message replace the forwarder coordinates with their own and immediately re-broadcast if they are located within a forwarding area represented by the intersection of a Reuleaux Triangle of radius R_c oriented towards the sink with a vertex at the location of the previous forwarding node, and a disk of radius $2R_s$ located at the *ideal forwarding position*, the point on a direct line from the previous forwarding node to the sink R_c away from the forwarding node.

As re-broadcasts occur immediately, increasing the possibility of media contention that will be dealt with by the medium access control (MAC), the forwarding path for any given notification is non-deterministic rather the predicatable *greedy forwarding* [2] scheme exhibited by CBF and BOSS.

On receipt of a notification, the sink, after a short delay (T_{ack}) broadcasts an acknowledgement containing all the fields in the notification except the payload and its length, with the forwarder coordinates replaced by those of the sink. T_{ack} exists to avoid contention between outgoing acknowledgements and incoming notifications. Notifications are implicitly more important than acknowledgments, and are given higher transmission priority.

On receipt of an acknowledgement, nodes re-broadcast after replacing the previous forwarder's coordinates with their own if they are located within a forwarding region similar to the one used for notifications but oriented towards the notification sender, the coordinates of which are implicitly in the acknowledgement as a result of being in the corresponding notification. To facilitate message suppression (Section III-B) and optimised event reliability (Section III-C), SOFIE requires a node to maintain a list of the messages it has previously seen. Practical implementations would of necessity make this an appropriately sized circular buffer.

B. Message suppression & collision avoidance

Notifications and acknowledgements are suppressed (not re-broadcast) if the potential forwarder node is located outside the forwarding region for the message in question. The geometry

of the forwarding region changes with the ratio R_c/R_s . For values of R_c at or slightly above $2R_s$, forwarding areas approximate to the Reuleaux Triangle of radius R_c with a vertex at the previous forwarding node. As R_c increases for a fixed R_s , forwarding regions become an increasingly small sub section of the Reuleaux Triangle until $R_c/R_s > 4$ when the forwarding region is simply described by the intersection of the disc of radius R_c centered on the previous forwarding node and the disk of radius $2R_s$ centred on the ideal forwarding position, as shown in Fig. 1(a).

Other than the delay sinks introduce when broadcasting an acknowledgement, described in Section III-A, SOFIE does not attempt to avoid collisions, leaving that task to the MAC, e.g. non-beaconed IEEE 802.15.4. When an event occurs, multiple nodes may detect it and simultaneously attempt to broadcast a notification. If the wireless channel is idle, which it is likely to be, given the infrequent nature of rare events, all nodes detecting the event will attempt to send a packet containing their notification. These signals will almost certainly interfere with each other causing the MAC to mediate channel access by all competing nodes.

C. Event reliability

For minimally effective event detection, only one notification needs to be received by the sink, and all subsequent notifications for the same event are redundant. However, for more sophisticated analysis after the initial notification, such as event location estimation through multilateration, multiple notifications may need to be successfully delivered, though not necessarily all of them. SOFIE assumes individual nodes are unaware of which others sensed the event. For the scenario considered in this paper, an event is regarded as having been reliably delivered if at least one notification is received.

After sending a notification upon sensing an event, the notification will be re-sent if an acknowledgement is not received within a pre-defined short time frame:

$$T_{retry} = T_{ack} + \frac{D_{sink}}{R_c} \times T_{hop}$$

where D_{sink} is the distance from the sensing node to the nearest sink and T_{hop} represents an estimate of the mean time taken for a notification to travel a single hop on its route to the sink. Setting T_{hop} too low can result in notification re-sends when an acknowledgement for the original notification has already been broadcast but not yet received. To mitigate this possibility, if a re-sent notification is received by a node that has already forwarded the corresponding acknowledgement, the acknowledgement is re-broadcast and the re-sent notification is suppressed.

IV. COMPARATIVE ANALYSIS

SOFIE, CBF and BOSS are implemented in QualNet 5.2 with all nodes based on Advanticsys CM5000 IEEE 802.15.4 compliant motes configured as non-beaconing full-function devices with default carrier sense multiple access with collision avoidance (CSMA/CA) settings.

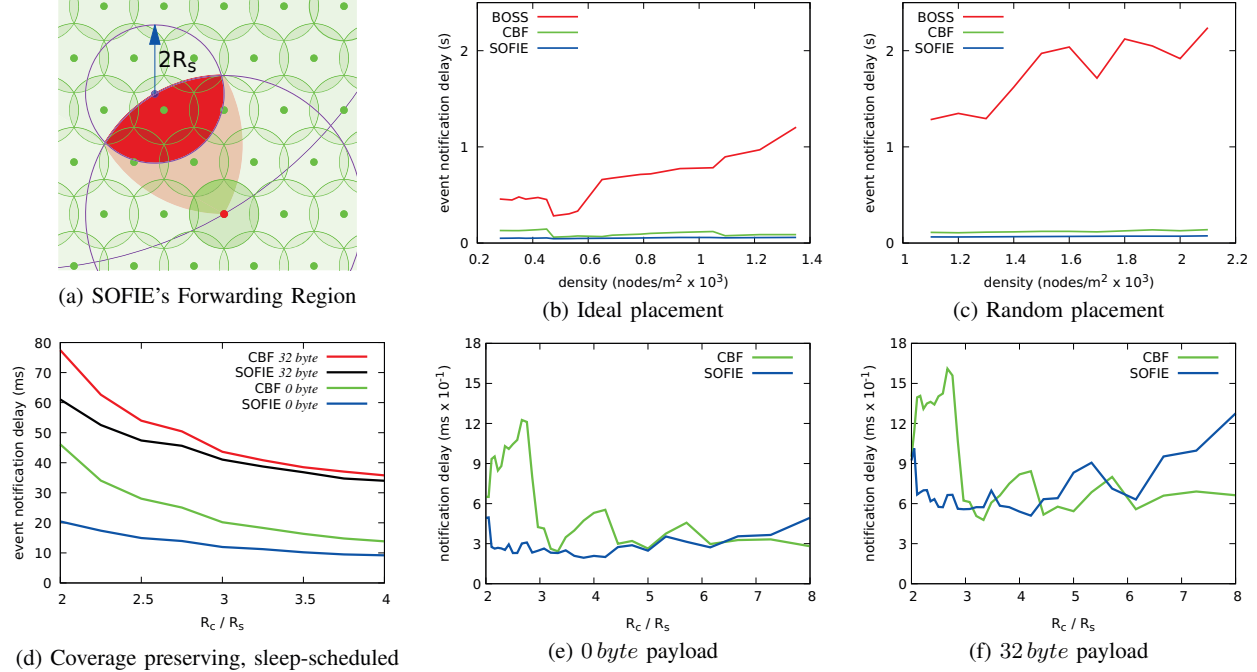


Fig. 1: Event notification delay: (b) & (c) by node density, 64 byte payloads, $R_c/R_s = 2.2$. (d) active node density of 0.00088 nodes/ m^2 by increasing R_c for fixed R_s . (e) & (f) for ideal placements with decreasing R_s for fixed R_c .

Nodes are deployed in a $400m \times 400m$ perfectly flat sensing area with a sink is placed at one corner. Coordinate fields in all messages are 32 bits, all others are 16 bits with the exception of the payload which varies by evaluation. 109 sensing events occur at pre-determined random locations throughout the sensing area at pre-determined random times over a simulated six hour period. In all cases, 100% of the events are detected by at least one node and all notifications are successfully received by the network sink.

Notification delay, the mean elapsed time for the first event notification message to reach the network sink, is the only metric of interest. Hops taken, transmission errors, energy consumed whilst transmitting and receiving, and the proportion of event notifications received at the *first attempt*, i.e. those received without requiring a re-transmission, are examined to reason about changes in notification delay.

CBF uses an area suppression scheme based on a forwarding area restricted to a Reuleaux Triangle and exposes a single tunable parameter, T_{cbf} , representing the maximum time a forwarding node waits before forwarding a received message. BOS exposes an equivalent parameter, T_{boss} .

In all evaluations, $T_{ack} = 60 ms$, $T_{hop} = 80 ms$, $T_{cbf} = T_{boss} = 45 ms$. Each simulation is repeated with 100 distinct random seeds that affect occurrence of errors in the simulated physical layer and one element of BOSS.

With $R_c/R_s = 2.2$ for fixed R_s , hexagon based planned node layouts of increasing density are generated, starting with an ideal placements where sensing area overlap is minimised. Similarly, random placements of increasing node density and

perfect area coverage are generated, their minimum density necessarily being higher than the planned layouts.

A. Delivery Ratio

CBF and BOSS do not guarantee data delivery even in a network known to be connected. SOFIE achieves perfect event notification delivery for the planned and random placements, described in Section IV. To add an equivalent guarantee of event notification to CBF and BOSS, evaluations described in Section IV-B and Section IV-C are undertaken after adding Automatic Repeat Request (ARQ) functionality to the application layer. This ARQ implementation is functionally equivalent to SOFIE's aggressive notification resend algorithm for event reliability described in Section III-C.

B. Fixed Topology

Fig. 1(b) and Fig. 1(c) show SOFIE maintains a lower event notification delay for 64 byte payloads in all circumstances. At higher node densities, and particularly in random distributions, the difference in receive errors is less significant. Energy consumed in transmit and receive states is higher for CBF and BOSS than for SOFIE. This is a side-effect of the aggressive application layer ARQ modification described in Section IV-A that results in a high incidence of re-sends by originating CBF and BOSS nodes.

Whilst BOSS successfully achieves the lowest error rates, as it was designed to do, it does so at the expense of significantly higher notification delay and, by doing so, disqualifies itself as a suitable forwarding protocol for critical events. Hereafter, we will only compare SOFIE with CBF.

C. Variable Topology

Extending the operational life of a network deployed to sense critical rare events can be achieved by (a) over populating the sensing area with more nodes than are minimally necessary for perfect coverage and (b) collaboratively duty cycling the nodes so energy utilisation is equalised whilst sensing coverage is preserved [6]. As nodes collaboratively power on and off, the network topology changes making this scenario an ideal candidate for opportunistic forwarding.

Here, an overpopulation of 240 nodes are randomly placed in the sensing area, subsets being periodically selected for activation such that perfect area coverage is maintained. Events are generated an order of magnitude less frequently than the topology changes

Evaluations undertaken in Section IV-B used a 64 byte sensing data payload. Packet size is known to affect error rates in wireless networks; in certain sensing scenarios receipt of notification message with a zero length payload may be sufficient to indicate an event has occurred. Here, payloads of 0 bytes and 32 bytes are used.

Fig. 1(d) shows notification delay for increasing R_c/R_s for payloads of 0 bytes and 32 bytes. R_c/R_s was modified by increasing R_c for fixed R_s , the effect of which was to reduce the number of hops for each notification, SOFIE maintains its notification delay advantage over CBF, the difference being most significant for the most efficient, lower values of R_c/R_s .

D. Optimum ratio of R_c to R_s

In Section IV-C, R_c was increased while keeping R_s constant. When R_s is decreased while keeping R_c constant, the ratio change is the same but the effect on CBF and SOFIE is noticeably different. In this simulation, R_s starts at exactly $\frac{1}{2}R_c$ and decreases until it is $\frac{1}{8}R_c$ for payload lengths between 0 bytes and 32 bytes. To maintain perfect area coverage, as R_s is reduced, node density increases.

Fig. 1(e) and Fig. 1(f) show that for $R_c/R_s = 2$, SOFIE achieves lower notification delays than CBF, and continues to show this advantage as R_s reduces. However, as R_c approaches $3R_s$, the advantage is lost. Regardless of the sensing payload size, SOFIE will eventually exhibit a higher notification delay than CBF especially at large R_c/R_s ratios; this occurs when $R_c \approx 6R_s$.

The distance based suppression algorithm in CBF leaves it susceptible to sharp changes in notification delay in planned placement networks as the density oscillates around values that leave the best placed next forwarding node close to the ideal position; the ideal forwarding position being one that allows CBF to select a very short suppression delay leading to minimal notification delay.

SOFIE forwards event notifications on receipt and is consequently less susceptible to changes in node density whilst maintaining a broadly equivalent hop count, an indication that the routes taken by forwarded messages are similar regardless of forwarding algorithm. However, as density increases, fewer event notifications reach the sink at the first attempt leading to increased re-transmissions and increased notification delay.

V. CONCLUSION

In perfectly area covered wireless sensor networks, SOFIE achieves significantly lower event propagation delay than two general purpose geographic forwarding algorithms when node communication range is between two and three times sensing range, regardless of node density and sensing payload size.

At low node densities, most easily achieved by planned placements, this advantage is gained at the cost of a greater channel contention leading to higher transmission (receive) errors; however, at higher node densities, those typified by random distributions, the transmission error ratio between SOFIE and the best compared algorithm narrows. Further, SOFIE maintains a lower event propagation delay in duty cycling networks where changes in topology caused by nodes entering and exiting sleep state occur frequently when compared to the event occurrence rate.

Differences in energy consumption during transmit and receive operations are observed between the algorithms under test. However, as the target scenario requires all active nodes have their transceivers energized at all times, the cost of idle listening incurred by all the compared algorithms will dwarf that of transmit and receive, rendering any observed differences inconsequential.

It should be noted that SOFIE has a scenario-driven single aim, minimising notification delay. Existing forwarding algorithms have primary concerns including avoiding collisions and minimising energy consumption, but for critical rare events where delay in delivering an event notification message can have potentially life threatening consequences, all other considerations becomes subsidiary to the pursuit of the fastest possible message propagation.

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