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 network (WSN) nodes are typically small battery powered or energy harvesting devices consisting of a micro controller, a small amount of random access memory, possibly some non-volatile storage, one or more sensors, and a low power radio transceiver which is the most power hungry component. The finite charge storage capacity of batteries and the limited capabilities of small scale energy harvesting devices shapes WSN research to the extent that minimising energy consumption becomes a preoccupation; the less energy consumed, the longer the network will continue to operate with the simplest way to reduce energy consumption being to power down the transceiver for extended periods.

WSNs have been classified by their data delivery profile as being *continuous*, *event-driven*, *observer-initiated* (query-based), or a *hybrid* [1], 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 [2] and employ algorithms that minimise overuse of individual routing nodes [3]. Similar techniques can be adopted for networks where data collection is initiated by base station requests [4].

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 can take no 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) [5, 6, 7] 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.

The body of this paper is organized as follows. Related work is examined in Section II, while Section III describes SOFIE with emphasis on message suppression, collision avoidance, and event reliability. Section IV presents the results of a comparative analysis of SOFIE against two algorithms with similar aims, including details of algorithmic differences. Section V draws conclusions and highlights areas suitable for continued research.

II. Related Work

Opportunistic forwarding algorithms for ad-hoc wireless networks have long been studied [8, 9, 10] yet as far as the authors are aware, no algorithm specifically targeting networks exhibiting perfect area coverage has previously been proposed.

Routing protocols in wireless networks can be classified as either *proactive*, *reactive* or a hybrid [11]. Proactive protocols typically maintain routing tables by sending and receiving topology messages, available routes between any two nodes being determined in advance of data transmission. Reactive protocols do not periodically share network topology but send out routing probes when data transmission to a particular destination is required, forwarding the data messages once the route has been determined. 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. Position based routing [12] uses an understanding of the location of network elements to inform routing decisions. In networks where the network topology is constantly changing, either through node mobility [13] or duty cycling [14, 15], opportunistic, broadcast forwarding algorithms have been shown to provide better throughput than unicast routing protocols [16, 17].

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 [18]. In the simplest case, the one addressed by SOFIE, nodes are aware only of their own location and those of the network sinks.

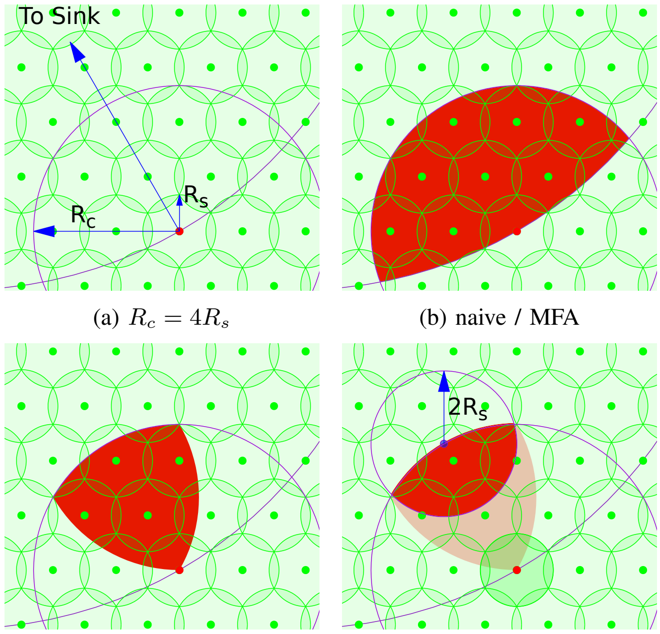
Existing opportunistic forwarding algorithms have a number of common themes: collision avoidance, energy conservation and hole avoidance.

Collision Avoidance is desirable to reduce occurrence of dropped packets and avoid energy draining re-transmissions. An established contention-based forwarding scheme (CBF) [19] gives forwarding nodes in more advantageous locations priority, with nodes that are less well-positioned suppressing their forwarding transmissions. A more complex beacon-less on demand strategy (BOSS) [20] uses multiple small messages to locally coordinate selection of the next forwarding node. In both situations, the sensible caution taken to avoid collisions results in increased latency that adversely impacts detection delay.

Energy Conservation is of significant importance to WSNs where power source are finite and/or limited and network longevity is key. However, sensing critical rare events changes priorities to the extent that high but short duration forwarding costs become acceptable as they are incurred infrequently but deliver significant benefit. The well established geographic random forwarding (GeRaF) algorithm [21] quite reasonably trades latency against energy usage, but for critical events minimal latency is key and energy consumption during the rare transmissions is of little significance compared to the energy involved in keeping the network connected by maintaining transceiver power. A more recent opportunistic routing algorithm for asynchronous WSNs [22] assumes energy saving full-node duty cycling along the transmission path; transmission delays introduced by this otherwise sensible strategy may prove unacceptable for critical event sensing.

Hole Avoidance [23, 24, 25] attempts to route around geographical areas where the network is not connected. For rare event sensing, perfect event detection demands the sensing area be covered with active sensors, ensuring communication range is at least twice sensing range to achieve a network that is connected [26] with no holes.

Whilst no previous work has focused on the unique situation, sensing critical rare events introduces 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 and BOSS are selected for comparison with SOFIE.



(a) $R_c = 4R_s$ (b) naive / MFA (c) Reuleaux Triangle (d) SOFIE's Reuleaux $\triangle$

Fig. 1: Comparison of forwarding regions

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 [26]. 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)

Small packets are more likely to reach their destination [27] so choosing appropriate field sizes can have a significant impact on detection delay; event notifications that fail to reach the sink at the first attempt have to be resent. If a high location accuracy is necessary, a high precision, possibly three dimensional coordinate system will be required; such coordinates require significantly more space in the event notification (message) than a less precise, two dimensional system would demand.

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 the forwarding area highlighted as the darkest area in Fig. 1(d). This forwarding area being 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. Forwarding areas are based on Reuleaux Triangles as a compromise between Maximum Communication Area (MCA) and 60° Radian Area (DRA), where Maximum Forwarding Area (MFA) is deemed as the naive approach [28].

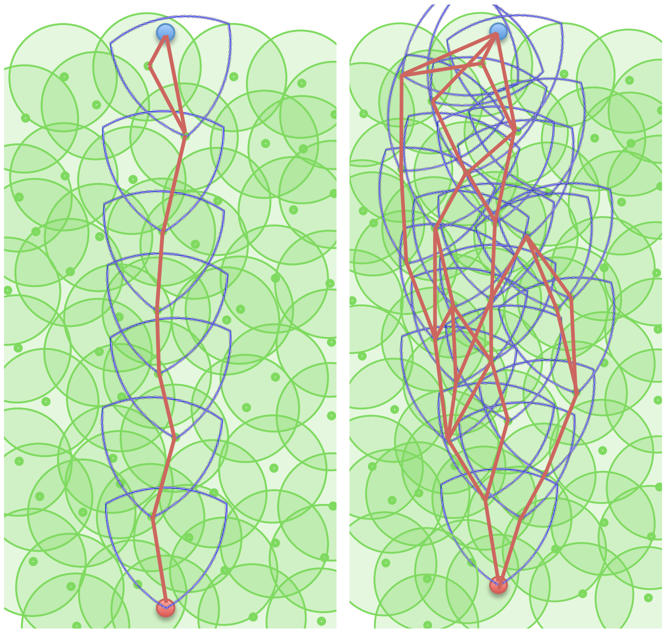
As re-broadcasts occur immediately, increasing the possibility of media contention that will be dealt with by the medium access control (MAC), the forwarding path for any given notification is therefore non-deterministic; Fig. 2 illustrates the difference between our scheme and *greedy forwarding* [9] employed 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. Examples of routes taken by CBF, BOSS and SOFIE are shown in Fig. 2 .

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 shown as the darkest area in area in Fig. 1(d), 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 an optimisation in the provision of 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 rebroadcast) 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 show in Fig. 1(d).



(a) (b)

Fig. 2: Possible paths for (a) greedy (CBF/BOSS) forwarding; (b) non-deterministic (SOFIE) forwarding. $R_c = 2R_s$

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 standard MAC (or modifications to it for time-critical events [29]) to make use of its carrier sense multiple access with collision avoidance (CSMA/CA) capabilities 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 other nodes sensed the same 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 CSMA/CA parameters as shown in Table I.

TABLE I: CSMA/CA Parameters

Min Backoff Exponent	3
Max Backoff Exponent	6
Max CSMA Backoffs	4
Max Frame Retries	3
Turnaround Time	12 symbol periods
Unit Backoff Period	20 symbol periods
Ack Wait Duration	650 symbol periods

Nodes are deployed in a $400m \times 400m$ perfectly flat sensing area. A sink is placed at one corner of the sensing area. Coordinate fields in all messages are $32\,bits$, all others are $16\,bits$ with the exception of the payload which varies by evaluation. A total of 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, but are not of prime interest.

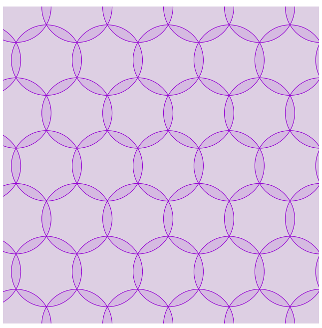
CBF uses an area suppression scheme based on a forwarding area restricted to a Reuleaux Triangle as shown in Fig. 1(c) and exposes a single tunable parameter, T_{cbf}, representing the maximum time a forwarding node waits before forwarding a received message. For a given forwarding node, CBF waits $R_c/D_{prev} \times T_{cbf}$, where D_{prev} is the node's euclidean distance from the previous forwarder, before re-broadcasting the message. If whilst waiting to re-broadcast, the node receives a re-broadcast of the same message from a node closer to the sink, the waiting node suppresses the message by not re-broadcasting it.

BOSS nodes also suppress messages based on receiving re-broadcasts from more advantageously placed nodes whilst waiting to forward the same message. The suppression algorithm is based on Discrete Dynamic Forwarding Delay (DDFD), itself based on a weighted banding of the naive forwarding area shown in Fig. 1(b), where the number of bands are configurable, as the Number of Sub Areas (*NSA*), and the maximum suppression delay, represented here as T_{boss}.

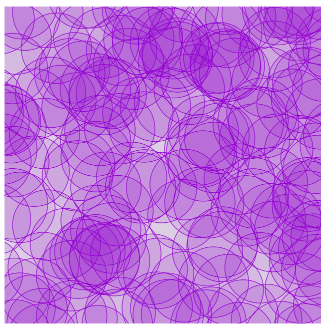
Whilst CBF and SOFIE have a single in-bound message type, BOSS is predicated on research that shows small wireless transmissions are more likely to be error free than large transmissions, and hence uses three types of light-weight coordination messages to avoid re-broadcast of heavy-weight data packets. BOSS's primary motivation is to avoid collisions and consume minimal bandwidth, this being achieved at the expense of extended propagation delays. This clearly contradicts the goal of achieving low latency detection delay of rare event data.

In all evaluations, $T_{ack} = 60\,ms$, $T_{hop} = 80\,ms$, $T_{cbf} = T_{boss} = 45\,ms$, and BOSS $NSA = 10$. Each simulation is repeated with 100 distinct random seeds that affect occurrence of errors in the simulated physical layer and one element of DDFD in BOSS.

With $R_c/R_s = 2.2$ for fixed R_s, hexagon based planned node layouts of increasing density are generated, starting with the ideal placement shown in Fig. 3(a) 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. Fig. 3(b) shows a random placement of density 0.0011 $nodes/m^2$.

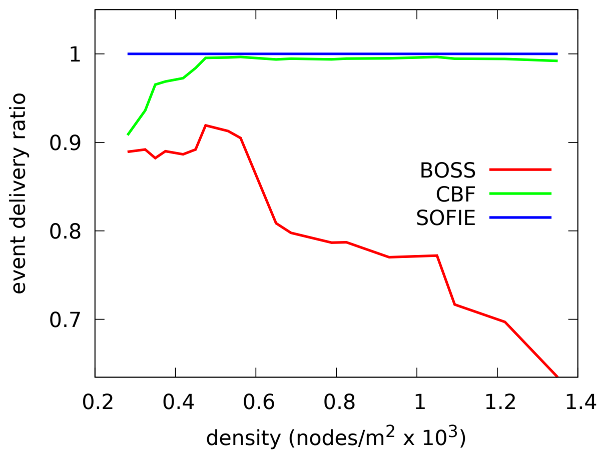


(a)

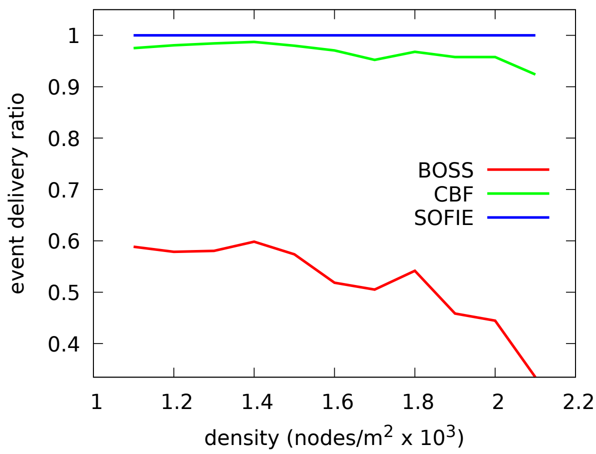


(b)

Fig. 3: (a) ideally (hexagonally) and (b) randomly (Poisson point distribution) placed sensing nodes providing 100% sensing area coverage. R_s indicated by circles, overlap is shaded proportionally. R_c not shown.



(a) Ideal Placement



(b) Random Placement

Fig. 4: Delivery ratio by node density

A. Delivery Ratio

CBF and BOSS do not guarantee data delivery even in a network known to be connected. Fig. 4(a) and Fig. 4(b) show SOFIE achieves perfect event notification delivery for the planned and random placements, described in Section IV and shown in Fig. 3. 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. 5(a) and Fig. 5(b) show SOFIE maintains a lower event notification delay for $64\,byte$ payloads in all circumstances. For planned placements, SOFIE experiences more receive errors than CBF or BOSS as their more cautious forwarding strategies are, at least in part, designed to avoid collisions. Fig. 5(c) shows a clear distinction between receive errors, especially at low node densities.

At higher node densities, and particularly in random distributions, the difference in receive errors is less significant, as shown in Fig. 5(d). Energy consumed in transmit and receive states, Fig. 5(e) and Fig. 5(f), 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, and the resulting increase in transmitted packets inevitably increasing the energy cost.

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

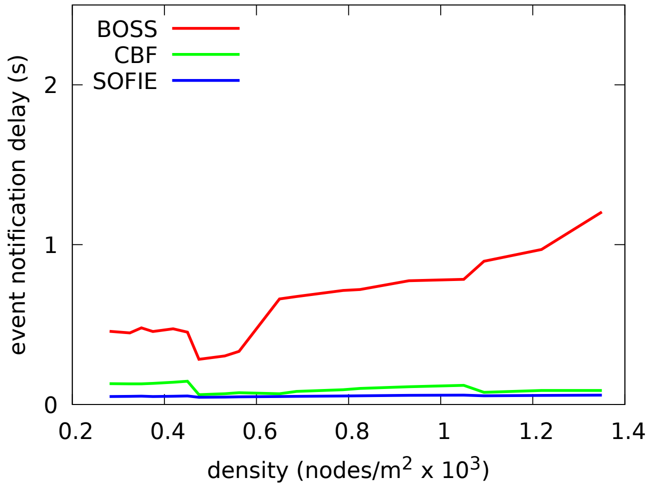
C. Variable Topology

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 [30]. As nodes collaboratively power on and off, the network topology changes making this scenario an ideal candidate for opportunistic forwarding.

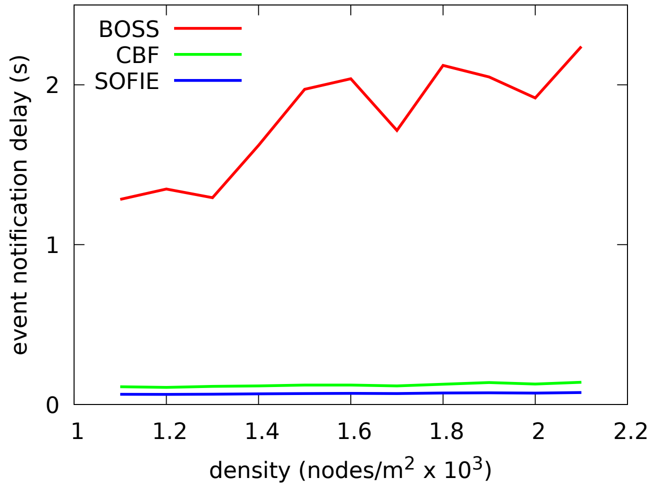
Here, an overpopulation of 240 nodes are randomly placed in the sensing area, from which 48 subsets of 140 nodes are pre-selected such that each subset provides perfect area coverage. Individual nodes can be in zero or more subsets. Every 12 seconds a new subset is activated; nodes in the new subset that are not currently energized are powered up, and the 100 nodes not in the new subset are powered down. Note that a given node may be in both the previously active subset and the new one, in which case it remains energized. Nodes also remain energized if they are currently waiting for an acknowledgement of a previously sent event notification; once the acknowledgement is received, the node then powers down unless it is now in the current active subset. Attention is drawn to the relative frequency of duty cycling operations compared to event occurrences; during each 6-hour simulation, nodes duty cycle 1,800 times whereas only 109 events occur.

Evaluations undertaken in Section IV-B used a $64\,byte$ sensing data payload, which is more than half the maximum payload capacity for a single unencrypted IEEE 802.15.4 packet. Packet size is known to affect error rates in wireless networks [27]; 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. 6(a) and 6(b) show notification delay for increasing R_c/R_s for payloads of $0\,bytes$ and $32\,bytes$ respectively. R_c/R_s was modified by increasing R_c for fixed R_s, the



(a)



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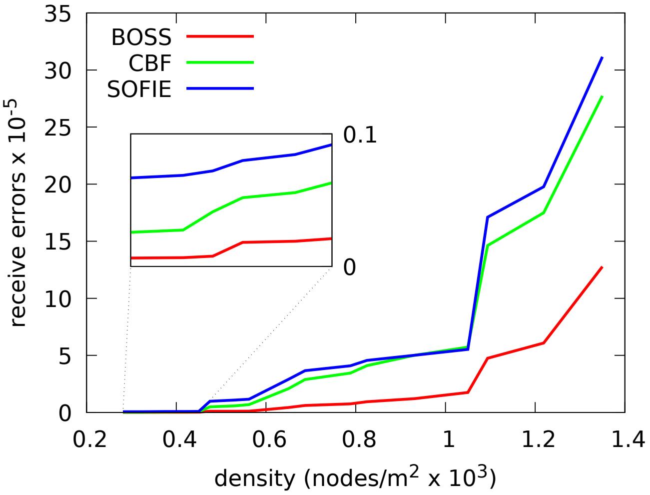
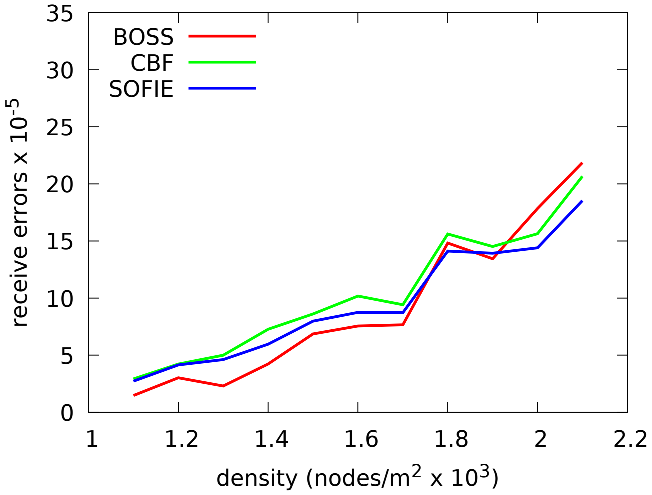
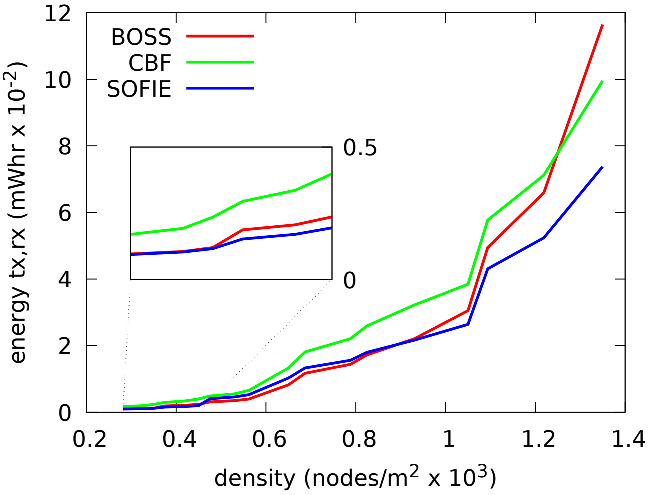


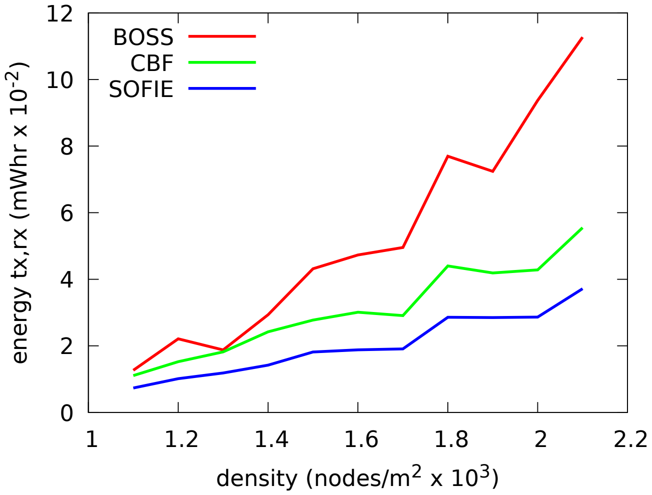
(c)



(d)



(e)



(f)

Fig. 5: (a) & (b) Notification Delay, (c) & (d) Receive Errors and (e) & (f) Energy Consumed (in non idle transceiver states) for $64\,byte$ payloads in (a), (c) & (e) ***planned***, hexagonal placements and (b), (d) & (f) Poisson distributed ***random*** placements of increasing node density.

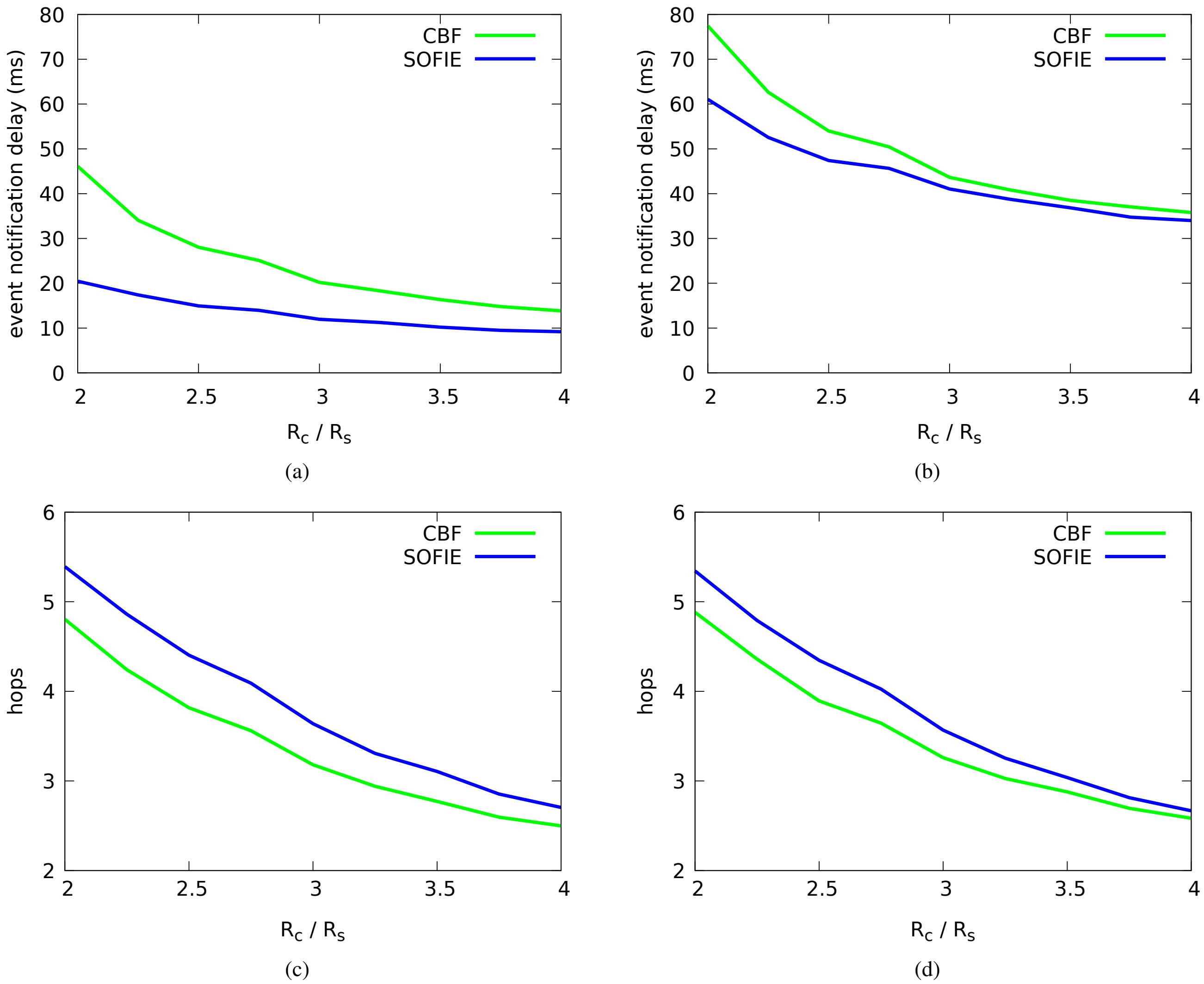


Fig. 6: Notification delay and hops taken for coverage preserving, sleep-scheduled network with active node density of 0.00088 nodes/m^2 by increasing R_c for fixed R_s. (a) & (c) $0\,byte$ payload, (b) & (d) $32\,byte$ sensing data payload.

effect of which was to reduce the number of hops for each notification, as shown in Fig. 6(c) and 6(d). 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. On the other hand, 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. 7(a) and Fig. 7(b) 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, as show in Fig. 7(c) and Fig. 7(d). However, as density increases, fewer event notifications reach the sink at the first attempt leading to increased retransmissions and increased notification delay.

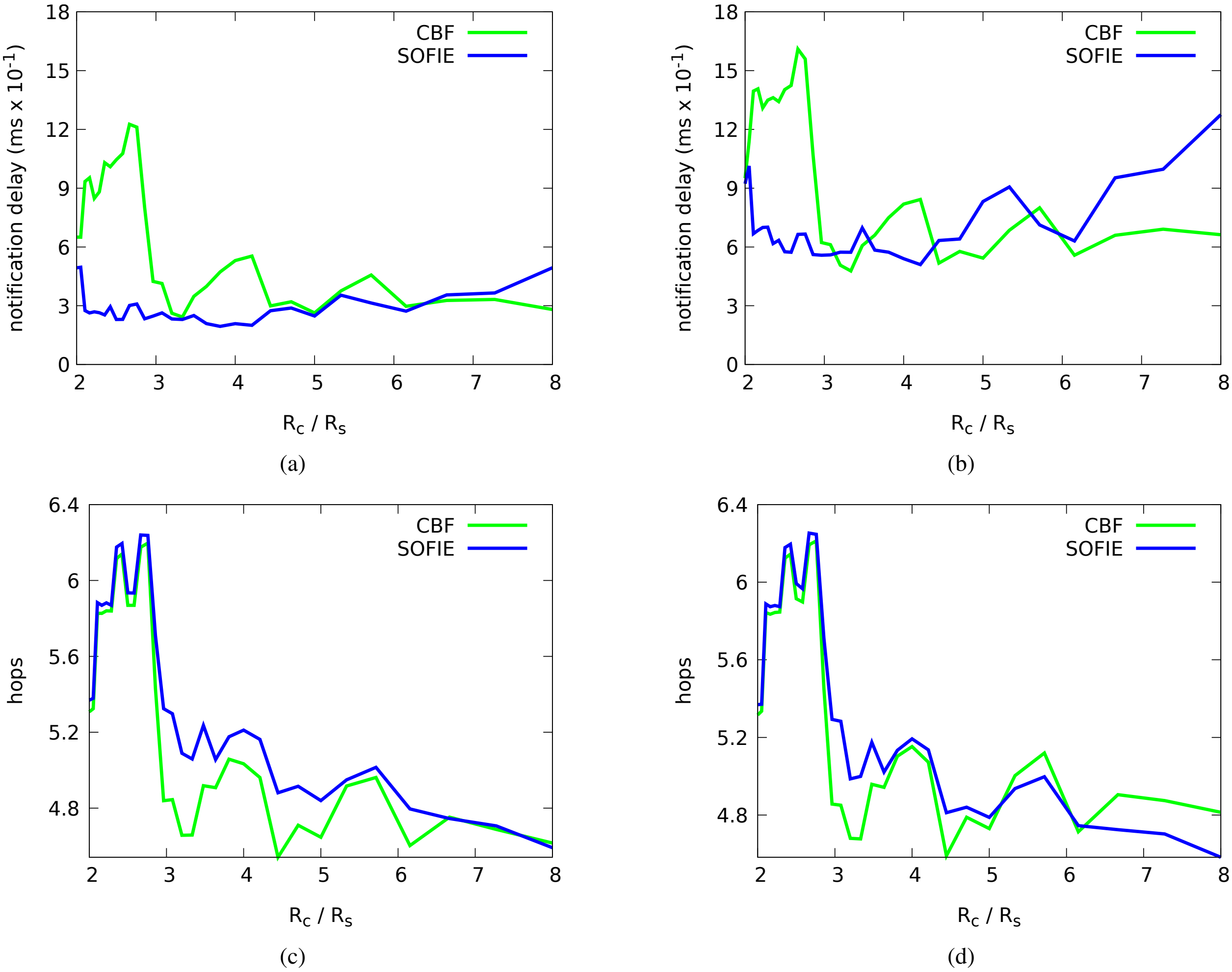


Fig. 7: Notification delay and hops taken for planned placements with decreasing R_s for fixed R_c. (a) & (c) $0\,byte$ payload; (b) & (d) $32\,byte$ payload.

V. Conclusion and Future Work

In perfectly area covered wireless sensor networks, SOFIE achieves at least a 50% 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.

Ongoing work addresses the following areas: In *multi-sink scenarios*, SOFIE will simultaneously forward to all sinks whereas the compared algorithms assume a single sink per packet. Multi-sink capabilities can be simulated in algorithms that embed the destination location in their messages by having the application layer initiate a message for each sink. A comparison of which technique is more effective is of interest.

In dense sensing networks, multiple nodes can detect the same event. In some circumstances, it may be desirable to employ *event de-duplication* where messages are not forwarded if they are heuristically determined as being a duplicate of some previously forwarded message originating at a different node. Our implementation of SOFIE includes functionality to undertake time and location aware de-duplication via multilateration; investigations are underway to determine in what circumstances this is of demonstrable benefit.

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