Routing Protocols for Wireless Sensor Networks that have an Opportunistic Large Array (OLA) Physical Layer

LAKSHMI V. THANAYANKIZIL, ARAVIND KAILAS, AND MARY ANN INGRAM

School of Electrical and Computer Engineering,

Georgia Institute of Technology, Atlanta, GA 30332-0250, USA

Email contact: {lakshmi, mai}@ece.gatech.edu, aravindk@ieee.org *

Abstract

The Opportunistic Large Array (OLA is a simple strategy that provides a Signal-to-Noise Ratio (SNR) advantage from the spatial diversity of distributed single-antenna radios. In this paper, we present a collection of broadcasting and upstream routing protocols that have been developed for the OLA physical layer. We consider several benefits of OLA transmissions, namely, energy efficiency, survivability during network partitions, improved latency, and robustness against mobility. The strategies for broadcast are OLA with Transmission Threshold (OLA-T) and Alternating OLA-T (A-OLA-T), and the main upstream routing scheme is the OLA Concentric Routing Algorithm (OLACRA). These schemes exploit the nature of OLA broadcasts and limit the number of nodes participating in each hop to reduce the aggregate transmit energy consumed in the network. To increase the network survivability during partition, we propose a new survivable network protocol that detects a network partition and triggers the creation of a large enough OLA to overcome the partition. All of the OLA-based routing schemes share the properties of no centralized control, no individual node addressing, no inter-node coordination, no reliance on node location knowledge, and no dependence on density, given that the density is at least sufficient to support OLA transmission. These properties imply that the OLA-based protocols are scalable with node density and robust against mobility.

Key words: Broadcasting, cooperative transmission, energy-efficiency, mobility, network life extension, disconnected networks, opportunistic large arrays, survivability, wireless sensor networks

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*Mary Ann Ingram, Aravind Kailas and Lakshmi Thanayankizil are with the School of Electrical and Computer Engineering, Georgia Institute of Technology, Altanta, GA 30332–0250, USA. The authors gratefully acknowledge support for this research from the National Science Foundation under grants, 0313005 and CNS-0721296.

1 INTRODUCTION

Solving the key issues of longevity and connectivity of a Wireless Sensor Network (WSN) of battery-powered sensors continues to attract significant research attention [1]. While energy-efficient wireless communication protocols are critical for typical WSN applications, a protocol's ability to recover from network partitioning is equally important. Cooperative Transmission (CT) is a way that one or more single-antenna radios can help another single-antenna radio send a single message efficiently and reliably, by forming a "virtual array" [2], [3]. Through spatial diversity, the virtual array achieves an SNR advantage comparable to that of a real array, without the expense and large form factor of a multi-antenna radio. The Opportunistic Large Array (OLA) [4] is a very low-overhead form of CT that requires no individual node addressing, which leads to scalability with node density. In this paper, we present a collection of routing and acknowledgement (ACK) protocols that are based on the OLA physical (PHY) layer. Based solely on autonomous node decisions (i.e. there are no "cluster heads"), our OLA-based broadcasting and upstream routing algorithms save transmit energy by preventing nodes from relaying that are in a poor position or are not needed to contribute to message propagation in the desired direction. Also based on autonomous node decisions, our OLA-based ACK protocol can overcome network partitions that would defeat a non-cooperative multi-hop routing protocol. Because an OLA-based 'link" involves transmission between two *clusters of nodes*, instead of between just two nodes, OLA-based routing protocols are more tolerant to node mobility than non-cooperative routing protocols. This paper is our attempt at a unified collection of results that we have published, at least in part, in a number of other papers [19]–[21], [23], [25]–[27].

CT strategies provide spatial diversity, which enables dramatic reduction of the fade margins (i.e., the transmit powers) in a multipath fading environment, thereby saving transmit energy or extending range [2], [3]. In an OLA, nodes behave without coordination between each other, but they naturally fire at approximately the same time in response to energy received from a single source or another OLA [4]. All the transmissions within an OLA are repeats of the same waveform, therefore the signal received from an OLA has the same model as a multipath channel. Small time offsets (because of different distances and computation times) and small frequency offsets (because each node recovers a different oscillator frequency) are like excess delays and Doppler shifts, respectively. As long as the receiver, such as a RAKE receiver, can tolerate the effective delay and Doppler spreads of the received signal and extract the diversity, decoding can proceed normally. As an example, if OFDM is being used, the guard interval would need to be at least as large as the *sum* of the "artificial" delay spread, which would be caused by the OLA in free space, and the "natural" delay spread of the multipath channel. Even though many nodes may participate in an OLA transmission, transmit energy can still be saved because all nodes can reduce their transmit powers dramatically and large fade margins are not needed. It is noted that carrier sensing must be disabled for an OLA transmission, or else the OLA participants that provide the spatial diversity are suppressed.

1.1 OLA-based Broadcasting

OLA transmission has been proposed for energy-efficient broadcasting [4], [15]–[21]. [4] proposes what we refer to in this paper as Basic OLA. In a Basic OLA broadcast, the first OLA comprises all the nodes that can decode the transmission from the originating node; then the first OLA transmits and all nodes that can decode that transmission form the second OLA, and so forth. There are no collisions resulting from a single broadcast because OLA nodes relay exactly the same packet; this means that a relay cannot impress any of its own information, such as its address, on the packet. The resulting OLAs form concentric rings around the originating node. Our broadcast protocols extend Basic OLA through the introduction of the "Transmission Threshold." A node that successfully decodes the message (e.g. by passing a Cyclic Redundancy Check (CRC)), compares its received SNR to this threshold and relays only if its SNR is *less* than the threshold; the nodes that relay are in the best position to participate in the next OLA transmission. We call the broadcast protocol based on this idea, OLA with Transmission Threshold (OLA-T). OLA-T has no overhead and requires only the memory of the threshold value, so it is especially suitable for mobile networks. We note that the Dual Threshold Cooperative Broadcast (DTBC), proposed in [16], is the same idea as OLA-T, however DTBC was not analyzed in [16]. In this paper, we give the condition for successful OLA-T broadcast and compare OLA-T with Basic OLA in terms of transmit energy [19], [20].

The other broadcast protocol presented in this paper, Alternating OLA-T (A-OLA-T), optimizes multiple, consecutive OLA-T broadcasts, so that different sets of nodes relay in each broadcast and eventually all nodes relay the same number of times. Because A-OLA-T drains the batteries efficiently and uniformly across the network, it is most appropriate for static networks. This paper summarizes the conditions for a successful A-OLA-T broadcast and compares the performance of A-OLA-T with that of Basic OLA and OLA-T in terms of transmit energy consumption [21].

Flooding, the strategy where every node in the network retransmits its received message, is well known to lead to severe contention, collision and redundant transmissions, a situation referred to as "broadcast storm" [5]. Hence, one of the important problems in ad hoc networks is to reduce the number of unnecessary retransmissions. The earliest effort to preventing the broadcast storm was to intentionally limit the number of relaying nodes. The nodes that should relay the message from a particular source were predetermined. One of the prominent works in this area was the Border Retransmission Protocol (BRP) [6], where only the border nodes (i.e. nodes at the edge of the decoding range) of a particular source relay the message. Relay nodes are limited probabilistically, based on their location and distance from the source. Even though this scheme is similar to our OLA-T algorithm in allowing only the border nodes to relay without centralized control, BRP requires initial local handshaking messages to determine the border nodes. Hence with BRP the overhead and memory requirements on a node go up with density.

Even though BRP reduces collisions and redundant retransmissions, it still entails large node participation. More recently, the focus of broadcast routing has been to minimize the number of nodes participating by designing optimal spanning trees in the network. A spanning tree is a minimal graph structure that is rooted at the source node and supports network connectivity. One of the most efficient spanning tree algorithms is the Broadcast Incremental Protocol (BIP) [7]. Even though spanning tree algorithms are very energy efficient, most of them require centralized control to determine the optimum tree, which is not practical in highly dense and/or mobile deployments.

We point out a fundamental distinction between broadcast trees and OLA broadcasting. Ideally, in a broadcast tree, a node receives the signal the first time from just one transmitter. In other words, the relays are chosen so that there are no collisions. OLA transmission is just the opposite; a receiver is *supposed* to receive the signal simultaneously from multiple transmitters.

1.2 OLA-based Upstream Routing

Besides broadcasting, the other type of routing considered in this paper is unicast, specifically, the upstream route from a sensor to the sink, or Gateway Node. For this, we propose the OLA Concentric Routing Algorithm (OLACRA), which uses the concentric rings created by an OLA or OLA-T broadcast, to guide the upstream message back to the Sink. Below we discuss the advantages and disadvantages od OLACRA in the context of existing unicast works.

WSNs are inherently multi-hop because the decoding range of a single, highly energy-constrained node is small compared to the total area of the network. A common approach at the network layer to the energy-efficiency problem is energy-aware routing. The objective of energy-aware protocols has been either minimizing the energy consumption or maximizing network lifetime. The aim of minimum-energy routing [12], [13], is to minimize the total consumed energy to reach the destination, which in turn minimizes the energy consumed per unit flow. This method does not yield long network life because if all the traffic is routed through the same minimum energy path, the batteries of the nodes along the path will drain quickly, while the other nodes will remain intact. On the other hand, the objective of the maximum network lifetime scheme [14], has been to increase the time to network partition. It turns out that to maximize the network lifetime, the traffic should be routed such that the energy consumption is balanced among the nodes in proportion to their energy reserves [14]. However the above-mentioned energy-aware protocols do not consider cooperative transmission.

Lately CT has been extended unicast transmission. Several works in this area assume that a conventional multi-hop route has been previously identified and power is allocated to nodes along the route or near the route to assist with cooperative transmission [8], [9]; the corresponding routing metric is the total path transmit power. Besides requiring a pre-determined route, one disadvantage of using these schemes is that they require coordination and addressing of relay nodes, which OLA-based schemes dont entail. In previous works on OLAs, routing is accomplished using flooding [16], this is inefficient for upstream routing. To our knowledge, the only work on OLAs, other than OLACRA, which limits flooding in the upstream is [17], where nodes exploit knowledge of their location, which can be obtained using a Global Positioning System (GPS). However this assumption might not be practical in some sensor network scenarios. Also, even if nodes know their coordinates, a routing algorithm that doesnt require location knowledge, such as OLACRA, may have lower computational complexity.

Another advantage of CT not often mentioned is the ability to overcome network partitions that would defeat multi-hop routing without cooperation. Partitions can develop because of node mobility, limited radio power, node failure, uneven deployment, and obstacles like hills or walls. Ad hoc networking applications such as battlefield and disaster recovery communications, environmental monitoring, and wide area surveillance are prone to partitions. Unfortunately, most existing multi-hop ad hoc routing protocols will fail to deliver messages under these circumstances since no route to the destination exists. Most of the works in this area consider proactive schemes [10] that prevent node partitioning by efficient routing schemes. The only reactive partition recovery mechanism proposed is a ferrying scheme proposed in [11]. However ferrying schemes are not feasible in static WSNs. In this paper, we propose a Two-Hop ACK Scheme that detects a network partition and then an OLA-Size Adaptation Mechanism grows a large enough OLA to go over the partition. These schemes require no centralized control. To the best knowledge of the authors, this is the only distributed network partition recovery scheme proposed for WSNs.

In addition to the transmit energy savings and range extension in disconnected networks, which are properties of all cooperative transmission schemes, we explore other benefits which are unique to distributed CT schemes like OLA, namely, reduced end-to-end delay and robustness to mobility. Since OLA transmissions have no contention for a single data stream, the time required for channel access and reattempts in the face of collision can be avoided with OLAs. Additionally, because of the range extension of OLAs, messages are transmitted with fewer "OLA-hops" compared to non-cooperative multi-hop schemes. Unlike other cooperative schemes, OLA transmissions are more robust to mobility as the cooperating nodes are not predetermined. We compare our scheme with the multi-hop Dynamic Source Routing (DSR) to show the benefits.

This paper focuses mainly on a node's radiated energy, as do many key papers in multi-hop routing. An assessment of the total energy consumption (i.e. including circuit energy in both transmission and reception) is very important, and is underway at the time of the submission of this paper. Because all nodes in a broadcast must decode the signal, the transmit energy gains we report here for broadcasting imply overall energy gains, which we quantify in this paper. For unicast, the translation is not trivial and the conclusion is not clear; it depends on many factors, including hop distance and rate adaptation [32], the specific radio parameters, the number of nodes decoding but not transmitting and how much of the packet they decode [31], and other factors, such as routing overhead. OLA-based unicast may not always be an energy efficient strategy, but it has other features, such as simplicity, no requirement of a pre-existing route, scalability, ability to overcome a partition, and robustness to mobility, that may still recommend it for certain applications.

This paper is organized as follows. Section 2 outlines the network model that we use in our protocol. In Sections 3 and 4 we propose energy-efficient broadcast and unicast routing schemes for OLA-based networks. Section 3 presents our OLA-based broadcast protocols, namely, OLA-T and A-OLAT and Section 4, we turn from broadcasting in to upstream routing and explain in great detail our OLA-based upstream routing protocol, OLACRA. Section 5 shows the ability of OLA-based protocols to survive network holes and partitions. In this regard, we propose a distributed Survivable Network Protocol, which detects partitions using a Two Hop ACK Scheme and an OLA Size Adaptation mechanism that straddles these partitions. Monte Carlo simulations are done to evaluate the above-mentioned protocols and their benefits in Section 6. Also in this Section, in addition to the benefits discussed so far (energy efficiency and survivability), we also explore two new properties of OLA-based networks, which are robustness to mobility and lower end-to-end delay.

2 NETWORK MODEL

For our analysis, we adopt the notations, assumptions and normalizations of [20], most of which were used earlier in [18]. Half-duplex nodes are assumed to be distributed uniformly and randomly over a continuous area with average node density ρ. The originating node is assumed to be a point source at the center of the given network area. We assume a node can Decode and Forward (DF) a message without error when its received SNR is greater than or equal to a modulation-dependent threshold [18]. Assumption of unit noise variance transforms the SNR threshold to a received power criterion, which is denoted as the decoding threshold τ_d . We note that the decoding threshold τ_d is not explicitly used in real receiver operations. A real receiver always just tries to decode a message. If no errors are detected, and the message was decoded properly, then it is assumed that the receiver power must have exceeded τ_d.

The path-loss function in Cartesian coordinates is given by $l(x, y) = (x^2 + y^2)^{-1}$, where (x, y) are the normalized coordinates at the receiver. As in [18], distance d is normalized by a reference distance d_0 . Let power P_0 be the received power at d_0. The average received power from a node distance d away is $P_{\text{rec}} = \min\left(\frac{P_0}{d^2}, P_0\right)$. Let the normalized source power, the normalized relay transmit power, and the normalized relay transmit power per unit area be denoted as P_s , P_r and $\overline{P_r}$, respectively.

We consider two network models, the Deterministic model and the Diversity Channel model. In the Deterministic model, the power received at a node is the sum of the powers received from each of the node transmissions, where path loss is the only channel impairment. This model implies that node transmissions occur on orthogonal non-faded channels. In the Diversity Channel model, node transmissions are assumed to be on a limited number of orthogonal Rayleigh-faded channels.

In the deterministic channel model [18], it is assumed that if a set of n relay nodes (say L_n) transmits simultaneously, the node j with normalized coordinates (x_0, y_0) receives with power

$$P^j_{\text{rec}} = P \sum_{(x,y)\in L_n} l(x - x_0, y - y_0), \tag{1}$$

where P is the normalized transmit power given by

$$P = \frac{P_t G_t G_r}{\sigma_n^2}\left(\frac{\lambda}{4\pi d_0}\right)^2, \tag{2}$$

where P_t is the un-normalized transmission power in mW , G_t and G_r are the transmit and receive antenna gains, σ_n^2 is the thermal noise power and λ is the wavelength in meters.

For ease of analysis of the OLA broadcast, and following [18], we assume a continuum of nodes, which means that we let the node density ρ become large ($\rho \to \infty$) while $\overline{P_r}$ is fixed. Then the expression for P^j_{rec} simplifies to

$$P^j_{\text{rec}} = P \int_x \int_y l(x - x_0, y - y_0), dxdy. \tag{3}$$

For the Diversity Channel model [25], the received power is given by

$$P^j_{\text{rec}} = \sum_{k=1}^{m} \gamma_k P^j_{\text{rec},k}, \tag{4}$$

where m is the number of orthogonal channels and $P^j_{\text{rec},k}$ is the average power received at the k-th orthogonal channel and γ_k is a zero mean, unit variance Exponential random variable.

In previous works involving OLAs, the ratio $\tau_d/\overline{P_r}$, which we called the Decoding Ratio, $\mathcal{D}$, in [20], figured prominently in the analysis. $\mathcal{D}$ can be shown to be the ratio of the receiver sensitivity (i.e. minimum power for decoding at a given data rate) to the power received from a single relay at the 'distance to the nearest neighbor,' $d_{nn} = 1/\sqrt{\rho}$. If ρ is a perfect square, then the d_{nn} would be the minimum distance between the nearest neighbors if the nodes were arranged in a uniform square grid. However, $\mathcal{D}$ relates to the node degree, $\mathcal{K}$, which is the average number of nodes in the decoding range of a transmitter, as $\mathcal{K} = \frac{\pi}{\mathcal{D}}$. In this paper, we will use $\mathcal{K}$.

In this paper, we assume that the effective delay spreads and effective Doppler spreads are within the tolerance of the receivers. In other words, we assume sufficient OLA transmit timing and frequency synchronization. We also assume perfect SNR estimation. Imperfect OLA synchronization and SNR estimation will affect the performance of the protocols, and investigations into these topics are underway at the time of the writing of this paper.

3 BROADCAST PROTOCOLS

In this section, we present our OLA-based broadcast protocols, namely, OLA-T and A-OLA-T. OLA-T is more suitable for mobile ad hoc networks, and A-OLA-T is more suitable for static networks. Both can be interpreted as extensions of "Basic OLA" in [4]. We will compare OLA-T and A-OLA-T to Basic OLA in terms of the transmit energy consumed.

3.1 OLA with Transmission Threshold (OLA-T)

The transmit energy efficiency of OLAs can be improved by letting only the nodes near the forward boundary retransmit the message. These nodes are similar to the "border nodes" of BRP [6]. By definition, a node is near the forward boundary if it can only barely decode the message. The state of "barely decoding" can be determined in practice by estimating the average magnitude of the error vector (the distance between the received and detected points in signal space [1]) or by measuring the received SNR and determining when it is low, conditioned on a successful CRC check.

On the other hand, a node that receives much more power than is necessary for decoding is more likely to be near the source of the message. The OLA-T method is simply OLA with the additional transmission criterion that a node will relay only if its received SNR is less than a specified "transmission threshold," τ_b. In contrast to τ_d , τ_b is used explicitly in the receiver to compare against the received SNR. So, the thresholds, τ_d and τ_b, define a range of received powers that correspond to the "significant" boundary nodes, which form the OLA. We define the Relative Transmission Threshold (RTT) as $\mathcal{R} = \frac{\tau_b}{\tau_d}$ and observe that $\mathcal{R} > 1$.

Figures 1(a) and (b) illustrate the concept of broadcast using Basic OLA and OLA-T, respectively, for a given network area (defined in Figure 1 by the dotted line). The rule for Basic OLA

[1]This is side information that is available in the symbol detector [33]

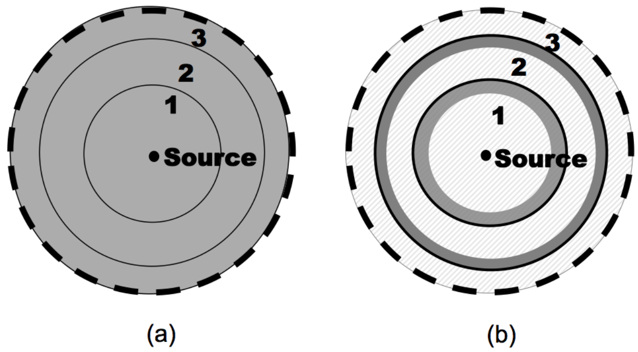


Figure 1: (a) Network broadcast using Basic OLA, (b) Energy-efficient broadcasting using a transmission threshold.

relaying is that a node relays a message immediately if it can decode and if it has not relayed the message before [18]. The aim is to succeed in broadcasting the message over the whole network. The originating node transmits a message and the group of neighboring nodes that decode the message form Decoding Level 1 (DL_1), which is represented by the disk enclosed by the smallest circle in both Figures 1(a) and (b). In Basic OLA, all DL_1 nodes relay thereby forming the first OLA. In OLA-T, the nodes that relay, and therefore constitute the first OLA, are the ones that satisfy the Basic OLA rule and the transmission criterion; these relay nodes are represented by the smallest grey ring in Figure 1(b). Next, the nodes outside of DL_1 that can decode the first OLA's transmission constitute DL_2, which is represented as the area between the two smallest solid-line circles in both Figures 1(a) and (b). Again, in Basic OLA, all DL_2 nodes form the second OLA, but in OLA-T, only the DL_2 nodes with sufficiently low SNR form the second OLA.

From [20], it is learned that if $\mathcal{K}$ and $\mathcal{R}$ are constant throughout the network, they must satisfy a necessary and sufficient condition to achieve infinite network broadcast,

$$2 \;\geq\; \exp\left(\frac{1}{\mathcal{K}}\right) + \exp\left(\frac{-\mathcal{R}}{\mathcal{K}}\right). \tag{5}$$

We observe that when $\mathcal{R} \to \infty$, OLA-T becomes Basic OLA, and (5) becomes

$$2 \geq \exp\left(\frac{1}{\mathcal{K}}\right) \Rightarrow \mathcal{K} \geq \frac{1}{\ln 2}, \tag{6}$$

which is the condition for successful Basic OLA broadcast [18]. From (5), we observe that $\mathcal{K}$ must approach infinity as $\mathcal{R} \to 1$ (i.e., as $\tau_b \to \tau_d$), in order to maintain successful broadcast.

We may re-write (5) in terms of a lower bound for $\mathcal{R}$ as follows,

$$\mathcal{R}_{\text{lower bound}} = -\mathcal{K} \ln \left[2 - \exp\left(\frac{1}{\mathcal{K}}\right)\right]. \tag{7}$$

3.1.1 *Energy Efficiency of OLA-T*

In this section, the total radiated energy during a successful OLA-T broadcast is compared to that of a successful Basic OLA broadcast. As $\mathcal{R} \to \infty$ (or $\tau_b \to \infty$), the OLA-T OLAs grow in thickness until they become the same as the Basic OLA decoding levels [18]. On the other hand, as $\mathcal{R} \rightarrow 1$, one would expect the transmitting strips to start thinning out. In other words, the inner and outer radii for each OLA become close and the OLA areas decrease. Because as $\mathcal{R} \rightarrow 1$, the favorably located "border nodes" play an increasingly dominant role, the thinner OLAs are more energy efficient, as will be shown below.

If the transmit energy consumptions for Basic OLA and OLA-T are compared for the same $\mathcal{K}$, then it can be shown that OLA-T saves over 50% of the energy consumed by Basic OLA [19]. However, as indicated in (5) and (6), Basic OLA can achieve successful broadcast at a lower $\mathcal{K}$ than OLA-T [18]. Hence, we need to compare these two protocols for a fixed value of τ_d (i.e. data rate) such that each is in its minimum energy configuration (lowest $\mathcal{K}$).

Let the outer and inner boundary radii for the k-th OLA ring be denoted as $r_{d,k}$ and $r_{b,k}$, respectively. The energy consumed by the first L levels in relaying the message in this multi-hop wireless network for a continuum case is mathematically expressed, in energy units, as

$$\xi^L = \overline{P_r} T_s \sum_{k=1}^{L} \pi (r_{d,k}^2 - r_{b,k}^2), \tag{8}$$

where T_s is the length of the message in time units. Because of the continuum assumption, the Fraction of transmission Energy Saved (FES) for OLA-T relative to Basic OLA can be expressed in terms of relative areas as

$$\text{FES} = 1 - \frac{\overline{P_r}_{(\text{OT})} \sum_{k=1}^{L} \left(r_{d,k}^2 - r_{b,k}^2 \right)}{\overline{P_r}_{(\text{O})} r_{d,L}^2}, \tag{9}$$

where $\overline{P_r}_{(\text{OT})}$ and $\overline{P_r}_{(\text{O})}$ are the lowest values of $\overline{P_r}$ that would guarantee successful broadcast using OLA-T and Basic OLA, respectively. We can multiply the numerator and denominator of the ratio by π/τ_d, and substitute the minimum node degrees, $\mathcal{K}_{(\text{OT})} = \frac{\pi \overline{P_r}_{(\text{OT})}}{\tau_d}$ and $\mathcal{K}_{(\text{O})} = \frac{\pi \overline{P_r}_{(\text{O})}}{\tau_d}$ to get

$$\text{FES} \quad = \quad 1 - \frac{\mathcal{K}_{(\text{OT})} \sum_{k=1}^{L} \left(r_{d,k}^2 - r_{b,k}^2 \right)}{\mathcal{K}_{(\text{O})} r_{d,L}^2}. \tag{10}$$

Next, we substitute $\mathcal{K}_{(\text{O})}$ by its smallest value of $1/\ln 2$ and can re-write (10) as

$$\text{FES} \quad = \quad 1 - \frac{\mathcal{K}_{(\text{OT})} \ln 2 \sum_{k=1}^{L} \left(r_{d,k}^2 - r_{b,k}^2 \right)}{r_{d,L}^2}. \tag{11}$$

3.1.2 Energy Analysis for Broadcasting Considering Receive Energy

FES defined in (11) is in terms of only the transmit energy, and can be rewritten as follows:

$$\text{FES} = 1 - \frac{\text{TT}}{\text{TB}}, \tag{12}$$

where TT is the total transmit energy of our broadcasting algorithm (e.g. OLA-T) and TB is the transmit energy of the Basic OLA. Let the total receive energy (RE) consumed by the network be proportional to TB: RE $= \alpha$TB. For example, if the receive energy is the same as transmit energy, then $\alpha = 1$. Then, we can define the whole energy fraction of energy saved (WFES) as follows:

$$\begin{aligned}\text{WFES} &= 1 - \left(\frac{\text{TT}+\text{RE}}{\text{TB}+\text{RE}}\right),\\ &= 1 - \left(\frac{\text{TT}+\alpha\text{TB}}{(1+\alpha)\text{TB}}\right),\\ &= 1 - \left(\frac{\text{TT}}{(1+\alpha)\text{TB}}\right) - \left(\frac{\alpha\text{TB}}{(1+\alpha)\text{TB}}\right),\\ &= \left(\frac{1}{1+\alpha}\right)\left(1-\frac{\text{TT}}{\text{TB}}\right),\\ &= \frac{\text{FES}}{1+\alpha}. \end{aligned} \tag{13}$$

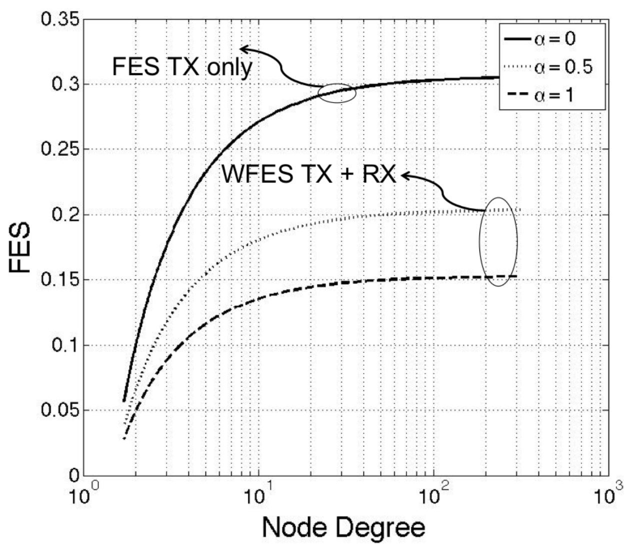


Figure 2: Variation of FES with the minimum OLA-T Node Degree, $\mathcal{K}_{(\text{OT})}$ for a network with 1000 levels.

Figure 2 shows FES versus $\mathcal{K}_{(\text{OT})}$ (on a logarithmic scale) for a network with 1000 decoding levels or hops for different values of α. We note that when $\alpha = 0$, we only consider the transmit energy, and when $\alpha \neq 0$, the receive energy is some fraction of the transmit energy. For example, for $\alpha = 0$, at $\mathcal{K}_{(\text{OT})} = 10$, FES is about 0.27. This means that at their respective lowest energy levels (OLA-T at $\overline{P_{r}}_{(\text{OT})}$, and Basic OLA at $\overline{P_{r}}_{(\text{O})}$), OLA-T saves about 27% of the transmit energy used by Basic OLA at this $\mathcal{K}_{(\text{OT})}$. On the other hand, when both the receive and transmit energies are considered, for for $\alpha = 1$ and $\mathcal{K}_{(\text{OT})} = 10$, the WFES is about 0.14. This means that at their respective lowest energy levels (OLA-T at $\overline{P_{r}}_{(\text{OT})}$, and Basic OLA at $\overline{P_{r}}_{(\text{O})}$), OLA-T saves about 14% of the total energy consumed during broadcast by Basic OLA at this $\mathcal{K}_{(\text{OT})}$. We remark that the minimum node degree required for successful broadcast using Basic OLA is 1.44, which is also the lowest possible node degree for OLA-T.

3.2 Alternating OLA with Transmission Threshold (A-OLA-T)

For a fixed source, such as the fusion node in a WSN, and for a static network, OLA-T causes the same subset of nodes to participate in all broadcasts. Therefore, participating nodes in OLA-T will eventually die ("death" happens when the batteries die), causing significant areas of the network to lose their sensing function and partitions to form. We note that a network of randomly moving nodes will not have this problem, as eventually, all nodes spend some time in the "OLA area," thereby sharing the broadcasting burden. If we define network life to be the length of time before the first node dies, and we assume that broadcasts are the only transmissions, then we observe that for a static network, OLA-T has no advantage over Basic OLA in terms of lifetime even though it consumes less total transmit energy in a single broadcast, especially when $\mathcal{K}$ is the same. So, we propose a variant of OLA-T called the Alternating OLA-T (A-OLA-T) that improves the network lifetime compared to Basic OLA and OLA-T.

The idea of A-OLA-T is that the nodes that do not participate in one broadcast make up the OLAs in the next broadcast. Figure 3 illustrates the concept. The grey areas on the left of Figure 3, are the OLAs in the first broadcast, while the grey areas on the right are the OLAs in the second broadcast. Ideally these two sets of OLAs have no nodes in common and their union includes all nodes. A-OLA-T can be extended to having three or more sets of OLAs that have no nodes in common, such that the union includes all the nodes in the network. Under the continuum assumption, more sets will increase the network life because border nodes play an increasingly dominant role. However, with finite node density, the practical limit in the number of sets is expected to be low.

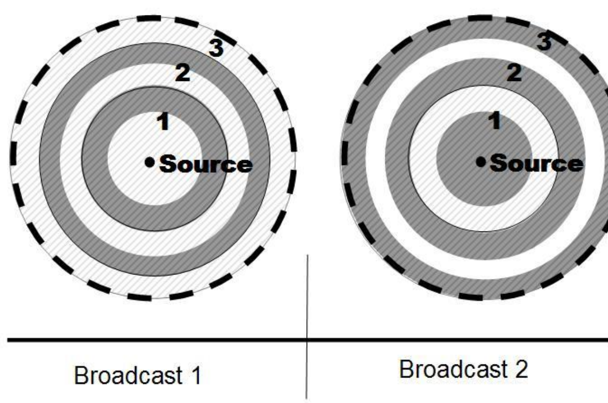


Figure 3: The grey strips represent the transmitting nodes (that form the OLA) which alternate during each broadcast.

A-OLA-T is a non-trivial extension of OLA-T. In other words, A-OLA-T will not work for every $\mathcal{R} > \mathcal{R}_{\text{lower bound}}$. Figures 4(a) and (b) contain illustrations of successful and unsuccessful broadcasts, respectively, using the A-OLA-T algorithm. We use this figure to help explain how to ensure that both broadcasts are sustaining. The upper parts of both drawings corresponds to Broadcast 1 and the

OLA radii $r_{d,k}$ and $r_{b,k}$ denote the outer and inner boundary radii for the k-th OLA ring, respectively. The lower parts of both drawings correspond to Broadcast 2 and the OLA radii $v_{d,k}$ and $v_{b,k}$ denote the outer and inner boundary radii for the k-th OLA ring, respectively. The initial conditions for the second broadcast are $v_{b,1} = 0$, and $v_{d,1} = \sqrt{\frac{P_s}{\tau_b}}$. In Figure 4(a), the first OLA during Broadcast 1 is denoted by *OLA 1,1* and is defined by the radii pair, $r_{b,1}$ and $r_{d,1}$. On the other hand, the first OLA during Broadcast 2 is denoted by by *OLA 1,2* and is the circular disk of radius $v_{d,1}$. Let $\widetilde{v}_{d,2}$ be the decoding range of *OLA 1,2* during Broadcast 2. The key idea is that $\widetilde{v}_{d,2}$ must be greater than $r_{b,2}$. In Figure 4(a), this inequality is satisfied, while in Figure 4(b), it is not. More generally, the network designer just needs to check that the decoding range, $\widetilde{v}_{d,k+1}$, of the k-th OLA in Broadcast 2 is always greater than $r_{b,k+1}$, for all k. Alternatively, we can compute the received power at $r_{b,k+1}$ and confirm that it is greater than the minimum.

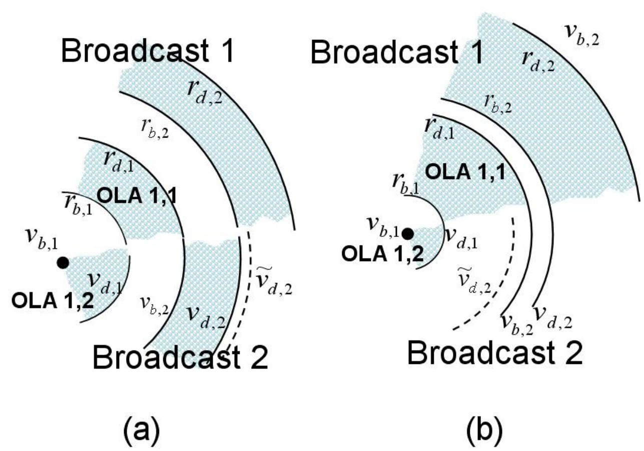


Figure 4: Illustration of the A-OLA-T Algorithm with (a) admissible $\mathcal{R}$, (b) inadmissible $\mathcal{R}$.

Intuitively, we observe that as $\mathcal{R}$ becomes very large, the OLAs during Broadcast 1 become larger and the OLAs of Broadcast 2 become relatively smaller, as shown in Fig. 4(b). As a result, the sets of nodes that did not transmit during Broadcast 1 (or the OLAs during Broadcast 2), eventually become so small that their decoding range (for *OLA 1,2*, this is indicated by the dashed line in Fig. 4(b)) cannot reach the next Broadcast 2 OLA to sustain propagation, i.e., $\widetilde{v}_{d,2} < v_{b,2}$. In other words, for a very high value of $\mathcal{R}$, the k-th OLA in Broadcast 2 may be so weak that no nodes between $v_{b,k+1}$ and $v_{d,k+1}$ can decode the signal. When this happens, OLA formations die off during Broadcast 2 and A-OLA-T fails to achieve network broadcast. Thus, it makes sense for $\mathcal{R}$ to have an upper bound.

For A-OLA-T with two alternating sets, for a fixed $\mathcal{K}$ and $\mathcal{R}$, in addition to satisfying inequality given by (7), satisfying the following upper bound, $\mathcal{R}_{\text{upper bound}}$, will guarantee successful network broadcast:

$$\mathcal{R} \le \underbrace{\frac{\mathcal{K}}{2} \ln \left\{ \exp\left(\frac{1}{\mathcal{K}}\right) + 1 + \sqrt{\left[\exp\left(\frac{1}{\mathcal{K}}\right) + 1\right]^2 - 4} \right\}}_{=:\mathcal{R}_{\text{upper bound}}}. \tag{14}$$

In [21], it has been shown that compared to Basic OLA, the 2-set A-OLA-T algorithm extends the network longevity for broadcast applications by 17% when both protocols operate in their minimum power configuration. It was observed that the ratio of the areas of adjacent OLAs (for example, the ratio of the area of the 4-th OLA of Broadcast 1 to the area of the 4-th OLA of Broadcast 2) approaches 1 as the OLA index approaches infinity, i.e $k \to \infty$. We show this in Figure 5, which is a plot of the ratio of adjacent OLA widths. We observe that after 9-10 levels, the ratio of the areas $\to 1$, i.e., at the minimum $\mathcal{K}$ for the two-set A-OLA-T, the ratio of adjacent OLA areas is approximately 1.

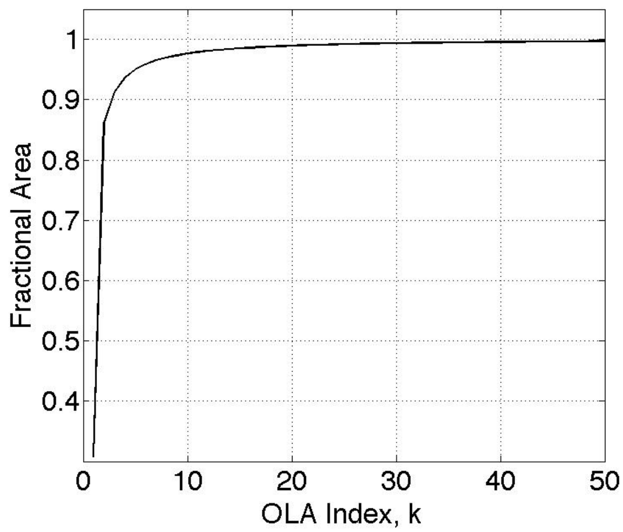


Figure 5: Ratio of Areas Versus OLA Index, k. Convergence of the ratio of areas to 1 implies that the widths of adjacent OLAs from Broadcast 1 and 2 become equal..

In other words, the respective accumulated areas of the two sets of OLAs are asymptotically equal. We call this the 'Equal Area Property.' Let us define the 'Fractional Area' to be

$$\tilde{\Psi} = \frac{\sum_{k=1}^{L} \left(r_{d,k}^2 - r_{b,k}^2 \right)}{r_{d,L}^2}, \tag{15}$$

where $r_{d,k}$ and $r_{b,k}$ denote the outer and inner boundary radii, respectively, for the k-th OLA ring formed during the Broadcast 1, and L is the number of OLAs in the OLA-T network. In [21], it was shown that for the $m = 2$ case, $\tilde{\Psi} = 1/2$ when operating in its minimum power configuration.

Assuming that the validity of the Equal Area Property for the $m > 2$ case would imply that $\tilde{\Psi} = \frac{1}{m}$ for all broadcast sets, when the system is in its lowest energy configuration. In [29], this assumption was verified numerically, and A-OLA-T with m sets, $m >> 1$ was shown to extend the network life by a maximum of 44% relative to the Basic OLA when both protocols operate in their minimum energy configuration. In fact, it can be proved that $\mathcal{K} \approx \frac{2m^2}{2m-1}$ to the second order, and $\mathcal{K} \to m$ as $m \to \infty$.

3.2.1 *Operating-Points for the OLA Broadcast Protocols*

We observe that our extensions of Basic OLA offer advantages of transmit energy-efficiency and network longevity relative to Basic OLA, but they come with a price. The introduction of additional system parameters increases the implementation/hardware complexity and power requirements compared to Basic OLA. In this section, we compare the different operating-points (such as $\mathcal{K}$ and $\mathcal{R}$) for these OLA broadcast protocols.

First, we compare the dependence of Basic OLA, OLA-T and A-OLA-T on the Relative Transmission Threshold, $\mathcal{R}$ for a fixed admissible node degree, $\mathcal{K}$. Table 1 compares the ranges of the $\mathcal{R}$, for the OLA-based protocols that guarantee successful network broadcast for a fixed $\mathcal{K}$. Since Basic OLA does not use any Transmission Threshold, $\mathcal{R} = \infty$. While $\mathcal{R}$ for OLA-T is lower-bounded, for A-OLA-T, there are lower and upper bounds on $\mathcal{R}$ for guaranteed broadcast success. Small "operating windows" of $\mathcal{R}$ may not be very desirable because of limited precision in the estimate of the SNR.

Table 1: $\mathcal{R}$ for Basic OLA, OLA-T, and A-OLA-T with two alternating sets, at a fixed $\mathcal{K}$.

Protocol	$\mathcal{R}$
Basic OLA	∞
OLA-T	$\mathcal{R}_{\text{lower bound}} \leq \mathcal{R}$
A-OLA-T with 2 alternating sets	$\mathcal{R}_{\text{lower bound}} \leq \mathcal{R} \leq \mathcal{R}_{\text{upper bound}}$

Table 2: The minimum node degree, $\mathcal{K}_{\text{min}}$ for Basic OLA, OLA-T and A-OLA-T at $\mathcal{R} = 2.5$ dB.

Protocol	$\mathcal{K}_{\text{min}}$
Basic OLA	1.4
OLA-T	2.1
A-OLA-T with 2 alternating sets	2.5
A-OLA-T with 5 alternating sets	5.5
A-OLA-T with 10 alternating sets	10.5
A-OLA-T with 100 alternating sets	100.5

Table 2 quantifies the minimum node degree, $\mathcal{K}$ for Basic OLA, OLA-T and A-OLA-T, for $\mathcal{R} = 2.5$ dB. We observe that as the number of sets of the broadcast protocol increases, the maximum $\mathcal{K}$ required to ensure successful broadcast increases. Among these three protocols, Basic OLA has the lowest node degree (can achieve successful broadcast with fewer nodes), and A-OLA-T has the highest node degree. Another way to interpret this trend is as follows. If we assume the same received power criterion (the decoding threshold, τ_d) for all the protocols, then this implies that the minimum $\overline{P_r}$ for the nodes in the network is highest for A-OLA-T and the lowest for Basic OLA. This is because fewer nodes participate during each broadcast cycle, these"border nodes" use at a slightly higher P_r to ensure the OLA formations don't die down. Among the different versions of A-OLA-T, it is observed that as the number of alternating sets, m, increases, the node degree increases. As m increases, the set of cooperating nodes becomes smaller which makes the OLAs thinner, which in turn, increases the $\overline{P_r}$ for the network.

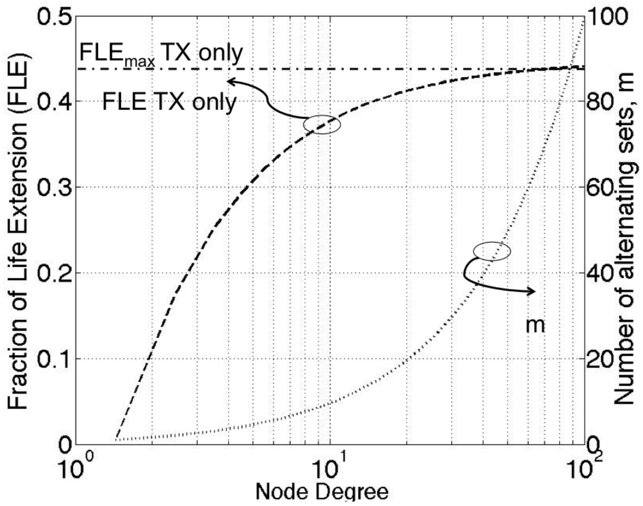


Figure 6: Relationship between the Fraction of Life Extension (FLE), number of alternating sets (m), and node degree, $\mathcal{K}$

Figure 6 aids in understanding the relationship between the Fraction of Life Extension (FLE) by A-OLA-T relative to Basic OLA, number of alternating sets (m), and node degree, $\mathcal{K}$. The two y-axes in Figure 6 are FLE (on the left) and m (on the right) and the x-axis is $\mathcal{K}$ on a logarithmic scale. The dashed curve is a plot of the FLE versus $\mathcal{K}$. We observe that as $\mathcal{K}$ increases, the FLE increases, and for a large value of $\mathcal{K}$, FLE approaches its asymptotic value (indicated by the dash-dot line) of about 0.44. Figure 6 shows that as m increases, FLE increases, but the node degree also increases. The dotted curve is a plot of m versus $\mathcal{K}$, and is also monotonically increasing function. As an example, for 40 alternating sets (i.e $m = 40$), the average number of nodes in the decoding range of a transmitter is ≈ 40, i.e. $\mathcal{K} = 40$, and the FLE $\approx 42\%$, very close to its asymptotic maximum value.

4 OLA CONCENTRIC ROUTING ALGORITHM (OLACRA)

We turn now from broadcasting to upstream routing. Our idea for upstream routing is to use the concentric rings produced by an OLA-based broadcast to guide the formation of the upstream OLAs. We call the basic approach the OLA Concentric Routing Algorithm (OLACRA) [25]. OLACRA has two phases. In the first phase, the Sink initializes the network with a broadcast using OLA-T or Basic OLA [4], [20], except there is a small change in the waveforms to indicate which levels are relaying. The Sink transmits waveform W_1 with power P_s. "Downstream Level 1" or DL_1 nodes are those that can decode and forward the Sink-transmitted message. Only the nodes in DL_1 whose received power is less than τ_b form the downlink OLA O_{D1}. The O_{D1} nodes transmit a waveform, denoted by W_2, which carries the original message, but the waveform can be distinguished from the source transmission, for example, by using a different preamble, spreading code or center frequency. This difference enables nodes that can decode the W_2 waveform and which have not relayed this message before, to know that they are members of a new decoding level, DL_2.

A node with received SNR less than τ_b forms the second OLA, O_{D2}, and relays using a different waveform W_3. This continues until each node is indexed with a particular level. The levels form concentric rings as shown in Figure 7(a). A feature shared by Basic OLA and OLA-T algorithms is that the distance between outer boundaries of consecutive downstream OLAs, also called the "step size" [4], grows with the downstream OLA index. For example, the step-size of DL_4 is shown in Figure 7(a). In other words, the rings that are farther from the Sink are thicker. This growth of the step-size can be controlled in OLA-T, but in Basic OLA the growth is dramatic.

The second phase of OLACRA is upstream communication. For upstream communication, a source node in DL_{n-1} transmits using waveform W_n. Any node that can decode and forward at W_n will repeat at W_{n-1} if it is identified with DL_{n-1} and if it has not repeated the message before. Downstream OLA boundaries formed in the initialization phase are shown by the dotted circles in Figure 7(a). Upstream OLAs formed are illustrated by the solid boundaries in Figure 7(b). Since each upstream OLA is associated with just one downstream level, OLACRA as defined above, is also referred to as *Single-Level* OLACRA to differentiate it from the other multi-level ganging variations discussed later. We shall refer to the n-th upstream OLA as UL_n, where UL_1 contains the source transmitter. In Figure 7(b) for example, UL_1 is indicated by the solid circle and UL_4 contains the Sink. For OLACRA, the *forward boundary* of UL_n divides the nodes of UL_n from those that are eligible to be in UL_{n+1} . For a given message, to ensure that OLA propagation goes upstream or downstream as desired, but not both, a preamble bit is required. As in OLA-T, transmit energy can be saved in OLACRA if the transmission threshold criterion is applied (that is only the nodes near the upstream forward boundary are allowed to transmit). In this case O_{U_k} and UL_k denotes the transmitting set and decoding sets respectively for the k-th upstream level. We call this variant as OLACRA-T. O_{U_k} and UL_k are the same in OLACRA without transmission threshold as shown in Figure 7(b).

A simulation example in Figure 8 illustrates OLACRA when the upstream source node is in DL_5. To indicate the level membership in this figure, downlink level nodes are shown using dots with contrasting shades (magenta dots for even indices and yellow dots for odd indices in the figure) and the upstream nodes are denoted using darker shades (blue dots in the Figure). This simulation plot is only for illustration purposes; the performance of OLACRA and its variants will be evaluated in Section 6.1.

We acknowledge that we are assuming only one flow at a time. Some applications, such as structural health monitoring in civil engineering, may be amenable to single flows, since the sensor reports may not be frequent, and the reporting schedule may be deterministic. As we mentioned earlier, there is no contention between the signals that are emitted from an OLA (because they are treated like multipath), so no Medium Access Control (MAC) is needed for a single flow. Because of this, a flow is expected to have a short delay [4]. If the flow schedule is not deterministic, a MAC will be needed to support multiple flows. For example, in OLACRA, two upstream flows that are initiated in the same DL at the same time on opposite sides of the network, will collide at some DL

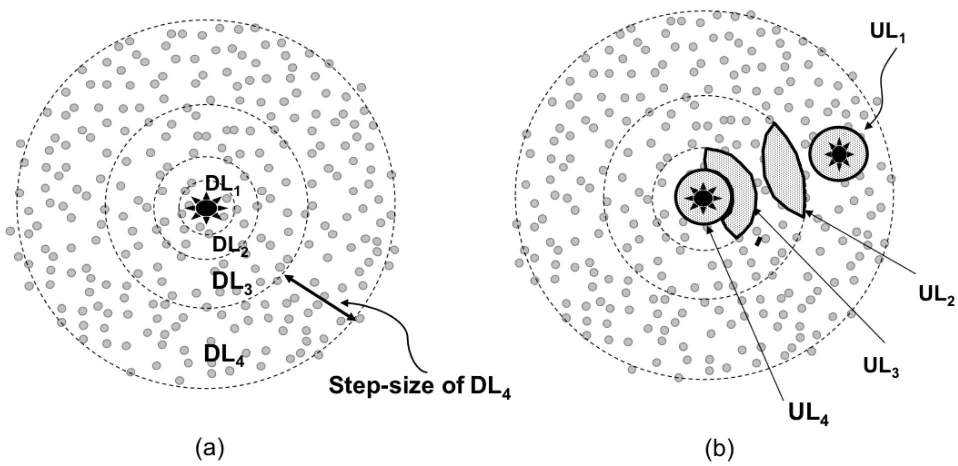


Figure 7: Illustration of OLACRA. (a) Phase 1 (b) and Upstream phase.

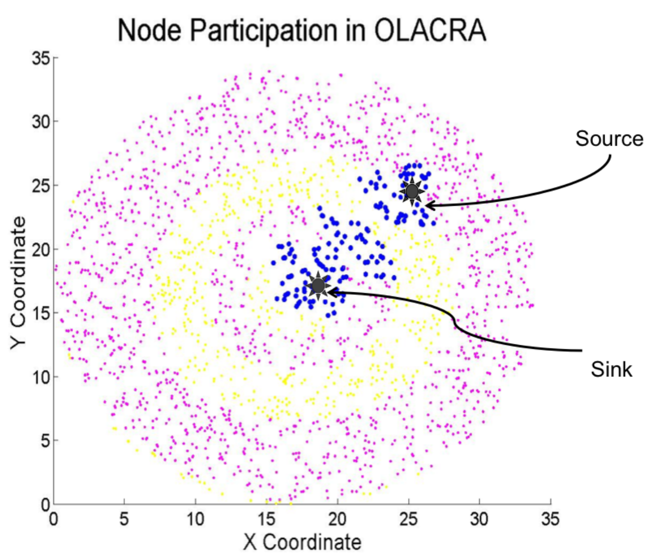


Figure 8: Simulation Example of Node participation in "single level" OLACRA.

closer to the Sink. For WSNs with a single Gateway or Sink Node, a simple but inefficient MAC would be a CSMA/CA protocol, where the Sink Node behaves similarly to an Access Point in an 802.11 network and the source of a flow is treated like a 802.11 user [34].

4.1 Improving the Upstream Connectivity of OLACRA

If the upstream source node is located far away from the Sink, and also far away from the forward boundary of UL_1, then the decoding range of the upstream source node may be too short and UL_2 may not form. This can happen for OLACRA transmission when the source node is many, e.g. 7, steps, steps away from the Sink, because downlink of levels of higher index are thicker as mentioned earlier. This causes the Packet Delivery Ratio (PDR) to fall, and motivates the need to explore new methods to improve the upstream connectivity/reliability of OLACRA. We are interested in methods that enhance the upstream connectivity and conserve transmit energy. Some of the solutions we considered are as follows.

4.1.1 *Ganging of Levels in the Upstream*

Ganging of levels can be done in the upstream to increase the number of nodes participating in the upstream and hence increase the PDR. We consider two types of ganging: Dual Level and Triple Level. When a node in DL_{n-1} transmits using W_n, any node that can decode and forward at W_n will repeat at W_{n-1}, if it has not repeated the message before and if it is identified with (1) DL_n or DL_{n-1} for Dual Level Ganging and (2) DL_n, DL_{n-1} or DL_{n-2} for Triple Level Ganging. As we will show in Section 6.1, Single-Level OLACRA is effective when combined with techniques explored below, and hence we use Single-Level OLACRA as the nominal configuration for all our simulations/protocol variations.

4.1.2 *Increase the Power of the Source Node for the Upstream Transmission*

While effective, the simple approach of just having the upstream source node transmit with a higher power is not practical because any node could be a source, therefore all nodes would require the expensive capability of higher power transmission.

4.1.3 *OLA or OLA-T Broadcast in Just the First Upstream Level*

The objective with this approach is to recruit more nodes in DL_n by allowing a few broadcast levels to "inflate" the OLA. This is achieved by allowing all nodes in DL_n that can decode a message to forward the message if they have not forwarded that message before until an OLA meets the upstream forward boundary of DL_n. Then all nodes in DL_n that have decoded the upstream message will transmit at the same time as an "extended source." We consider the following variations of this: OLACRA-FT and OLACRA-VFT.

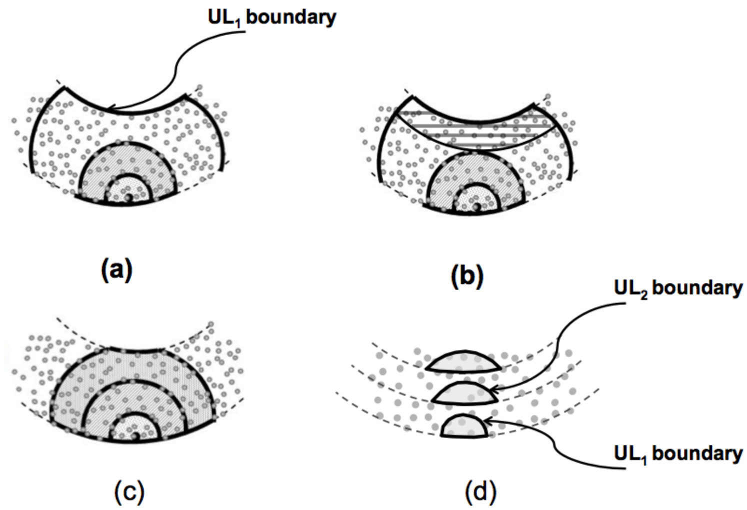


Figure 9: (a) UL_1 flooding; (b) Boundary nodes in extended source; (c) UL_1 flooding in OLACRA-VFT; (d) OLACRA-SC.

- *OLACRA-T with Limited Flooding (OLACRA-FT)*: The worst case number of broadcast OLAs required to meet the upstream forward boundary of DL_n can be known a priori as a function of the downstream level index. For example, in Figure 9(a), three upstream broadcast OLAs are needed to meet the upstream forward boundary of DL_n. The union of the upstream decoding nodes (e.g. all three shaded areas in Figure 9(a) in DL_n), are then considered the extended source. Next, the extended source behaves as if it were the first upstream level in an OLACRA upstream transmission; this means that all the nodes in the extended source repeat the message together, and this collective transmission uses the same waveform as would the first upstream OLA under the OLACRA protocol. In order for the nodes to know when it is time to transmit as an extended source, an OLA waveform distinction (example: different preamble bit), similar to the network initialization phase of OLACRA, must be used in this upstream flooding phase. To save transmit energy, the nodes in the extended source that transmitted in the downstream transmission could be commanded to not transmit in the extended source transmission; in other words, those nodes that were near the forward boundary in the downstream would be near the rear boundary in the upstream, and therefore will not make a significant contribution in forming the next upstream OLA. The OLA in this case is the hatched region in Figure 9(b).

- *OLACRA-FT with Variable Relay Power (OLACRA-VFT)*: Even though the extended source in OLACRA-FT gets to the reverse boundary of the downlink level containing the upstream source, the OLA width is very large, making it energy inefficient. This can be seen in Figure 9(a). In order to make this scheme more effective, we desire the smallest extended source that also gets to the downlink reverse boundary. In OLACRA-VFT, the transmit powers in these upstream flooding steps are reduced relative to OLACRA-FT, to reduce the size of the extended source, as shown in Figure 9(c). Transmit energy can be saved further by commanding the nodes that participated in the downlink OLA-T to not transmit as in OLACRA-FT. Instead of varying the relay power, we could also vary the upstream transmission threshold, τ_{bu}, or a combination of both to obtain similar results. While both methods, varying transmission threshold and varying relay power in the broadcast level, try to vary the size of the extended source, they achieve it in different ways. Reducing relay power increases the number of levels required to reach DL_{n-1}, thereby making more nodes transmit at a lower power. On the other hand, decreasing the transmission threshold decreases the number of nodes transmitting but the transmission is at a higher power. OLACRA-VFT has been simulated in this paper by optimizing the relay power of the upstream flood levels, P_{ru}. Note that the transmission threshold for the initial OLA flooding stages is fixed in this case and that only nodes in these flooding stages transmit using the optimized relay power, P_{ru}. The downstream OLA levels and OLACRA levels in upstream use relay power P_r as defined in earlier sections.

4.1.4 *OLACRA with Step-Size Control (OLACRA-SC)*

As will be shown in our results, OLACRA-FT and OLACRA-VFT have high reliability (high PDR), but their energy efficiency is very low as they make a large number of nodes participate in the transmission. So we consider another alternative to enhance upstream connectivity, while at the same time conserving transmit transmit energy. OLACRA-SC simply aims to reduce the downlink step-size, so that there are enough nodes in UL_2 to carry on the transmission. The downlink radii depend on the downlink transmission threshold and relay power [20]. Thus step-sizes in the downlink can be controlled by optimizing the transmission threshold or relay power on the downlink to have smaller downlink step-sizes. Unlike OLACRA-FT and OLACRA-VFT, the goal here is not to make the extended source larger, but to make UL_2 closer to the upstream source, as seen in Figure 9(d). To further increase the transmit energy savings, only the nodes that participated in the downlink OLA-T are allowed to relay the message in the upstream. This is in contrast to OLACRA-FT where transmit energy was saved in the extended source by commanding the nodes that did not relay in the downlink OLA-T to transmit in the upstream. Even though the scheme in OLACRA-FT is more efficient it is not possible in OLACRA-SC as there is a high probability that the nodes that relayed in OLA-T would not be taking part in the upstream OLACRA-SC transmission.

5 SURVIVABLE NETWORK DESIGN IN OLA-BASED NETWORKS

In the earlier sections our focus was transmit energy efficient protocols for OLA-based networks. In this section we explore another property of OLA-based networks, which is their ability to survive network partitions. We consider two kinds of network partitions in this work. The first kind of partition, which we call network hole, is caused by nodes depleting their energy reserves in a small area. In existing multi-hop routing strategies, a new route can be computed that goes around the network hole. However our scheme, in comparison, would consume less transmit energy per node. The second kind of partition, which we call the “Complete Partition,” separates the network into two parts, such that the gap cannot be spanned by a single-node transmission. In such cases, a multi-hop routing scheme will fail, unless the transmit power of the node is increased considerably. However, this is not an option in energy-constrained WSNs. In this section we explain our protocol that detects and also survives both the partitions discussed above. The proposed Survivable Network Protocol [26] has two phases, a Two Hop ACK scheme that detects the partition and an OLA Size Adaptation

Mechanism that implicitly triggers the creation of larger OLAs that straddle such holes during the forwarding process.

A single-hop ACK Scheme might not be sufficient to ensure the receipt of message by all the nodes in the subsequent hop/level for OLA-based networks as a ‘hop’ in an OLA network is no longer a single node but a collection of nodes. For example in Figure 10, suppose the upstream source is in DL_n and there is a hole in DL_{n-1}. All nodes in DL_n would still receive an ACK from the nodes, shown as black dots in the figure, in the DL_{n-1} forward boundary, but the message doesn’t get to the sink because of the network partition in DL_{n-1}. The Survivable Network Protocol is explained in the context of OLACRA-FT, but we note that our scheme is applicable to all the OLA-based schemes discussed above.

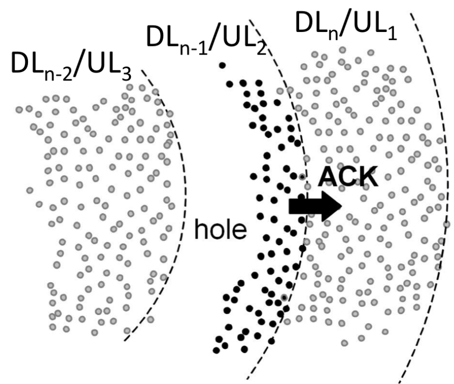


Figure 10: Single Hop ACK Scheme.

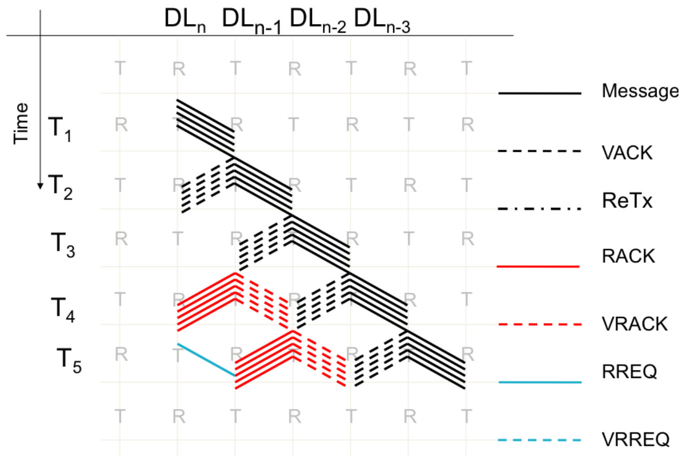
5.1 Protocol Description

The Survivable Network Protocol uses the following control messages:

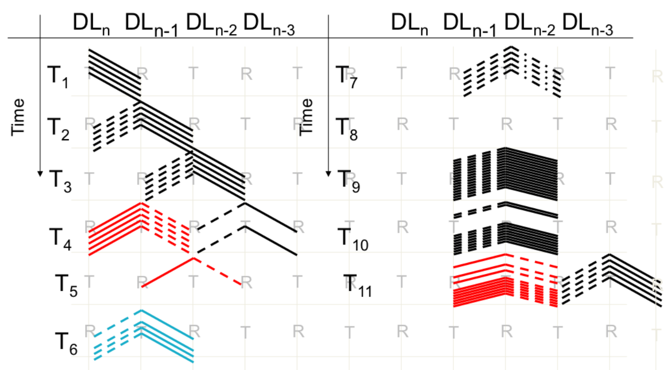
- VACK (Virtual ACK) is simply the OLA transmission that is decoded by nodes in the downstream direction because of omni-directional antennas, even though the signal is intended to travel upstream.
- RACK (Real ACK) is a very short message intended for the downstream direction. RACK is the ACK sent by nodes in DL_{n-1} to nodes in DL_n, which indicates that the nodes have decoded the VACK from DL_{n-2}.
- VRACK (Virtual RACK) is the RACK intended for DL_n, but heard by the nodes in DL_{n-2}.
- RREQ (Retransmission request): Nodes in DL_n that transmitted the original message but did not receive the RACK for it will transmit the short control message RREQ.
- ReTx: DL_{n-1} nodes that decoded the original message and RREQ transmit ReTx to recruit more nodes from the same level. ReTx includes the original data payload.

5.1.1 *Timing Diagrams*

Figure 11 shows the timing diagrams for our proposed Survivable Network Protocol. The vertical axis indicates time slots and the horizontal axis shows the downstream levels. For example, T_4 at DL_n in Figure 11(a) shows the activities of DL_n nodes in the fourth time interval. The different messages are color- and line-coded as shown in the legend. Figure 11(a) and (b) show operation without and with a partition respectively.



(a)



(b)

Figure 11: (a) Survivable Network Design (a) when there is no partition (b) when there is a partition in DL_{n-3}.

In Figure 11(a) at T_1, nodes in DL_n transmit the upstream message. Nodes in DL_{n-1} that can decode this transmission relay at T_2. Nodes in DL_n also decode this transmission and note the receipt of their VACK. Likewise when nodes in DL_{n-2} relay at T_3, nodes in DL_{n-1} will note the receipt of their VACK. DL_{n-1} nodes that can decode the VACK transmit the RACK at T_4. Therefore, a node in DL_n that decodes a RACK knows that the message was decoded by at least one node in DL_{n-2} and therefore the message must have made it past DL_{n-1}. However nodes in DL_n that do not decode the RACK transmit a RREQ at T_5.

Nodes in DL_{n-1} that hear RREQ from DL_n and RACK from DL_{n-2} simultaneously, ignore the RREQ and decode RACK, since RACK is a higher-level acknowledgement.

Figure 11(b) shows the case when there is a partition in front of DL_{n-2} and illustrates the *OLA Size Adaptation Mechanism*. Transmissions progress in the same way as in Figure 11(a) until T_3. At T_4 only a very few nodes in DL_{n-3} relay the message because of the partition, hence very few nodes in DL_{n-2} decode the VACK and transmit RACK. Therefore a large number of nodes in DL_{n-1} do not decode the RACK and will transmit RREQ at T_6. In this case, DL_{n-2} nodes receiving RREQ without a higher level RACK transmit ReTx at T_7 (they received this message back in T_2). It is necessary that nodes that do not have something to transmit be in the receiving mode even though the time-slot is labelled 'T' so that they hear the RREQ. ReTx transmission at T_7 is intended to recruit more nodes from the same level to relay the message so that the next OLA can be wide enough to go over the partition and thereby maintain connectivity. Then in T_9, all nodes in DL_{n-2} that ever decoded the original message transmit together as an enlarged OLA. We call this new larger OLA the 'extended level.' This OLA formation is similar to extended source formation in OLACRA-FT. However the goal here is to make the OLA wide enough so that its range is big enough to go over the partition. [4] showed that hop distance is proportional to the OLA width in a strip network. On the contrary, the goal in OLACRA-FT was to make the OLA big enough to reach the downlink boundary.

For the example considered for this timing diagram, the partition is restricted to a relatively small portion of DL_{n-3}, and hence a single ReTx transmission would form a wide-enough extended level. However if the partition is bigger, then the transmission might not cross over the partition, and nodes in DL_{n-2} will not hear the VACK at T_{10}. Therefore the DL_{n-2} nodes would have to do more ReTx transmissions iteratively to form an extended level of required width.

5.1.2 *Design for Orthogonal Preamble Decoding*

We note in Figure 11(a) that at T_4 DL_{n-1} nodes hear VACK from DL_{n-1} and VRACK from DL_n. If not carefully designed these two signals would collide and the nodes would not be able to decode the required signal, VACK in this case. *Orthogonal preamble encoding* can enable the retrieval of control information when a node experiences this kind of collision. We identify two types of collisions that can occur in the ACK scheme,

- Type 1 V-RACK and VACK for the same payload ID as seen in Figure 11(a) at T_4 in DL_{n-2}. VACK must be separately detected, regardless of the presence of V-RACK. Therefore V-RACK and VACK preambles are designed to be orthogonal.

- Type 2 RACK and RREQ for the same payload ID, as shown in Figure 11(a) at T_5, DL_{n-1}. Here RACK must be separately detected regardless of the presence of RREQ. Therefore, the RACK and RREQ symbols are designed to be orthogonal.

6 SIMULATION RESULTS

Closed form analytical results are difficult to obtain for the upstream using OLACRA and its variations because of the generally irregular shapes of the upstream OLAs. Hence Monte Carlo simulation is done to demonstrate the validity of and explore the properties of the OLACRA protocol. The simulator was developed using the C language and models the physical and network layers of the protocol stack; MAC is not needed as only a single flow is assumed in all our simulations. First we evaluate the benefits of different variations of OLACRA over the Deterministic Channel (with and without step-size control) and then over the Diversity Channel. Next we evaluate the performance of the Survivable Network Protocol followed by the benefits of OLA-based networks in terms of robustness to mobility and lower end-to-end delay.

In this section, the upstream protocol performances are evaluated using FES and PDR, which have been defined earlier. Since in this section we are considering finite node density, we modify the definition of FES for a single trial to be

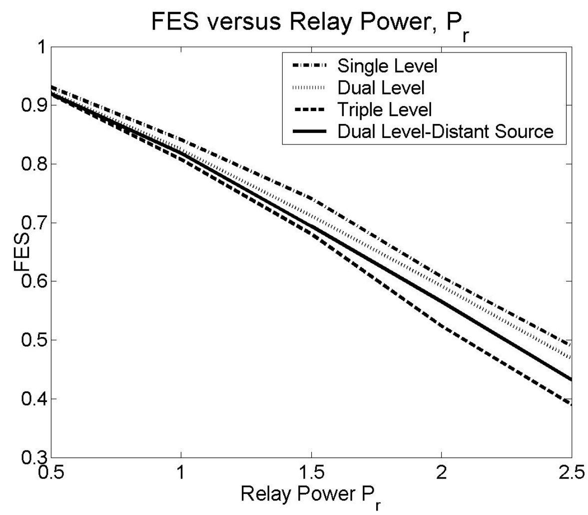
$$\text{FES} = 1 - \frac{\text{Number of nodes that transmit}}{\text{Number of nodes in the network}}. \tag{16}$$

An ensemble average over all the trials gives FES for the particular case considered. Our FES calculation only takes in to account only the transmit energy of nodes. However a more detailed energy evaluation, which considers a more realistic energy model, will be explored in a later paper. Similarly in order to find PDR for the unicast schemes (both OLA-based and multi-hop) we define a new function called 'connectivity function,' which is taken to be zero when there is no route between the source and destination and is one when there is a route between the source and destination. We obtain the ensemble average over all the Monte Carlo trials of the connectivity function at every time instant to obtain the PDR at the time instant. We note that this way of finding PDR is slightly different from the conventional definition of PDR, where a time average is found. However, this way of defining PDR reveals the dynamics of the system.

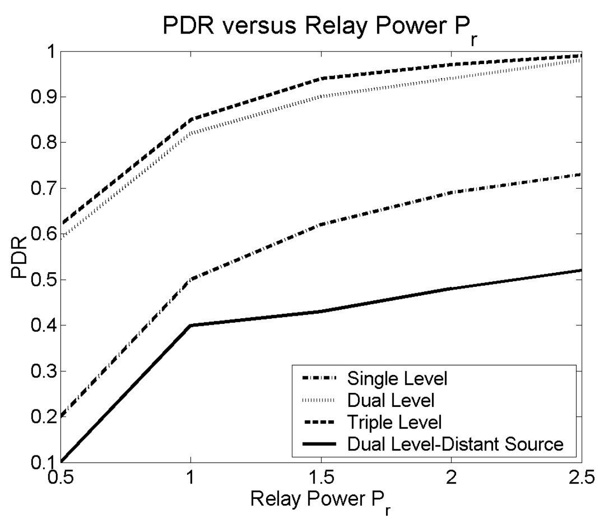
6.1 Transmit Energy Efficiency Evaluation Over Deterministic Channels Without Step-Size Control

Each Monte Carlo trial has static nodes randomly distributed in a circular area of radius 17 with the Sink located at the center. For all the results in this section, $\tau_d = 1$ and 400 Monte Carlo trials are performed. The downstream levels are established using OLA-T with source power $P_s = 3$ and relay power $P_r = 0.5$.

For these simulations, $\rho = 2.2$. $\mathcal{R} = 3$ dB and 0.41 dB are used for the downstream. Figures 12(a) and (b) compare different versions of OLACRA in terms of FES and PDR versus relay power. The upstream source node is located at a radius of 15 for the Dual-Level Distant Source (DLDS) and at a radius of 5 for the other cases. These two radii are considered to show the variations of FES and PDR with distance from the Sink. We observe that the Single Level case has the highest FES for all values of relay power; however the PDR is very low. The Dual Level and Triple Level cases have higher PDRs, with only a small degradation of FES relative to Single Level. Though the FES value



(a)



(b)

Figure 12: (a) FES and (b) PDR versus Relay power for different variants of OLACRA.

of Dual Level when the source is close to the Sink (radius 5) was comparable to Dual-Level Distant Source (DLDS) case, the PDR is very low for DLDS. The reason is that the distant source is in a downstream level so thick that the dual level upstream ganging is not enough to reach the upstream forward boundary.

Figures 13(a) and (b) compare the performances of the different variants of OLACRA in terms of their FES and PDR versus $\mathcal{R}$ (RTT in the figure) in dB. The upstream source node is located at a radius of 15. We assume $\overline{P_r} = 2.2$ for upstream routing. The relay power for the broadcast stage in OLACRA-VFT $P_{bu} = 0.6$. OLACRA-T with $P_s = 1$ has the highest FES of about 0.87 at $\mathcal{R} = 1.76$ dB (the left-most value); however the PDR at this $\mathcal{R}$ is very low = 0.12. The FES of OLACRA-FT is only slightly lower than OLACRA-T with $P_s = 1$, but the PDR for this case is much higher. A further improvement in FES of OLACRA-FT is obtained with OLACRA-VFT. We also see that OLACRA-T with a source power of 6 performs similarly to OLACRA-FT, which shows that the upstream source power requirement will be very high to achieve similar performance.

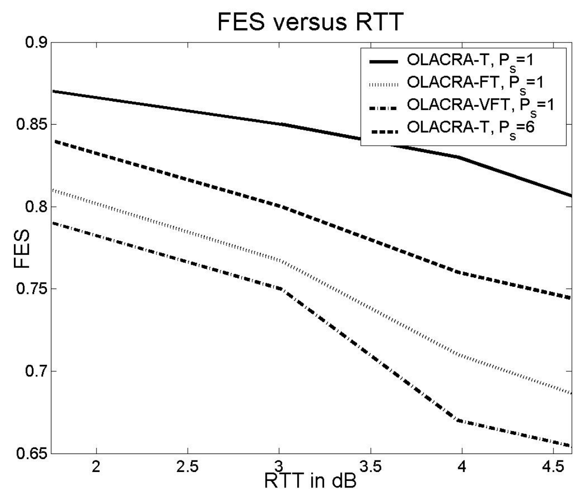
6.2 Transmit Energy Efficiency Evaluation over Deterministic Channels With Step-Size Control (OLACRA-SC)

For results in this section, a much higher density of 10 is considered. Downlink levels are established at $\overline{P_r} = 1.1$. As described in [20], the radius of a level depends on the $\mathcal{R}$ value and hence downlink step-sizes can be controlled by varying $\mathcal{R}$. For results in this section the $\mathcal{R}$ values in the downlink are the continuum-predicted $\mathcal{R}$ values that give fixed step-sizes [20]. Upstream $\overline{P_r} = 1.1$. Two step-sizes are considered: $0.8r_{d,1}$ and $r_{d,1}$, where $r_{d,1}$ denotes the first downlink radius.

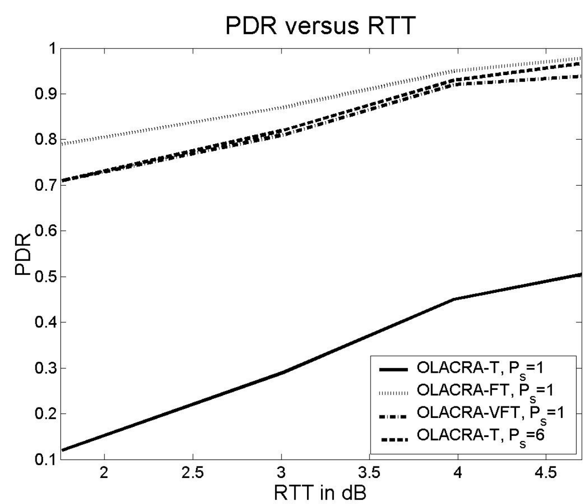
Figures 14(a) and (b) compare the FES and PDR performances of $0.8r_{d,1}$ and $r_{d,1}$. The $0.8r_{d,1}$ has a very high FES of 0.928 at a $\mathcal{R}$ of 1.76 dB, however the PDR at this $\mathcal{R}$ is very low. This is because of the low value of $\mathcal{R}$. A lower value of $\mathcal{R}$ suppresses a large number of nodes thereby reducing the PDR. This effect is more pronounced in the fixed step size case compared to the general OLACRA, because the small step-size alone prevents a large number of nodes from participating. Use of $\mathcal{R}$ removes a substantial amount of nodes from a set that already did not have many nodes to begin with. As $\mathcal{R}$ is increased to 4.5 dB, the PDR improves to about 0.927. Compared to the $0.8r_{d,1}$ case, the $r_{d,1}$ case has a lower FES and a higher PDR. But even the FES for the $r_{d,1}$ case is much higher than the FES observed for a general OLACRA or OLACRA-FT.

6.3 Transmit Energy Efficiency Evaluation over Diversity Channels

Our results so far have considered networks where transmissions occur on orthogonal and non-faded Deterministic channels. In this section we extend our simulations to the Diversity Channel model where transmissions are on a reduced number of orthogonal Rayleigh faded channels. The relays transmit Direct Sequence Spread Spectrum (DSSS) signals. To ensure mth order diversity gain we let each relay delay its transmission by a random 'artificial' delay selected from a pool of artificial delays $\{0, T_c, 2T_c, \ldots, (m-1)T_c\}$, where T_c is the chip time of the DSSS signal [22], [23]. To extract this diversity at the receiver, every node has a RAKE receiver with m fingers. Assuming maximal ratio combining, the total received power at each node is taken to be the sum of the received

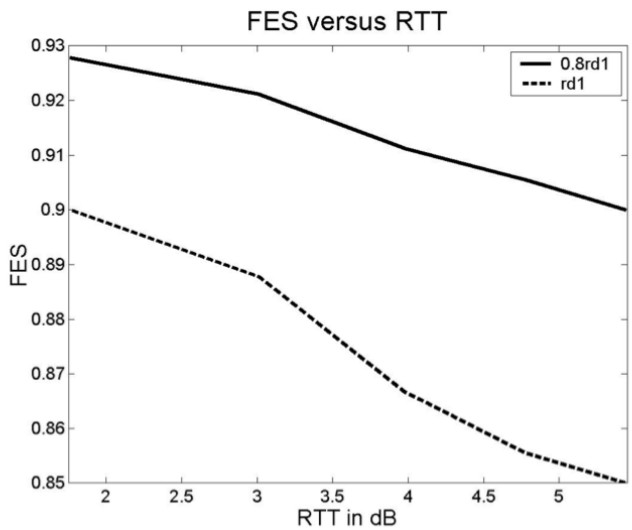


(a)

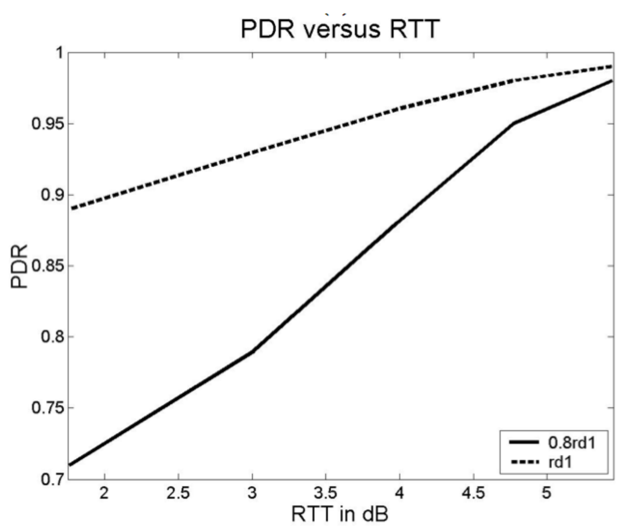


(b)

Figure 13: (a) FES and (b) PDR versus RTT, $\mathcal{R}$, for different variants of OLACRA.



(a)



(b)

Figure 14: (a) FES and (b) PDR versus RTT, $\mathcal{R}$, for OLACRA-SC.

powers at each of its RAKE fingers. To model Rayleigh fading, the received power at a RAKE finger is modeled as an exponential random variable with mean equal to the average power received at that finger. We make the ideal assumption that the average power at the k-th finger is the sum of average powers of all the signals that arrive at that node within the k-th "delay bin," which means their excess delay times t_r are such that $(k-1)T_c \leq t_r \leq kT_c$.

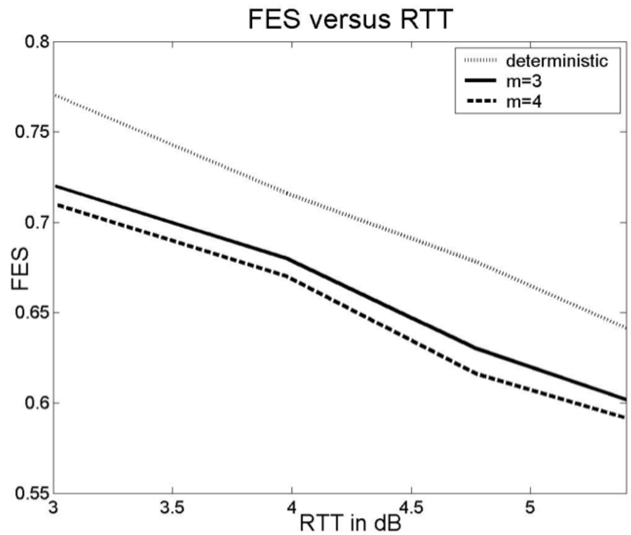
Each trial has 2000 static nodes randomly distributed in the circular field of radius 17 giving $\rho = 2.2$. The downstream levels are established using OLA-T with source power $P_s = 3$, $\overline{P_r} = 1.1$ and $\mathcal{R} = 4$. For upstream routing using OLACRA, the source node is located at a radius 13 with $P_s = 1$. A decoding threshold of 1 is chosen for the downlink and the uplink transmissions. $\overline{P_r}$ of 2.2 was used for the upstream levels. T_c was taken to be 500 time units.

Figure 15(a) compares the FES under OLACRA under the deterministic channel model and diversity channel model, for different values of $\mathcal{R}$, while Figure 15(b) shows the PDR, also versus $\mathcal{R}$. We observe that for $m = 3$ (third order diversity) FES is 0.72 at $\mathcal{R} = 3$ dB, whereas the FES for the deterministic case for the same value of $\mathcal{R}$ is 0.77. Similarly the probability of message delivery at the Sink is only 0.77 or the $m = 3$ case at $\mathcal{R} = 3$ dB, whereas the probability of success for the deterministic case is higher at 0.82 for the same $\mathcal{R}$. But when the diversity order was 4 ($m = 4$), the performance characteristics of the fading channel gets closer to the deterministic case. For $m = 4$ the probability was about 0.94 for an $\mathcal{R} = 4.7$ dB, when the deterministic case had a probability of 0.97. It should also be noted that the FES performance of the $m = 4$ case was not very different from the $m = 3$ case, meaning that the higher probability of message reception obtained by having an additional RAKE finger was not at the cost of transmit energy.

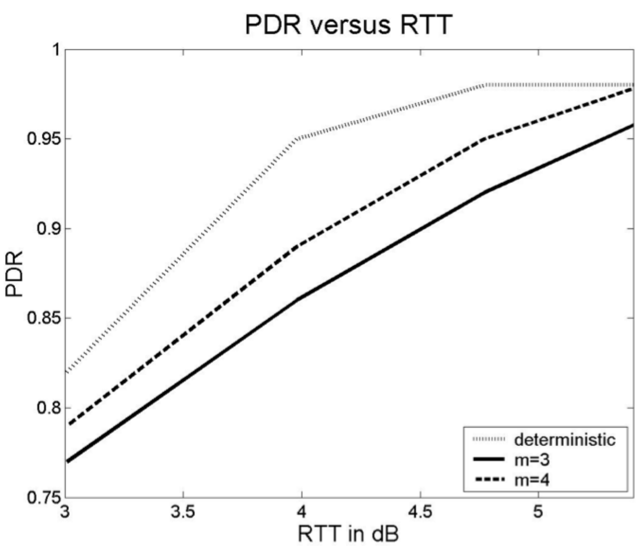
6.4 Survivability Results for OLACRA

In this section, we demonstrate the benefits of our proposed "Network Survivability Protocol" in disconnected networks where partitions have occurred either due to nodes depleting their energy or natural obstacles in the network. We assume the deterministic channel. Each Monte Carlo trial has nodes randomly distributed in a square field of dimensions 34 x 34 units with the Sink located at the center. The nodes are assumed to be static. For all results in this section, $\tau_d = 1$ and 400 Monte Carlo trials are performed. The downstream levels are established using OLA-T with source power $P_s = 2$ and relay power $P_r = 0.5$.

The upstream source node is located at a radius of 19 and a relay power of 1 is used for the upstream transmission. The multi-hop transmission is however assumed to be at a higher power of 2. The multi-hop route is chosen to be the route having the minimum number of hops between the Source and Destination, which is the case in popular multi-hop routing schemes like DSR [30]. We consider a Complete Partition as shown in Figure 16 that cuts through the network and divides it in two. As a part of our simulation we let the partition height, Y (as shown in Figure 17) be 0, 5, 10 or 15 units. Figure 17, shows the variation of the Packet Delivery Ratio (PDR) with the partition height for 3 cases. The first case that we consider is the multi-hop routing scheme. The other two cases,"early partition" and "late partition," have been considered to show two different kinds of partitions. In early partition we assume that the partition already existed in the network before the nodes were deployed, which will be the case if the partition is due to a natural obstacle



(a)



(b)

Figure 15: (a) FES and (b) PDR versus RTT, $\mathcal{R}$, for Diversity Channel Model.

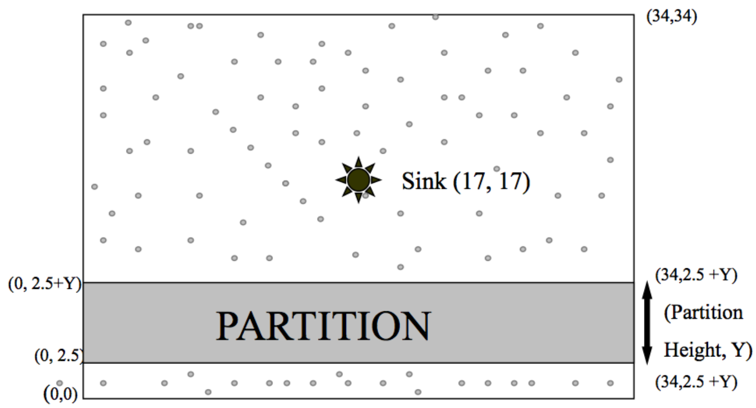


Figure 16: Illustration of the Network Partition. The shaded area denotes the partition where no nodes are present.

like a wall. In the other case, late partition, the assumption is that the partition is created sometime after the nodes are deployed and initialization of OLACRA has been carried out. This will be the case if the partition is caused due to nodes depleting their energy. We can see that the scheme fails to maintain connectivity even at partition heights of around 3 units. For the late partition case, we get a high PDR of close to 1 even at a height of 15 units. However for the late partition case the PDR begins to fail around 10 units. This is because the partition is so big that downlink levels fail to form in OLA-partition case. It also means that if the downlink levels have been created by the initialization phase, our size-adaptation mechanism is intelligent enough to overcome partitions of very large dimensions.

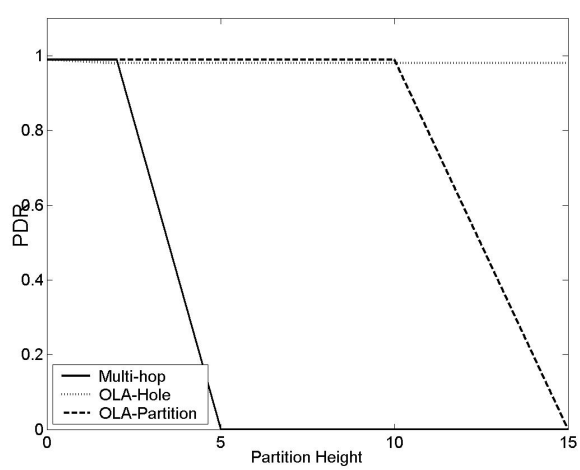


Figure 17: PDR versus Partition-height for OLACRA-FT.

6.5 Mobility Results for OLACRA

The focus in the earlier sections was to show energy-efficiency of OLA-based protocols in static networks, which is the usual scenario in WSNs. In this section, we analyze the performance of OLA-based protocols in Mobile Ad Hoc Networks (MANETs). The OLA-T protocol has no memory, and therefore its performance is insensitive to mobility. In other words, each time a node receives a broadcast, it tests its SNR against the threshold to decide if it should relay; with mobility, generally, different sets of nodes will relay in each broadcast. On the other hand, for OLACRA upstream routing, nodes must remember their level from the last initialization, so in MANETs, OLACRA performance will degrade over time, until the network is re-initialialized. Therefore, this section focuses only on upstream routing.

In MANETs, the nodes are not as energy constrained as in wireless sensor networks, hence the focus here is have a route that is robust to mobility, thereby avoiding the overheads and the associated delays involved in route discoveries and route refreshes. OLA-based schemes are expected to be more robust to mobility compared to multihop schemes, because OLA nodes form clusters that are spread over a significant, usually contiguous area. Therefore if nodes move randomly, there is a good chance that over short periods of time, any given node remains within its original OLA boundary. Even though some participating nodes may stray outside of their original OLA boundary, the OLA performance, for example in terms of decoding range, should not change dramatically over a short period of time. In contrast, a non-CT multi-hop route is more sensitive to mobility because the route is based on a specific sequence of nodes and the transmit powers depend on the distances between the consecutive nodes in the sequence. If any of the links break, then the route must be recomputed. OLA robustness to mobility was suggested in [4], however, to the best knowledge of the authors, the first and only attempts to quantify the benefits of an OLA-based scheme compared to a multi-hop scheme in a mobility scenario were done in previous work by the authors in [25], [27].

The nodes are distributed in a circular field of radius 17 m with Sink located at the center. The upstream source node is located at a radius of 7 m. A receiver sensitivity of -90 dBm is considered and the deterministic channel model is assumed. The Random Way Point Mobility model [28] is assumed and every node chooses its speed randomly from the interval 0-5 meters/s and a pause time of zero is assumed.

Figure 18 shows the mobility results for upstream routing. Results are obtained for both the stationary and the mobile upstream source nodes. The relays transmit at a power of -30 dBm for multi-hop routing and at -40 dBm for OLACRA. The Sink is assumed to be stationary. The PDR curve for OLACRA gradually degrades with time, whereas the PDR curve for DSR routing schemes has a saw tooth shape with diminishing peaks. The peaks of the saw-tooth correspond to route re-initializations and the troughs correspond to the time with least connectivity. As the time from the first initialization grows, the route initialization times vary greatly with trials, which is the reason for diminishing peaks and troughs. Even with a lower transmit power (which means higher network lifetime) it is observed that OLACRA requires fewer network initializations and is much more robust to mobility of nodes. Even after 6 seconds, the PDR for OLACRA with a mobile source is still about 0.8, whereas in DSR the third route discovery is about to be carried out. It is also observed that the PDR of OLACRA degrades with mobility of the upstream source. This is because an upstream source node might move to a different level where the nodes will not relay the message due to the

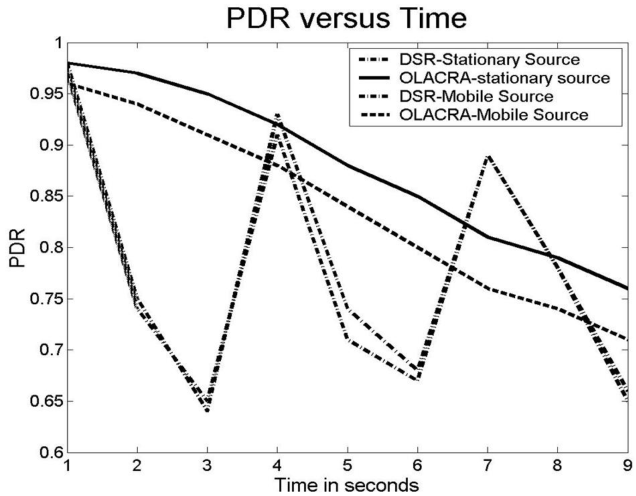


Figure 18: PDR versus time, for the mobility scenario.

Table 3: Variation of Relative Latency (RL) for different power levels for AODV and OLA-AODV.

P_t (AODV) (dBm)	P_t (OLA-AODV) Static SRC-DEST (dBm)	RL
-30	-40	0.806
-20	-30	0.917

protocol limitation.

6.6 End-to-End Delay Results for OLACRA

OLA transmission is expected to have a lower latency (lower end-to-end delay) for an isolated flow (i.e, a flow that doesnt interfere with another flow) because OLA hops are longer than single transmitter hops, due to array and diversity gains. This benefit was suggested in [18], however the benefits were not demonstrated. To quantify these benefits, we define a new performance metric called Relative Latency, which is defined as the ratio of end-to-end delay for the OLA-transmission to the end-to-end delay of a multi-hop transmission. In Table 3 we show the variation of Relative Latency (RL) for different power levels. We can see that even though the OLACRA uses a lower transmit power it requires less time to reach the Destination Node. We also observe that as the nodes start transmitting at higher relay powers, the end-to-end delay benefit of the OLA-based scheme decreases in comparison with the multi-hop scheme.

7 CONCLUSIONS

The OLA-based protocols presented in this paper, because of their energy efficiency, scalability and simplicity, may be useful for the wireless sensor networking applications of the future that will be characterized by a large number of energy-constrained nodes with a high node degree. The transmission threshold has shown to be a valuable "knob" to control the shape and direction of routes. The OLA-based protocols have many attractive features. We have shown how cooperative routes can be formed, without the need for an existing multi-hop route or explicit node location information, through simple decisions that nodes make on their own. OLA-based routing involves only communication between node clusters or from a source to a cluster – there are no communications between just one pair of nodes, so there is no need for individual node addressing. As long as the node degree is high enough to support OLA transmission, the complexity of the OLA-based protocols will be *constant* with respect to increasing node density. Finally, OLA-based protocols are robust against mobility, have low latency, and can overcome network partitions that block non-cooperative multi-hop routing schemes. However, there are many important issues remaining to be addressed, such as the requirements for synchronization, the effects of fading and imperfect SNR estimation on OLA-T, and how best to manage multiple OLA data streams.

Acknowledgment

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