Ad Hoc Networks 9 (2011) 1140–1153

Contents lists available at ScienceDirect

Ad Hoc Networks

journal homepage: www.elsevier.com/locate/adhoc

Opportunistic large array concentric routing algorithm (OLACRA) for upstream routing in wireless sensor networks

Lakshmi V. Thanayankizil [a,*], Aravind Kailas [b], Mary Ann Ingram [a]

[a] School of Electrical and Computer Engineering, Georgia Institute of Technology, Atlanta, GA 30332, United States
[b] Dept. of Electrical and Computer Engineering, University of North Carolina Charlotte, Charlotte, NC 28223, United States

ARTICLE INFO

Article history:
Received 24 June 2010
Received in revised form 25 November 2010
Accepted 31 December 2010
Available online 8 January 2011

Keywords:
Cooperative transmission
Opportunistic large arrays
Routing
Wireless sensor networks

ABSTRACT

An opportunistic large array (OLA) is a form of cooperative diversity in which a large group of relays or forwarding nodes operate without any mutual coordination, but naturally fire together in response to energy received from a single source or another OLA. When used for broadcast, OLAs form concentric rings around the source, and have been shown to use less transmit energy than conventional multi-hop protocols during broadcasting. The OLA concentric routing algorithm (OLACRA) and its variants, the main contributions of this paper, leverage the concentric ring structure of the OLAs during the initialization phase to limit the node participation on the upstream connection. For the simulation scenarios considered in this paper, OLACRA is shown to save over 80% of the transmit energy relative to other OLA-based schemes. This paper analyzes the performance of OLACRA over 'deterministic channels' or non-faded orthogonal channels and on 'diversity' or Rayleigh flat-fading channels with limited orthogonality. Enhancements to OLACRA to further improve its energy efficiency by limited broadcasting in the initial upstream level and limiting the downlink 'step-sizes' are also considered. A simple contention avoidance scheme for WSNs with multiple flows is also proposed. In addition to this, the robustness of OLACRA over mobile channels is also studied. The protocols are tested using Monte Carlo evaluation.

1. Introduction

Wireless sensor networks (WSNs) are typically assumed to consist of a large number of resource-constrained nodes that are densely and randomly deployed on the fly for unattended operation. Because typical wireless nodes are powered by batteries, one of the main design issues for a WSN, i.e., preserving the limited joules on the energy storage devices, has resulted in a number of energy-efficient routing schemes and transmission algorithms [1]. This paper presents a simple energy-efficient routing algorithm that is based on a physical layer that uses a form of cooperative transmission (CT). The routing algorithm derives its simplicity mainly from two features: (1) unlike other CT-based routing protocols, it requires no pre-existing conventional multi-hop routes, and (2) no inter-node coordination is needed at the node level, i.e., node operations are performed autonomously after executing simple logical operations.

CT is the strategy wherein users help each other, thereby transmitting multiple copies or versions of the same message through independently faded channels, to a destination node [2]. By sharing information this way, the users form a "virtual array" [3] and reap the benefits of array and diversity gains. Because of the diversity gain, all users can reduce their fade margins (i.e., their transmit powers) by as much as 12–15 dB, thereby reducing the energy consumed by each transmitter [2]. Because of the array gain (the simple summing of average powers from each transmit antenna), the required transmission power for a link can be divided across multiple radios; this provides a convenient

* Corresponding author. Tel.: +1 608 628 1443.
E-mail addresses: lakshmi@gatech.edu (L.V. Thanayankizil), aravindk@ieee.org (A. Kailas), mai@gatech.edu (M.A. Ingram).

1570-8705/$ - see front matter
doi:10.1016/j.adhoc.2010.12.004

mechanism for applications in which each node has extreme transmit power constraints or heat restrictions. Another advantage of CT not often mentioned is that CT can overcome network partitions that would defeat multi-hop routing without cooperation [4].

A particularly simple form of CT called the opportunistic large array (OLA) [5] avoids individual node addressing and is therefore independent of node density and is a strong candidate for mobile networks. An OLA is formed when nodes transmit the same message, without coordination between each other, but at approximately the same time, in response to energy received from a single source or another OLA [5]. The signal received from an OLA has the same model as a multi-path channel [5]. Small time offsets (because of different distances and processing delays) and small frequency offsets (because each node has a slightly different clock frequency) are like excess delays and Doppler shifts, respectively. As long as the receiver can tolerate the effective delay and Doppler spreads of the received signal, decoding can proceed normally. Demonstrations of OLA transmit synchronizations have been performed using GNU software defined radios [6,7]. In these experiments, it was shown that by synchronizing on the received packet from a single transmitter or an OLA, a relative delay spread of an OLA transmission of just 100 ns is obtained in an indoor environment [6].

In fading channels, an OLA can provide transmit spatial diversity if the waveforms transmitted by the different nodes in the OLA are orthogonal and the receivers can receive on those orthogonal dimensions and do diversity combining. The authors in [5] considered the case when all nodes' transmissions were orthogonal to each other and the receivers could separate all transmissions and do optimal diversity combining. The authors in [5] also considered a fading channel case when all nodes transmitted on the same channel (the non-orthogonal case). Although most authors make node transmissions orthogonal to each other to improve performance, the authors in [5] showed that *non-orthogonal transmissions* outperformed the *orthogonal* case in a very dense node deployment. This is because although the probability of having a good fading realization is very small, there is always a fraction of receivers that experience them and they boost the overall performance of the system.

Almost all transmit diversity schemes can be applied to OLAs. To keep the protocol simple, each relay can choose at random an orthogonal channel from a limited number of choices [8]. For example, to achieve second order diversity, 20 relays that receive the same signal can each at random choose one of the two halves of the Alamouti space–time block code when they relay [26]. The array gain of 20 is assured, and the chances are excellent that most of the diversity gain will be achieved, even though the group (or OLA) choosing the first half of the code may not have the same number of relays as the group choosing the second half of the code. A simple way to achieve diversity gain with non-coherent reception is for different relays to transmit the same data on different orthogonal carriers. Each carrier is modulated with the same binary frequency shift keying (BFSK) modulation. The receiver achieves equal gain combining by simply adding the non-coherently demodulated outputs of the different diversity channels. Alternatively, direct sequence spread spectrum (DSSS) transmitters can intentionally delay their transmissions to emulate a frequency-selective channel so that multiple RAKE fingers are excited [9,10], or nodes with orthogonal frequency division multiplexing (OFDM) transmitters can choose different sub-carriers.

This paper presents the OLA concentric routing algorithm (OLACRA), which is an upstream routing method that is appropriate for WSNs that use OLA-based cooperative transmission and are characterized by a Sink, or fusion node, in the center of a large, dense deployment of energy-constrained nodes. OLACRA exploits the concentric structure of OLAs that are naturally created in a broadcast to limit the size of the upstream OLAs and guide the message back to the Sink. OLACRA requires neither location knowledge nor centralized control for pre-computing of routes. Because the transmissions of individual nodes within an OLA are just effectively multi-path components, there is no contention within an OLA transmission, so no medium access control (MAC) is needed for a single flow. Further energy can be saved through the use of a transmission threshold; this variant of OLACRA is called OLACRA with transmission threshold (OLACRA-T). An energy-efficient variant of OLACRA, namely, OLACRA with step-size control (OLACRA-SC), is also introduced in this paper. In addition to this, the performance of OLACRA-SC over mobile channels is studied and compared against Ad Hoc On Demand Distance Vector (AODV) routing. We also propose a simple contention-based MAC protocol for managing multiple flows in WSNs. In addition to this, we study the performance of OLACRA over mobile channels.

This paper is organized as follows. Section 2 discusses previous work on multi-hop routing strategies in WSNs with emphasis on the multi-hop cooperative schemes that have been introduced so far. Section 3 outlines the network model that we use in our protocol. Section 4 explains in great detail the basic OLACRA protocol. Section 5 introduces the variants of OLACRA. Also, we propose a simple contention avoidance scheme suitable for these networks. In Section 6 we quantify the performances of these methods using fraction of energy saved (FES) and packet delivery ratio (PDR). Also, the benefits of OLACRA over mobile channels is studied in Section 6.

2. Prior works

WSNs are often 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 [13,14] 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 [15,16] 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 [15]. However the above-mentioned energy-aware protocols do not consider cooperative transmission.

Lately, CT has been extended to multi-hop networks. 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 [17–20]; the corresponding routing metric is the total path transmit power. A particularly well-developed example is proposed by Jakllari et. al. [20]. They propose a protocol that selects relays from among the nodes in a conventional route (the "primary path"), and uses CT to take longer hops along that same route. As another example, [19] considers a sequence of node clusters between the source and destination (presumably along a pre-determined route). One relay is selected from each cluster to minimize the probability of outage, either hop-by-hop, or end-to-end. 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 do not entail.

OLAs have been investigated for broadcasts in multi-hop networks and unicasts in mobile ad hoc networks. Two groups [5,11,25] independently proposed simple OLA-based broadcasting, which we refer to as "Basic OLA" in this paper. Basic OLA was extended in [12] to include a "transmission threshold" that reduces the number of nodes that transmit in a broadcast, relative to Basic OLA, for the purpose of saving energy. In the present paper, the transmission threshold is used for a different reason, to control step-size. For unicasts in ad hoc networks, again, two groups [23,25] independently proposed similar OLA-based protocols. The protocol explored in this paper is similar to the route request and route reply phases in [23] and [25]. However, besides the basic difference between ad hoc networks (any pair of nodes can be a source and destination) and sensor networks (the Sink is always the upstream destination), this paper explores a number of ways to improve the connectivity of the upstream path, including level ganging, local flooding, variable transmit power, and step-size control. The OLACRA concept has been treated in some previous publications by the authors [22]. The novelties in the present paper include a medium access control protocol, how energy savings varies with locations of the Source and the Sink in the network, and a mobility analysis. In addition to this, this paper also considers for the first time OLA networks with multiple flows.

3. System model

The nodes are assumed to be half-duplex and distributed uniformly and randomly over a continuous area with average density ρ. We assume a node can decode and forward a message without error if its received signal-to-noise ratio (SNR) is greater than or equal to a modulation-dependent threshold [5]. Assumption of unit noise variance transforms the SNR threshold to a received power criterion, which is denoted by the decoding threshold, τ_d .

Let the normalized *transmit* power be given by

$$P = P_t G_t G_r \left(\frac{\lambda}{4\pi d_o}\right)^2 \tag{1}$$

where P_t is the un-normalized transmit power in mW, G_t and G_r are the transmit and receive antenna gains, respectively, d_o is a relatively short reference distance in meters, and λ is the wavelength in meters. The normalized transmit power P (which is actually the received power at the reference distance) is denoted P_r for relay nodes and P_s for the source node. As in [5], we define distance d to be normalized by the reference distance, and the normalized relay transmit power per unit area as $\overline{P}_r = P_r\rho$, where ρ is the normalized density (number of nodes per normalized distance squared). Continuing to follow [5], we define the normalized received power, P_{rec} as

$$P_{rec} = \min\left(\frac{P}{d^2}, P\right) \tag{2}$$

The min function is used to avoid arbitrarily high-received powers for very small d [5].

We consider two channel models, the Deterministic Channel model and the diversity channel model [5]. In the Deterministic Channel model, the power received at a node is the sum of the powers received from each of the node transmissions, and path loss is the only channel impairment. This model implies that node transmissions occur on orthogonal non-faded channels. In the Diversity Channel, transmissions occur on a limited number of orthogonal Rayleigh-faded channels [5,7].

In the Deterministic Channel model [5], it is assumed that if a set, L_n, of n relay nodes transmits simultaneously, the node J with normalized Cartesian coordinates (x_o, y_o) receives with power

$$P^J_{rec} = P \sum_{(x,y)\in L_n} l(x - x_o, y - y_o), \tag{3}$$

where $l(x,y) = (x^2 + y^2)^{-1}$ is the path loss function.

Many of the results in the paper will be given in terms of the normalized variables defined above. However, one set of normalized parameters can correspond to different sets of un-normalized parameters, depending on the chosen values of reference distance and un-normalized transmit power. Table I gives some of the possible un-normalized sets. For example, we observe that $P_r = 1$ and $\rho = 2.2$ correspond to Examples 2, 4, and 5, ranging from a high density of 2.2 nodes per square meter to a low density of 2.2 nodes per square kilometer. All three of these cases have a node degree (average number of nodes in the decoding range of the transmitter) of 6.9. To get a lower node degree, one could lower the transmit power (as in Example 1) or increase the path loss by increasing the carrier frequency.

For the diversity channel model [7], the received power is given by

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

where m is the number of orthogonal channels, $P^{j}_{rec,k}$ is the average power received at the k^{th} orthogonal channel and γ_k is a zero mean, unit variance exponential random variable. The value of m can represent a combination of naturally created orthogonal channels and intentionally created orthogonal channels. For example, frequency selective multipath fading can excite multiple fingers in a RAKE receiver. However to ensure diversity gain, some of the nodes in the OLA can intentionally delay their transmission by one or more chip periods.

In an earlier work [12], the introduction of a user-defined parameter called the transmission threshold, τ_b, was found useful in limiting node participation. A node tests its received SNR against τ_b, and if the SNR exceeds τ_b, then the node does not participate. This test limits the participation to the "significant" boundary nodes, which are those nodes that can just barely decode. The quantity $10\log_{10}\frac{\tau_b}{\tau_d}$, referred to as the relative transmission threshold (RTT), defines the 'window' in dB to allow for relaying. The algorithm OLA with transmission threshold (OLA-T) is simply the application of RTT to OLA broadcasting [12]. We shall also use OLA-T in this paper to make OLACRA more energy-efficient.

4. OLACRA

4.1. Downstream (initialization phase)

The OLA concentric routing algorithm (OLACRA) has two phases. In the first phase, the Sink initializes the network with a broadcast using OLA with transmission threshold (OLA-T) or Basic OLA. This is explained as follows. The Sink transmits waveform W_1 with power, P_{sink}. "Downstream Level 1" or DL^1 nodes are those that can decode the Sink-transmitted message. OLA-T is defined by allowing only the nodes in DL^1 whose received power is *less* than τ_b to 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, header, spreading code or center frequency. This enables the nodes in the decoding range that have not participated/relayed this message before to learn about their DL^2 membership.

A DL^2 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 Fig. 1a.

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" [5], grows with the downstream OLA index. For example, the step-size of DL^4 is shown in Fig. 1a. In other words, the rings that are farther from the Sink are thicker. This step-size growth can cause a problem with upstream connectivity, and will be discussed in Section 5.

4.2. Upstream

The second phase of OLACRA is upstream communication. For upstream communication, a source node in DL^{n-1} transmits using W_n. Any node that can decode 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. Upstream OLAs are illustrated by the solid boundaries in Fig. 1b. 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 Fig. 1b for example, UL^1 is indicated by the rightmost solid circle and UL^4 contains the Sink. For OLACRA, the *upstream 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 the broadcast, energy can be saved in OLACRA if the transmission threshold criterion is applied; that is, only the nodes near the upstream boundary are allowed to transmit. In this case O_{Uk} and UL^K would denote the transmitting set and decoding sets respectively for the k^{th} upstream level. We call this variant OLACRA-T. O_{Uk} and UL^K are the same in OLACRA without transmission threshold, as shown in Fig. 1b. A simulation example in Fig. 2 illustrates OLACRA when the upstream source node is in DL^5. To indicate the level membership, downlink level nodes are shown using circles with contrasting shades (magenta circles for even indices and yellow circles for odd indices in the figure[1]) and the upstream nodes are denoted using darker shades (blue circles in the figure). It is remarked that the plot in Fig. 2 is only for illustration purposes; the performance of OLACRA and its variants will be evaluated in Section 6.

The two important performance issues in wireless networks in general and WSNs in particular are energy efficiency and reliability. We define two metrics to measure these in the context of OLACRA, the Fraction of Energy Saved (FES) and the Packet Delivery Ratio (PDR).

The fraction of energy saved (FES) compares the transmit energy consumed by OLACRA in the upstream direction with that of Basic OLA. FES is defined as

$$FES = 1 - \frac{\text{Total transmit energy consumed in the network in OLACRA}}{\text{Total transmit energy consumed in the network in Basic OLA}},$$

where the transmit powers are chosen to be the minimum transmit power required for a 'successful transmission,' where successful transmission implies sustained propagation for Basic OLA and successful reception at the Sink in the case of OLACRA. Since the transmit energy consumed in the network is proportional to the number of nodes transmitting, FES also gives an intuitive understanding of the average number of nodes participating in a successful transmission for a particular source–destination pair. However, since failed packets also contribute to the total network energy consumption, FES does not give an accurate view of the total network energy consumption (and do not add to the transmit energy consumption), and hence is actually an estimate of the "fraction of transmit

[1] For interpretation of color in Fig. 2, the reader is referred to the web version of this article.

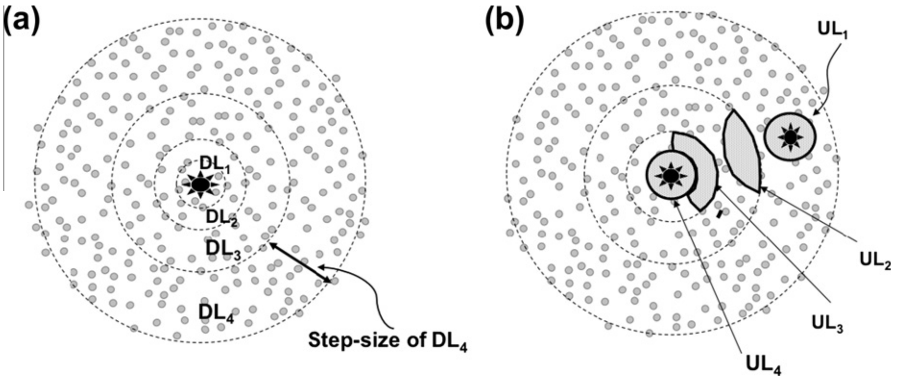

Fig. 1. Illustration of OLACRA. (a) phase 1 (b) and upstream phase.

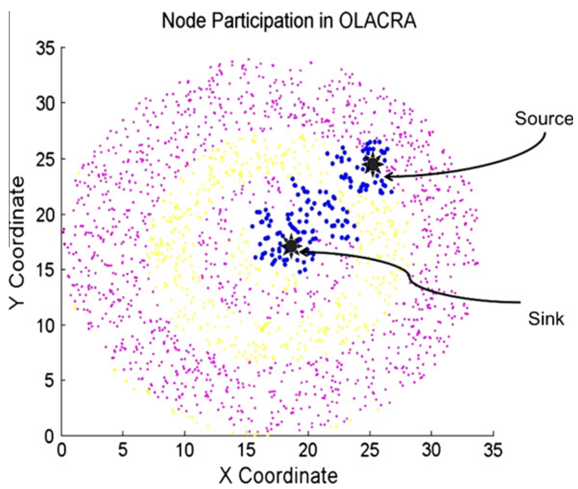

Fig. 2. Node participation in Single Level.

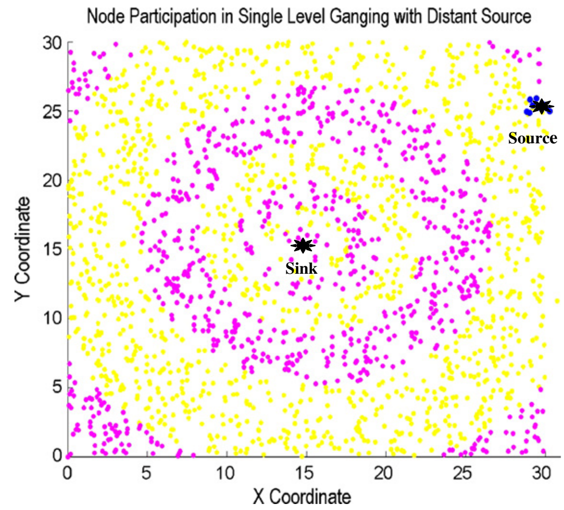

Fig. 3. An example of a failed upstream connection.

energy saved per packet delivered". While calculating FES, we do not take into account the nodes that relayed in the initialization broadcast (route discovery) phase.

The packet delivery ratio (PDR) is the probability that a packet transmitted by the upstream source node is successfully decoded at the Sink.

5. Upstream connectivity issues in OLACRA

If the upstream source node is located far away from the Sink, and also far away from the upstream boundary of UL^1, then the decoding range of the upstream source node may be too short and UL^2 may not form. This is shown in Fig. 3, where the upstream source node is present away from the upstream boundary of DL^6. The range of UL^1 does not get beyond DL^6 and hence does not fire any nodes in DL^5. As a result, we observe that the upstream transmission does not get to the Sink. This can happen for an OLACRA upstream transmission when the source node is many, e.g. 7, steps away from the Sink, because downlink levels of higher index are thicker. This causes the 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 energy. Some of the solutions we considered are as follows.

5.1. 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 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, 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.

5.2. Increase the power of the source node for 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.

5.3. Limited OLA or OLA-T broadcast in just the first upstream level

This scheme allows all nodes in DL^n that can decode a message to forward the message if they have not forwarded that message before until the set of all such nodes meets the upstream 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".

5.3.1. Olacra-T with limited flooding (OLACRA-FT)

The worst case number of broadcast OLAs required to meet the upstream boundary of DL^n can be known a priori as a function of the downstream level index. For example, in Fig. 4a, three upstream broadcast OLAs are needed to meet the upstream boundary of DL^n. The union of the upstream decoding nodes (e.g. all three shaded areas in Fig. 4a in DL^n), are then considered the extended source. Next, the extended source behaves as if it were a single source node 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 preamble as would a source node under the OLACRA protocol. In order for the nodes to know when it is time to transmit as an extended source, a OLA waveform distinction (example: different preamble bits), similar to the network initialization phase of OLACRA, must be used in this upstream limited-broadcast phase. To save energy, the nodes in the extended source that transmitted in the downstream transmission could be commanded to not

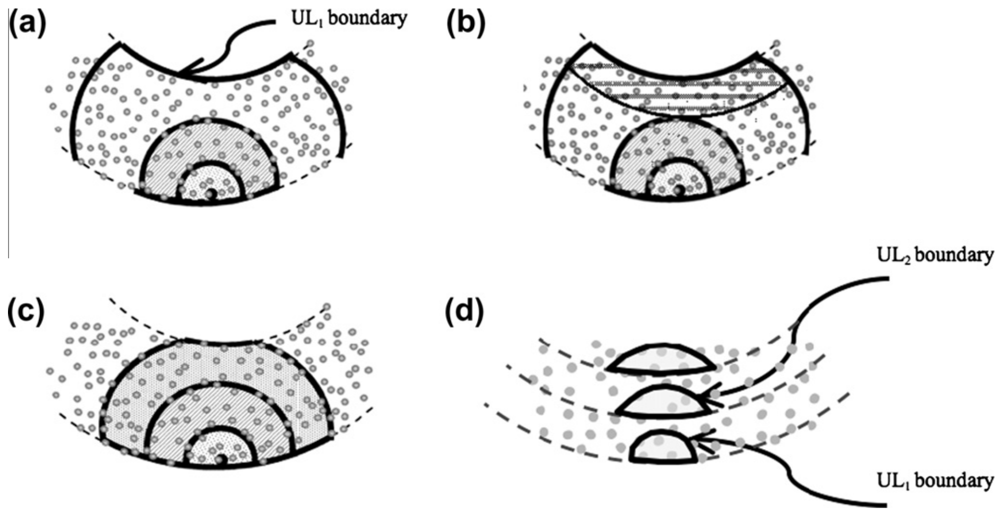

Fig. 4. (a) Broadcasting within UL^1, (b) boundary nodes in extended source, (c) using power optimization in OLACRA-VFT, and (d) OLACRA-SC.

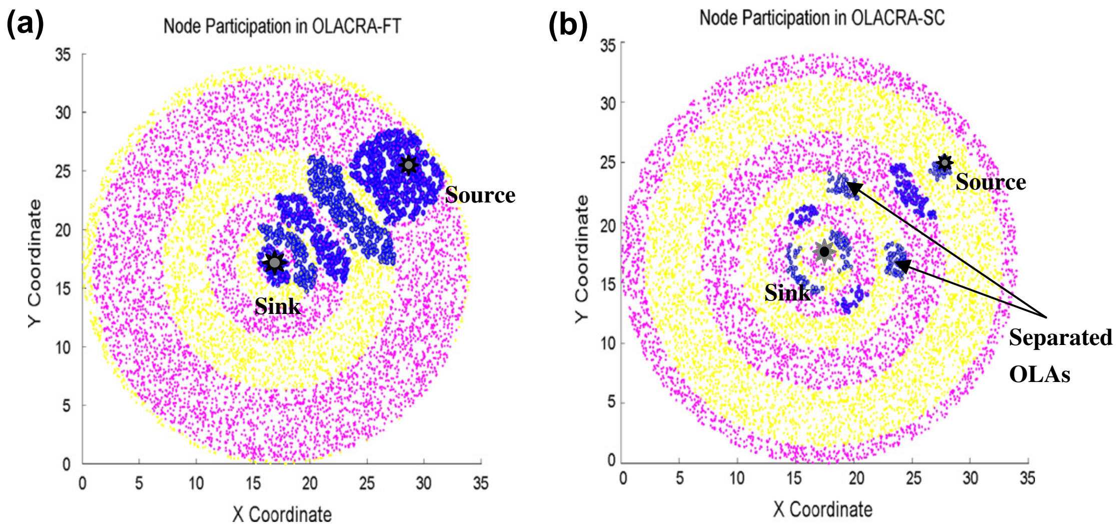

Fig. 5. Node participation in (a) OLACRA-FT (b) OLACRA-SC.

transmit in the extended source transmission; in other words, those nodes that were near the downstream boundary in the initializing broadcast would be near the rear of the OLA during upstream transmission, and therefore will not make a significant contribution in forming the next upstream OLA. This is shown in Fig. 4b. Fig. 5a illustrates node participation in OLACRA-FT.

5.3.2. Olacra-FT with variable relay power (OLACRA-VFT)

Even though the extended source can meet the upstream boundary of the downlink level containing the upstream source in OLACRA-FT, its width is very large, making it energy inefficient. This can be seen in Figs. 4a and 5a. In order to make this scheme more effective, we desire the smallest extended source whose decoding range is just beyond the upstream boundary of DL^n. In OLACRA-VFT, the relay transmit powers in these upstream broadcast steps, P_{rf}, are reduced relative to OLACRA-FT, to reduce the size of the extended source, as shown in Fig. 4c. Assuming sufficient density and uniformity of channel model, these power levels are designed in (i.e., designed apriori). 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 transmission threshold, τ_f, which is the decoding threshold for the upstream steps, or a combination of both, to obtain similar results.

While both methods, namely varying transmission threshold and relay power in the flooding level 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 flood levels, P_{rf}. 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_{rf}. The downstream OLA levels and OLACRA levels in upstream use relay power P_r as defined in earlier sections.

5.4. Olacra with step-size control (Olacra-SC)

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 (this will be shown in Section 6). So, another alternative to enhance upstream connectivity is considered, while at the same time conserving energy. OLACRA-SC simply aims to reduce the downlink step-size, so that the upstream boundary of DL^n is easier to reach. The downlink radii depend on the downlink transmission threshold and relay power [12]. Thus, step-sizes on the downlink can be controlled by optimizing the transmission threshold or relay power. Unlike OLACRA-FT and OLACRA-VFT, the goal here is not to make the extended source touch the upstream boundary of DL^n, but to make the extended source strong enough to reach a sufficient number of nodes in UL^2 to carry the transmission back to the Sink as can be seen in Fig. 4d. A simulation example for this case is also shown in Fig. 5b. In this Fig., to further increase the 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 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 possibility that the nodes that relayed in OLA-T would not be taking part in the upstream OLACRA-SC transmission. This is the case in Fig. 5b.

We observe in Fig. 5b, in the third upstream level, UL^3, there are two well separated OLAs. Please note that these separated OLAs occur because of the use of a transmission threshold in the upstream, which prevents some nodes from transmitting. In spite of the fact that the two upstream OLA paths go beyond the Sink, this type of discontinuous OLA formation was found to be quite energy-efficient.

5.5. Effect of node density on upstream connectivity

Because the number and placement of the nodes is random, there is a chance that there might not be enough nodes in the vicinity of the source to form an OLA when the node density is low. If this happens, there are no relays, and the packet would not be delivered. We present preliminary analysis of this, and call it as the ‘initial bottleneck’.

A little analysis of this initial bottleneck can be performed. Let A be the event that there are no nodes within the decoding range of the source, and let B be the event that the message fails to get to the sink. Then $A \subseteq B$ and $P(A) \leqslant P(B)$. It is straightforward to calculate $P(A)$. The hypothesis is that even with all the enhancement schemes described above, like OLACRA-FT, OLACRA-VFT and OLACRA-SC, the probability of outage cannot be less that $P(A)$. One of the solutions to this problem is to use a higher source power (thereby increasing the node degree) for just the upstream source node. An alternative way to decrease the probability of outage due to initial bottleneck is to explore retransmission diversity schemes. However this is beyond the scope of this paper. $P(A)$ will be evaluated in Section 6.

5.6. Contention avoidance in Olacra

OLACRA has been explained in the earlier section assuming there is only a single flow. However, multiple upstream flows may originate in the same level at the same time, and because of the concentric rings, the flows will collide at some level. In general, designing contention avoidance schemes for OLA-based routing schemes is non-trivial since the suppression regions of irregularly shaped OLAs are difficult to predict in advance whereas the suppression region of each transmission in a conventional multi-hop link is deterministic and circular. Hence, multiple flows in networks with CT-based routes should be scheduled so such that they do not fall within neighbor suppression regions without causing collisions, which is not a trivial problem. We propose a simple contention

Table 1
Examples of Un-normalized variables (τ_d = 1 and Receiver Sensitivity = −90 dBm for all the entries).

Example	Un-normalized parameters				Normalized parameters		
	Frequency	d_o in m	P_t (dBm)	Node Density	P_r	Density	Node degree (K)
1	2.5 GHz	1	−53.01	2.2 nodes/m^2	0.5	2.2	3.5
2	2.5 GHz	1	−50.0	2.2 nodes/m^2	1	2.2	6.9
3	2.5 GHz	1	−59.58	10 nodes/m^2	0.11	10	3.5
4	2.5 GHz	1000	10	2.2 nodes/km^2	1	2.2	6.9
5	900 MHz	1	−58	2.2 nodes/m^2	1	2.2	6.9

avoidance scheme where flows are scheduled sequentially, so that there is only a single flow within the network at any one time. The scheme basically treats the entire network as one big 802.11 (one hop) Basic Service Set. Since OLA flows are faster (i.e., they have less delay than a conventional multi-hop route) [5], treating one flow like one big hop is not so inefficient. When a node has a message to transmit and the medium is free it sends a request-to-send (RTS) to the Sink using OLACRA. The RTS is a small message that contains information about the type of data being reported and also the duration of the transmission. The Sink broadcasts a clear-to-send (CTS) on receipt of the RTS using OLA-T with the identity of the upstream source node and also the duration of the transmission. All the nodes in the network delay their transmissions by that time period. Even though the proposed scheme is very simple, it is of practical significance since most of the data transmitted in WSNs is not time sensitive and hence the additional delay does not degrade the network performance significantly.

6. Performance 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 OLACRA protocol and explore its properties. First we evaluate the variations of OLACRA over the Deterministic Channel, with *step-size* control considered separately from the other variations. Next, we consider the Diversity and mobile channels.

For all the results in this section, normalized values of the relay power, transmission threshold, decoding threshold, and density are chosen such that they satisfy the OLA-T broadcast criterion given in [12]. The source power was chosen to ensure sufficient node degree to maintain connectivity, and was generally higher than the relay power, as the first hop transmission is a non-cooperative one.

In this section, we will use simulation to compare the OLACRA variations in terms of FES and PDR. We will find that the PDR values span a large range, with the last variation, OLACRA-SC, giving the highest values.

6.1. Energy efficiency evaluation over deterministic channels

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

6.1.1. Without step-size control

A node density of 2.2 is considered in these simulations. A fixed RTT of 4 dB and a $\overline{P}_r$ of 1.1 are used for the downstream. This corresponds to Example 2 in Table 1.

Figs. 6a 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

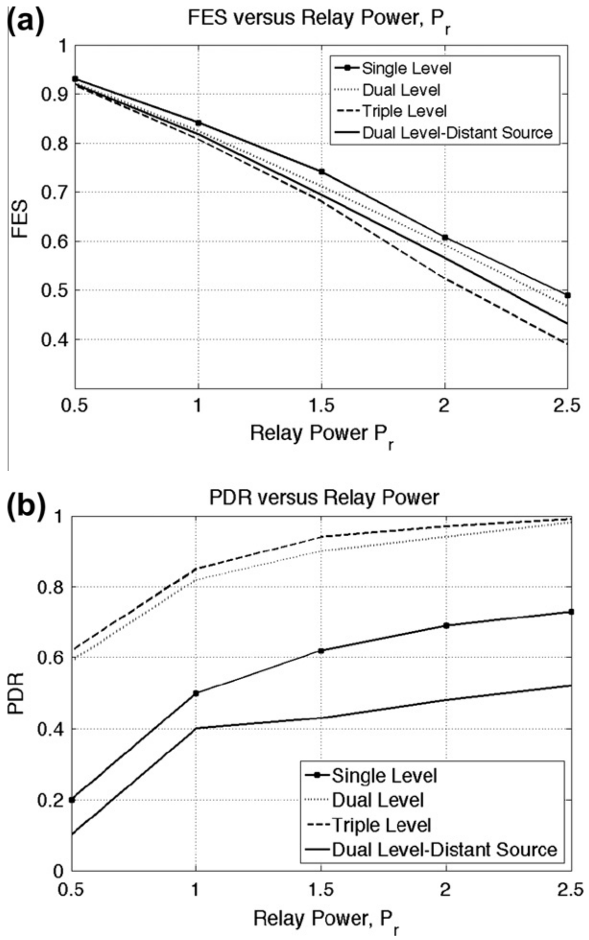

Fig. 6. (a) FES and (b) PDR versus Relay power for different variants of OLACRA.

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 of Dual Level when the source is close to the Sink (radius 5) was comparable to the 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 boundary. Hence DLDS does not scale well to large networks.

Fig. 7a and b compare the performances of the different variants of OLACRA in terms of their FES and PDR versus RTT in dB. The upstream source node is located at a radius of 15. $\overline{P}_r$ of 2.2 is assumed for upstream routing. The relay power for the flooding stage in OLACRA-VFT P_{rf}, is 0.6. OLACRA-T with a source power of 1 has the highest FES of 0.87 at RTT of 1.76 dB (left edge of the graph); however the PDR at this RTT is very low, at 0.12. The FES of OLACRA-FT is only slightly lower than OLACRA-T with source power = 1, but the PDR for this case is very high. 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 is similar to OLACRA-FT, implying that the performance of upstream source power requirement will be very high to achieve similar performance.

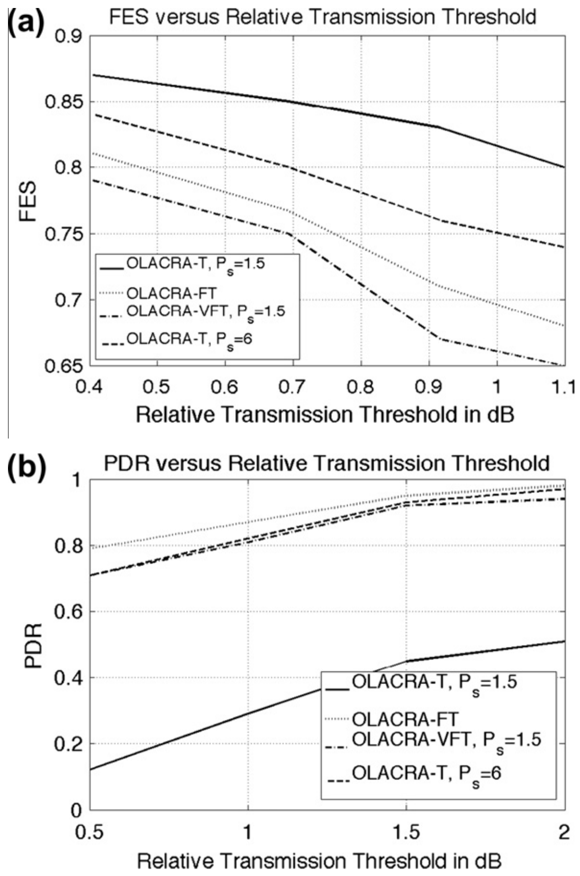

Fig. 7. (a) FES and (b) PDR versus RTT for different versions of OLACRA.

6.1.2. 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. This corresponds to Example 3 in Table 1. As described in Section 5.4, the radius of a level depends on the RTT value and hence downlink step-sizes can be controlled by varying RTT. For results in this section, the RTT values in the downlink are chosen as the continuum-predicted RTT values that give fixed step-sizes. Upstream $\overline{P}_r$ is 1.1. Two step-sizes are considered: 0.8 $r_{d,1}$ and $r_{d,1}$, where $r_{d,1}$ denotes the radius of DL^1. We also consider a special case, $r_{d,1}$-*boundary*, where the Sink and upstream source are located at the boundary of the network.

Fig. 8a and b compare the FES and PDR performances of 0.8 $r_{d,1}$, $r_{d,1}$, and $r_{d,1}$-*boundary*. The 0.8 $r_{d,1}$ has a very high FES of 0.928 at a RTT of 1.76 dB, however the PDR at this RTT is very low. This is because of the low value of RTT. A low value of RTT 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 RTT removes a substantial amount of nodes from a set that already did not have many nodes to begin with. As RTT is increased to 4.5 dB, the PDR for *0.8* $r_{d,1}$ improves to about 0.927. Compared to the 0.8 $r_{d,1}$ 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. On comparison with $r_{d,1}$, we find that $r_{d,1}$-*boundary* has a higher FES and lower PDR. This is because, in this case, the OLAs formed will be narrower. Since the transmission range of the OLA is proportional to the width [21], this results in a lower PDR. However, since the OLAs are narrower (meaning fewer nodes per OLA), this results in a higher FES. Hence to ensure reliability, a higher value of RTT should be considered to take into account different placements of the Sink and the upstream source.

We have seen above that step-size control enables PDRs exceeding 0.9, and gives the best PDR performance among all the OLACRA versions considered. However, we have not compared the PDR of OLACRA-SC to any non-CT multi-hop routing protocol.

Fig. 9 shows the variation of FES with distance from the Sink for a *fixed network size*. Step-size optimization is done for the downlink to obtain fixed step-sizes of 0.8 $r_{d,1}$ and all other parameters are chosen as in the previous result. We observe that the FES has a general decreasing trend as the distance of the source from the Sink increases. This is very intuitive, as more nodes in OLACRA have to take part when the source is at a greater distance from the Sink, while Basic OLA always broadcasts over the whole (fixed size) network. We also observe that FES has a saw-tooth variation within a level. Within a level, the highest FES is observed when the source is close to downlink boundary of DL^n. This was because when the upstream source is at this location, a minimum number of nodes are activated in the next upstream level, whereas when the upstream source node is closer to the downlink forward boundary it activates maximum number of nodes in the next upstream level. The sharp saw-tooth fall of FES happens because of the change in level of the node. For example, suppose a node at 1.414

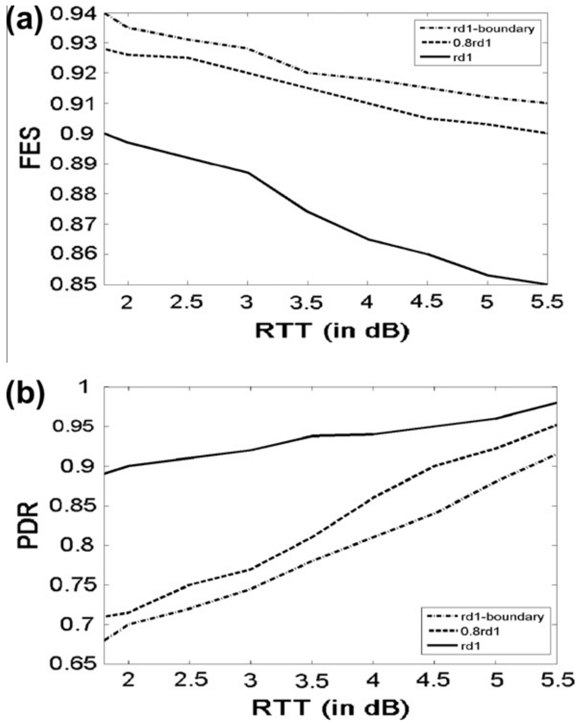

Fig. 8. (a) FES and (b) PDR versus RTT (in dB) for OLACRA-SC.

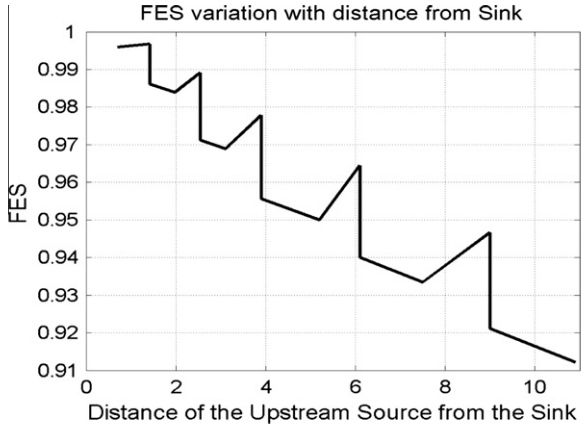

Fig. 9. FES variation with distance of the upstream source node from the sink.

is a part of DL^1 and hence is 1 hop away from the Sink, whereas a node at 1.4141 is in DL^2 and is 2 hops away and hence activates many more nodes.

The distance between two saw-tooth peaks in Fig. 9 corresponds to the downlink step-size. We can see that the step-size strays away from fixed values as the distance from Sink increases. This is because our RTT values in the downlink were chosen using the continuum approach as described earlier. The continuum tool is valid at very high densities, however the validity of continuum-based prediction falls at lower densities. Even though higher densities (density of 10) were chosen for the step-size control section compared to our other results, the continuum-based prediction is not accurate even at this density.

6.2. Energy efficiency evaluation over diversity channels

Our results so far have considered networks where transmissions occur on orthogonal and non-faded channels (Deterministic Channel). In this section we extend our simulations to the diversity channel model where transmissions are on orthogonal or quasi-orthogonal Rayleigh-faded channels. There are many ways to create these orthogonal channels [6], such as space–time block coding (e.g. Alamouti code) [8] or using orthogonal waveforms (e.g. different sub-carriers on an OFDM waveform). In this section, we focus on the DSSS signal as a way to create orthogonality. We assume a spreading sequence that has an impulse autocorrelation function. To ensure m^{th} order diversity gain we let each relay delay its transmission by a random 'artificial' delay selected from a pool of artificial delays $\{0, T_C, 2T_C, \ldots (m\text{-}1)T_C\}$, where T_C is the chip time of the DSSS signal [6,7]. 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 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 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 $(k-1)T_c \leqslant t_r \leqslant kT_c$.

Each trial has 2000 nodes randomly distributed in the circular field of radius 17 giving ρ = 2.2. The downstream levels are established using OLA-T with source power P_s = 3, $\overline{P}_r = 1.1$, and RTT = 4 dB. For upstream routing using OLACRA, the source node is located at a radius of 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 chosen as 500 time units.

Fig. 10a compares the FES under OLACRA under the Deterministic Channel model and Diversity Channel model, for different values of RTT, while Fig. 10b shows the PDR, also versus RTT. We observe that for m = 3 (third order diversity) FES is 0.72 at RTT = 3 dB, whereas the FES for the deterministic case for the same value of RTT is 0.77. Similarly the probability of message delivery at the Sink is only 0.77 for the m = 3 case at the RTT of 3 dB, whereas the probability of success for the deterministic case is higher at 0.82 for the same RTT. But when the diversity order is 4 (m = 4), the performance characteristics of the fading channel is closer to the deterministic case. For m = 4, the probability is about 0.94 for an RTT of 4.7 dB, when the deterministic case has a probability of 0.97. It should also be noted that the FES performance of the m = 4 case is not very different from the m = 3 case, meaning that the higher probability of message reception obtained by having an additional RAKE finger is not at the cost of energy.

Fig. 11 captures the variation of the probability that a message is not decoded by the Sink versus node density

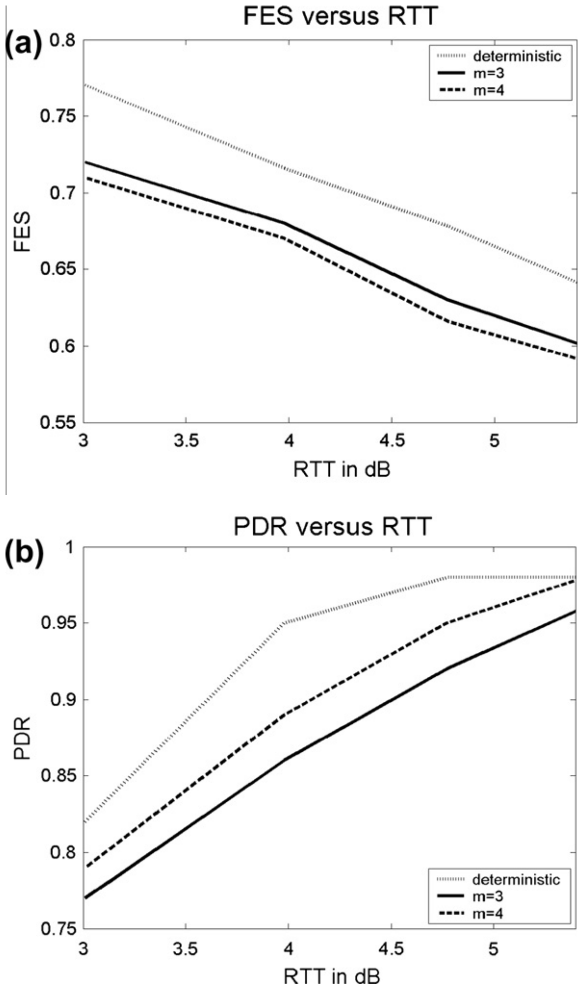

Fig. 10. (a) FES and (b) PDR versus RTT for the diversity channel model.

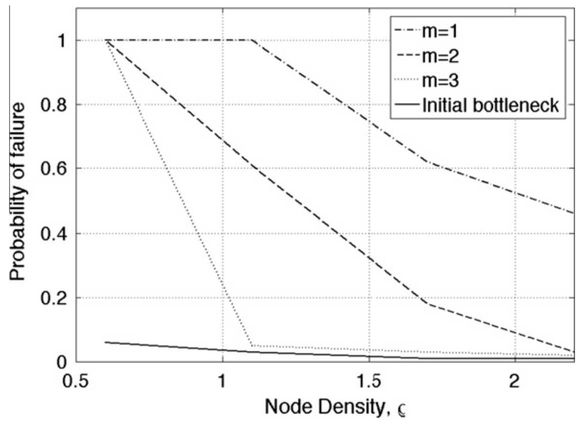

Fig. 11. PDR versus node density.

ρ for different values of m (diversity order). The curve labeled 'initial bottleneck' shows the probability that there were no nodes in the first level in UL^1. At $m = 1$, which corresponds to the 'no diversity case,' we observe that the probability of failure was 1 for $\rho < 1.15$.Even at a much higherdensity, $\rho = 2$, the probability of failure drops only to 0.54. That it drops with increasing density is consistent with the claim in [5] regarding non-orthogonal transmissions. However, when $m = 2$, the probability of failure tends to zero at a node density of 2.2. When $m = 3$, probability of failure drops to 0.01 at a node density of 1.1. It should be observed that the $m = 3$ and 'initial bottleneck' lines are very close for $\rho \geqslant 1.1$, implying that at $m = 3$, the probability of failure is dominated by the probability that there are no nodes in the first level ('initial bottleneck') since the probability of outage due to fading tends to zero.

6.3. OLACRA over mobile channels

In this section, we consider the performance of OLACRA-SC over mobile channels, and compare it with the performance of Ad Hoc On Demand Distance Vector Routing (AODV), which is a widely used shortest-hop routing protocol. Nodes are distributed randomly in a $100\ \text{m} \times 100\ \text{m}$ area. The Sink is at (50,50) and the upstream source at (10,100). For modeling mobility we use the Random Way Point Mobility Model [24]. Nodes randomly choose their speed from an interval (1–5 m/s). The pause time, T_{pause}, is taken to be zero. Receiver sensitivity is −90 dBm. a packet size of 128 bytes and a bit rate of 250 kbps are considered. The Source and Destination transmit at a higher power of −45 dBm, this is done to ensure there are sufficient neighbors near the Source/Destination to carry the transmission forward. When we compare OLACRA and AODV, the node density will be the same, but the relay power will be 10 dB lower for OLACRA than for AODV. We do this in an effort to make the per-hop total transmit powers of the two protocols *roughly* equal and hence make the comparison fair.

We define the Relative Stability Ratio (RSR), as the time when the route first breaks in OLACRA to the time when the route first breaks in AODV. Please note that in these simulations, we only calculate the time when the route breaks first, and hence we have not implemented route repair mechanisms. Table 2 shows the RSR for different values of node density (ρ). In these simulations, the node density is increased keeping $\overline{P}_r$ constant. We see that the robustness of OLACRA over AODV increases as the density increases. This is because at higher densities nodes transmit at lower power (to keep $\overline{P}_r$ constant) and hence the AODV route from Source to Destination has larger number of shorter-length hops. If any one of

Table 2
RSR for different Node Densities.

Node density (Nodes/m^2)	*Pt* (AODV) in (dBm)	*Pt* (OLACRA) in (dBm)	RSR
0.1	−30	−40	1.8
1	−40	−50	3.1
2	−43	−53	3.6
5	−47	−57	4.2
10	−50	−60	4.8

these hops fails, the route fails. So the time when the route breaks first decreases with the number of hops. In contrast, the number of hops in OLAROAD is determined by $\overline{P}_r$, and hence the time the route breaks first does not vary with density.

6.4. OLACRA with two flows

In this section, we do a small study on the effect of multiple sources on the performance of an OLACRA-based system. Specifically, we analyze the end-to-end delay when there are two upstream sources in the system, and compare it with the end-to-end delay of AODV. The simulation setup is same as Section 6.3, but we consider static nodes here. Receiver sensitivity is −90 dBm, and noise power is −90 dBm. Transmit Power is −10 dBm for AODV, and −40 dBm for OLACRA. Carrier sensing threshold of −92 dBm was chosen (Usual for physical carrier sensing schemes, the carrier sensing threshold is chosen to be twice the transmission range. Since we cannot determine the transmission range in OLACRA apriori, this value was randomly chosen, however this will be optimized in future work).

We consider two flows in our simulations. The node participation of the two flows are shown in Fig. 12; the source/destination coordinates are chosen such that they are ∼57 m from the Sink. The distance between the upstream sources are varied as part of the simulation, and its effects on end-to-end delay are shown in Table 3. When the distance between the sources is m, we see that OLACRA greatly outperforms AODV. However when the distance between the upstream sources is increased, the end-to-end delay of AODV remains unchanged, whereas the end-to-end delay of OLACRA increases. This is because of the following reasons: OLAs have larger suppression regions because of larger node participation. In Case 1, the flows do not fall within each others suppression region. Hence the main factor that determines the end-to-end delay is the number of hops. Since OLAs have larger ranges and hence fewer number of hops, they fare better than AODV. However, as can be seen in Case 2, when the sources/flows are closer to each other, OLAs fall within each other's suppression regions for OLACRA, and the end-to-end delay increases. On the other hand, the flows are not within each others suppression regions for the spacings considered in AODV, and hence its end-to-end delay remains unchanged.

Table 3
End-to-End Delay for OLA-based networks with 2 flows.

No.	End-to-End Delay for AODV (in milliseconds)	End-to-end delay for OLACRA (in milliseconds)
Case 1	88.4	34
Case 2	89.04	58

Please note that to analyze the end-to-end delay of OLA_based networks further, all node placements should be considered. In addition to this, the effect on more number of upstream sources transmitting simultaneously should be considered. In addition to this, different performance metrics like throughput, etc., should also be considered. However this is beyond the scope of this work.

7. Conclusion

OLACRA is a simple routing scheme that requires no centralized control and no knowledge of geographical location by the nodes. To the best knowledge of the authors, OLACRA is the only routing protocol that achieves cooperative diversity in upstream routing in WSNs without requiring node addressing, node localization, or a preexisting route. OLACRA has been demonstrated successfully in simulation over deterministic channels where node transmissions are on non-faded orthogonal channels and also over diversity channels that are on faded channels with limited-orthogonality. Intentional delay dithering is done to create the diversity. Variants of OLACRA to enhance upstream connectivity are compared and the most

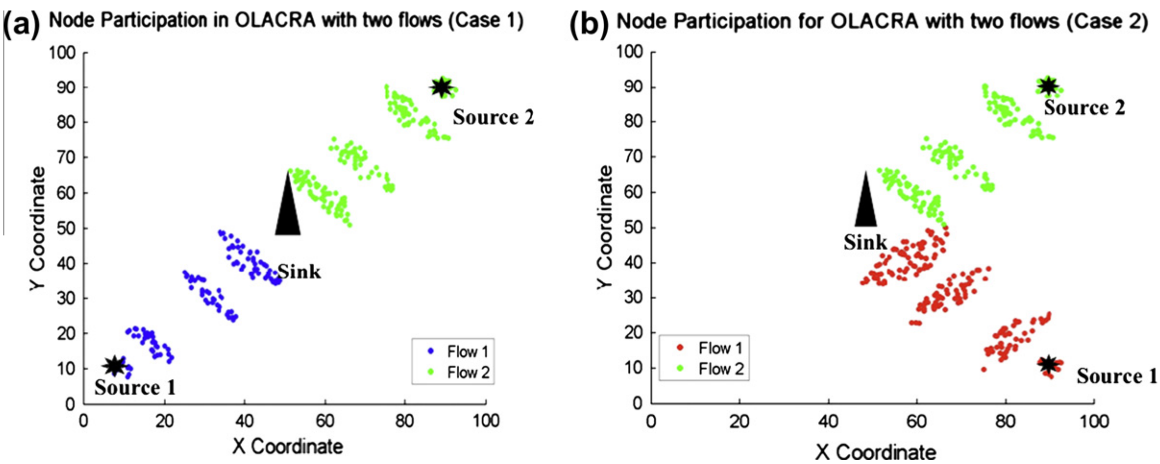

Fig. 12. Node Participation in OLCRA with two flows: (a) Case 1 and (b) Case 2(only nodes participating in the two flows are shown).

efficient scheme was found to be OLACRA-SC, which limits the downstream step-sizes. The protocols were tested using Monte Carlo simulations and it was shown that OLA-CRA-SC, which is the most efficient OLA-based unicast strategy has transmit energy efficiencies of over 80% relative to Basic OLA for a range of practical simulation parameters. In addition to this, it was shown that OLACRA is more robust to mobility and other channel variations, making it a good candidate for routing in mobile ad hoc networks too.

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Lakshmi Thanayankizil received her MS (2008) and BS (2004) degrees in Electrical and Computer Engineering from Georgia Institute of Technology and University of Calicut respectively. Currently, she is working towards the PhD Degree in Electrical and Computer Engineering Department at Georgia Tech. Since 2006, she has been a Graduate Research Assistant at Georgia Tech, where she is working on designing reliable and robust routing schemes for sensor and ad hoc wireless networks. She has also held Industry positions at IBM Research, where her work was on vehicular ad hoc networks and smart-grid-based home sensor networks and at the Indian Space Research Organization (ISRO). She was awarded the IEEE SENSORCOMM Best Paper Award (2008) and NSF ADVANCE Fellowship for Professional Training (2009), and was elected the Workshop Co-Chair for IEEE/ACM N2W (2010).

Aravind Kailas is currently an Assistant Professor in the Dept. of Electrical and Computer Engineering (ECE) at the University of North Carolina Charlotte. Dr. Kailas received his Ph.D. in ECE from Georgia Institute of Technology in 2010, and his doctoral research work addressed the key issue of network sustainability with the design of novel, simple decentralized cooperative diversity-based protocols and intelligent exploitation of energy scavenging using hybrid energy storage systems. He received his M.Sc. in Applied Mathematics from Georgia Institute of Technology in 2010, M.S. in ECE from the University of Wisconsin-Madison, Madison in 2005, and B.E. in Electronics and Telecommunications from Mumbai University, India in 2002 with the highest honors. Dr. Kailas is a recipient of the ECE Graduate Research Assistant Excellence Award (2010) and the Colonel Oscar P. Cleaver Award (2007) at the Georgia Institute of Technology. In addition, he has been a recipient of many scholarships and awards for his teaching and academic excellence throughout his undergraduate and graduate years. Dr. Kailas has held visiting research appointments at DOCOMO Communications Laboratories, Inc. (USA DOCOMO USA Labs) (2010) and the Center for TeleInfraStruktur (CTIF), Aalborg University, Aalborg (summers of 2007-2008), and industry positions at QUALCOMM Inc. (2004-2006) and General Electric (GE) (summer of 2003).

Mary Ann Ingram received the B.E.E. and Ph.D. degrees from the Georgia Institute of Technology (Georgia Tech), Atlanta, in 1983 and 1989, respectively. After graduating in 1989, she joined the faculty of the School of Electrical and Computer Engineering at Georgia Tech, where she is currently Professor. Her early research areas were optical communications and radar systems. In 1997, she established the Smart Antenna Research Laboratory (SARL) at Georgia Tech, which emphasizes the application of multiple antennas to wireless communication systems. She holds the Georgia Tech ADVANCE Professorship for the College of Engineering for 2006-2011. She was a visiting professor at Aalborg University, Aalborg, Denmark in the summers of 2006-2008. The SARL performs system analysis and design, channel measurement, and prototyping relating primarily to wireless local area, ad hoc, and sensor networks, with a focus on the lower three layers. Prof. Ingram is a Senior Member of the IEEE.