Two Energy-Saving Schemes for Cooperative Transmission with Opportunistic Large Arrays

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***Abstract*— An opportunistic large array (OLA) is a form of cooperative diversity in which a large group of simple, inexpensive 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 energy than conventional multi-hop protocols. This paper proposes two schemes, one for general OLA transmission and one specifically for upstream routing in the topology of wireless sensor networks, that each save over 50% of the energy of flooding. The OLA-T scheme uses a transmission threshold to suppress nodes that would make weak contributions. The OLA Concentric Routing Algorithm (OLACRA) takes advantage of the concentric ring structure of broadcast OLAs to limit flooding on the upstream connection. Combination of these two schemes and variations of OLACRA are evaluated in terms of energy savings and probability of successful upstream routing.**

Keywords — Wireless communication, relays, cooperative communication, routing, ad hoc networks, multi-hop networks, wireless sensor networks.

I. INTRODUCTION

This paper proposes two simple methods to reduce the energy consumed by ad hoc wireless networks that use a form of cooperative transmission called the Opportunistic Large Array (OLA) [1]. The first method is generally applicable to all OLA transmissions. The second is an upstream routing method that is appropriate for wireless sensor networks (WSNs) that use OLA transmission. The second method takes advantage of the topology of a WSN, which is characterized by a sink, or fusion node in the center of a large, dense deployment of low-cost, energy-constrained nodes.

In an OLA, nodes transmit without coordination between each other, but they naturally fire together in response to energy received from a single source or another OLA. Each node has just one omni-directional antenna, however because the nodes are separated in space, the nodes in an OLA collectively provide diversity protection from multi-path fading [1, 2]. Because interfering transmissions are helpful rather than hurtful, OLAs reduce the need for contention-based, energy-consuming medium access control (MAC) and routing protocols for ad hoc networks [3, 4]. When the requirements on source and relay transmit powers and maximum data rate are met, OLAs form successively as contiguous concentric rings, until they cover the whole network [5]. OLA transmission has been shown to have advantages in terms of energy and speed for WSNs [3].

In spite of these advantages, the OLA approach still relies on flooding the network. For both broadcasts and unicasts, nearly all nodes participate by transmitting. One method called 'RNG Relay Subset Protocol' [8] for ad hoc networks uses neighbor graphs to limit node participation; however, network overhead goes up with the node density for this protocol. In contrast, the first scheme reported here, named OLA with transmission threshold (OLA-T), is a simple, distributed, no-overhead way to limit the transmitting nodes to only those that contribute significantly. It exploits the fact that not all the nodes in an OLA contribute significantly to the formation of the next OLA [7]. We show that OLA-T saves more than 50% of the transmission energy consumed by OLA flooding on the downstream. We note that the OLA-T concept was also expressed in [9], however [9] provided no analysis and did not consider variable thresholds.

The second scheme, named OLA Concentric Routing Algorithm (OLACRA), exploits the natural concentric structure of OLAs for energy-efficient upstream routing in WSNs with very little network overhead. Unlike OLA flooding [1], OLACRA uses only a fraction of the nodes on the uplink. In the only other paper we have found on OLA routing [6], a node's decision to relay is based on knowledge of its location. Location is presumably derived from the Global Positioning System (GPS), whose operation consumes significant energy. In contrast, OLACRA requires neither location nor pre-computing of routes. We show that, to keep a low source transmission power, OLACRA can be combined with limited flooding and a transmission threshold to save over 50% of energy in transmission relative to OLA flooding for the upstream.

II. NETWORK MODEL AND OLA FLOODING

We assume the "random network" of [5], which implies that half-duplex nodes are distributed uniformly and randomly over a continuous area. We also assume the "deterministic channel" model of [5], which implies node transmissions are

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mutually orthogonal (their powers add) and the only channel impairment is path loss with an exponent of two. While the path-loss-only and mutual orthogonality assumptions may not be practical, they greatly simplify analysis and they yield the similar OLA shapes and behaviors as the non-orthogonal transmissions and fading channels [5]. For the theoretical results, we assume the "continuum" model [5], which represents node density and relay transmit power with one variable: relay power per unit area, $\overline{P}_r$.

We assume a node can decode a message without error when its received signal-to-noise ratio (SNR) is greater than or equal to a modulation-dependent threshold [5]. Network slot-time synchronization is assumed [3]. For the protocol, "Basic OLA" in [5], if a node that is not the destination decodes a message that it has not previously relayed, then it will relay that message, i.e. the node will "decode and forward" (D&F). Nodes that decode the same message at approximately the same time form a "Decoding Level" (DL). Nodes that transmit the same message at approximately the same time form an OLA [5]. In Basic OLA, a DL is also an OLA. Borders of OLAs formed in a broadcast are illustrated by dashed circles in Fig. 1(a), where the nodes are grey dots and the sink is in the center. In a downstream broadcast, the outer boundary of DL will be called the "forward boundary," and the inner boundary will be called the "rear boundary." In Fig. 1(a), DL^4 is the fourth decoding level formed between the forward and rear boundaries, with radii $r_{d,4}$ and $r_{d,3}$, respectively.

In Basic OLA the "step size," or the distance between forward and rear boundaries of a decoding level, grows with the decoding level index [5]. In other words, the decoding levels that are farther from the sink are thicker. This step-size growth plays a role in both schemes proposed in this paper.

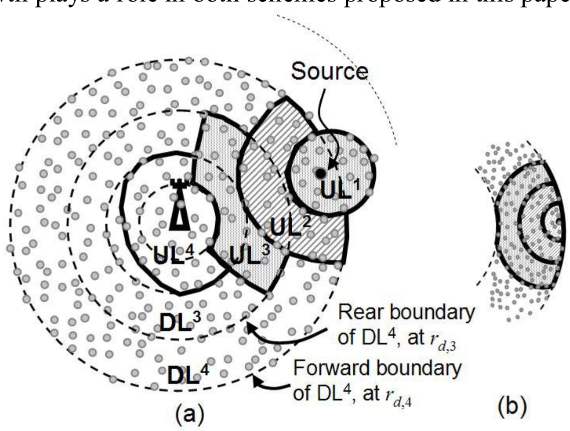

Figure 1. (a) OLA flooding and OLACRA; (b) limited upstream flooding (OLACRA-FT) (nodes not shown).

III. OLA WITH TRANSMISSION THRESHOLD (OLA-T)

Energy efficiency of OLAs can be improved by letting only the nodes near the forward boundary retransmit the message. 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 measuring the average length of the error vector (the distance between the received and detected points in signal space), 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 "rear" boundary, that is, near the source of the message. The OLA-T method is simply OLA with the additional transmission criterion that the node's received SNR must be less than a specified "transmission threshold," τ_b^k, where the superscript denotes the k^{th} OLA or "level." We recall that the forward and rear boundaries delineate sets of decoding nodes; with OLA-T the OLAs are only subsets of the decoding nodes. Thus, with OLA-T, the OLA rear boundary is not the same as the rear boundary of the decoding level.

Next, we provide some analytical results that show the energy savings from OLA-T. Numerical expressions for the OLA-T boundaries for the squared-distance path-loss model are now derived for the broadcast scenario, by slightly modifying the continuum approach in [5]. Let P_s be the source power. By assuming unity noise variance, the SNR criterion becomes a received power criterion, which is denoted as the decoding threshold τ_d. As in [5], distance d is normalized by a reference distance. Transmit power P is the received power at $d=1$. Received power from a node distance d away is $P_r = \min(P/d^2, P)$ [5]. Let $l(x,y) = (x^2+y^2)^{-1}$ be the squared-path-loss function, where (x,y) are the normalized coordinates of a receiver. Also as in [5], we define

$$f(q,p) = \int_0^q \int_0^{2\pi} l(p - r\cos\theta, r\sin\theta) r\, d\theta\, dr$$

as the aggregate path-loss from a circular disc of radius q to a point p. Let $r_{d,k}$ and $r_{b,k}$ denote the forward and rear boundaries, respectively, of the k^{th} OLA in OLA-T. These boundaries can be found recursively using

$$\overline{P}_r\left[f(r_{d,k}, r_{d,k+1}) - f(r_{b,k}, r_{d,k+1})\right] = \tau_d\,,$$
$$\overline{P}_r\left[f(r_{d,k}, r_{b,k+1}) - f(r_{b,k}, r_{b,k+1})\right] = \tau_b^k.$$

Using the initial conditions $r_0 = 0$, $r_{d,1} = \sqrt{P_s/\tau_d}$, and $r_{b,1} = \sqrt{P_s/\tau_b^k}$, for $k \ge 2$, the radii for the OLAs are $r_{d,k}^2 = \phi(\tau_d)$ and $r_{b,k}^2 = \phi(\tau_b^k)$, where

$$\phi(\tau) = \frac{\exp\left(\tau/(\pi\overline{P}_r)\right) r_{d,k-1}^2 - r_{b,k-1}^2}{\exp\left(\tau/(\pi\overline{P}_r)\right) - 1}.$$

The difference parameter ε_k is defined as $\tau_b^k - \tau_d = \varepsilon_k$. Because of the step-size growth with level index (k), we reasoned that ε_k must also grow with k to sustain OLA propagation. Therefore, we *arbitrarily* chose the following dependence on k:

$$\varepsilon_k = \begin{cases} 2.5, & k = 1 \\ \varepsilon_2 + (k-2)\gamma, & k \ge 2, \end{cases}.$$

where ε_2 and γ are independent parameters. We found that successful broadcast over a finite network strongly depended on the size of the first OLA, which is why we made ε_1 large and an exception to the linear rule. Let the ratio of the number of nodes that relayed under OLA-T over number of nodes that relayed with unlimited flooding (OLA) [5] be represented as β, then fraction of energy saved (FES) is given by 1- β.

Fig. 2 shows the behavior of the FES for of choices of ε_2 and γ for a continuum network analytically. The results are for a circular topology with radius 22 (in normalized distance units), source power 3 and relay power per unit area 1.11. Based on the results, the maximum theoretic savings are about 51% (over OLA flooding) for a choice of ε_2 = 0.78. It is also observed that in the lower left corner of the graph, there exist (ε_2, γ) pairs for which the OLA formation dies out before covering the network, for which we assign an FES of 0. The dashed line separates the scenarios when network broadcast fails from those that are successful. As the values of ε_2 and γ are increased, the fraction of nodes that relay increases and the FES drops significantly. In other words, the performance of OLA-T would approach that of Basic OLA for high values of ε_2 and γ.

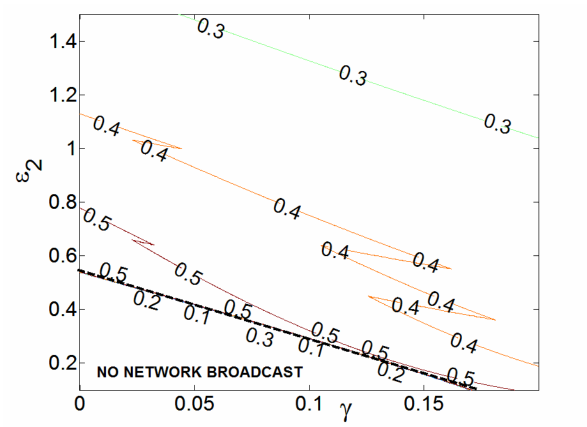

Figure 2. FES as a function of ε_2 and γ.

IV. OLA CONCENTRIC ROUTING ALGORITHM (OLACRA)

In this section we define OLACRA and its several versions that save energy and that enhance the probability of successful upstream transmission.

A. Basic OLACRA

The OLA Concentric Routing Algorithm (OLACRA) begins with the sink initializing the network by flooding the whole network using either basic OLA or OLA-T, but with one important difference. In Basic OLA, there is no need for a node to know its level. However, identifying each node with a particular level is required for OLACRA. This identification is achieved as follows. The sink transmits at carrier frequency f_1 with power P_{sink}. "Decoding Level 1" or DL^1 nodes are those that can D&F the sink transmission, except they retransmit using a different frequency f_2. This change of frequency distinguishes our approach from previous OLA works. Sensor nodes that can D&F the signal at f_2 and which have not relayed this message before will repeat the message with frequency f_3 and join DL^2. This continues until each node is indexed or identified with a particular decoding level.

We note that using the carrier frequency to signal the routing information is not the only way—spreading codes or preambles may also be used. However, frequency has the advantage that a simple filtering and energy detection is all that is needed to route the message.

For upstream communication, a source node in DL^{n-1} transmits using f_n. Any node that can D&F at f_n will repeat at f_{n-1} *if it is identified with the proper level(s)* and if it has not repeated the message before. We consider three cases of "proper levels" or "level ganging": (1**)** *Single-level*: DL^{n-1}; (2) *Dual-level*: DL^n or DL^{n-1}; (3) *Triple-level*: DL^n, DL^{n-1} or DL^{n-2}. Ganging all levels is the OLA flooding approach of [5]. For a given message, to ensure that OLA propagation goes upstream or downstream as desired, but not both, a preamble bit is required. In a previous work [10], the authors found that dual-level ganging was most effective, so that is used for the simulation results in this paper. Upstream OLAs formed by dual-level ganging are illustrated by the solid boundaries in Fig. 1(a). We shall refer to the n^{th} upstream OLA as UL^n, where UL^1 contains the source transmitter. In Fig. 1(a) for example, UL^1 is indicated by the solid circle and UL^4 contains the sink in the middle of the network. 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}.

B. OLACRA-T

As in OLA-T, energy can be saved in OLACRA if only the nodes near the upstream forward boundary are allowed to transmit. In OLACRA-T, nodes will not participate in an upstream transmission unless they meet the criteria for OLACRA *and* their received signal power is less than a specified threshold.

C. Enhancing Upstream Connectivity

The step-size growth mentioned in Section II can cause UL^2 to fail to form for an OLACRA upstream transmission when the source node is many, e.g. 7, steps away from the sink. The problem happens when there is a large gap between the boundary of UL^1 and the rear boundary of DL^n, where DL^n contains the source. Three possible remedies to this problem follow:

1) ***Increase the power of the source*** node for the upstream transmission. While effective, this approach is not practical because any node could be a source, therefore all nodes would require the expensive capability of higher power transmission.
2) ***Allow OLA or OLA-T flooding in just the first upstream level*** (i.e. allow all nodes in DL^n that can decode a

message to forward the message if they haven't forwarded that message before) until an OLA meets the upstream forward boundary of DL^n. We call this variation 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 Fig. 1(b), 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 Fig. 1(b)) in DL^n, are then considered an "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 frequency 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 carrier frequency coding, similar to the network initialization phase of OLACRA, must be used in this upstream flooding phase. To save 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. Simulation examples of OLACRA-FT are given in Section V.

3) ***Limit the step sizes of downstream OLAs.*** Step-size can be limited by reducing either the relay power or by reducing the transmission threshold in OLA-T. Reduced step size means more steps or OLAs will be needed to cover a network of a given size. Therefore, the step-size reduction approach may not be appropriate for delay-sensitive data. Another disadvantage of step-size reduction is that for a low node density, too slender an OLA may not have any nodes in it, whereas there will always be power with the continuum assumption.

Next, we will investigate the behavior of the maximum step size for the same continuum network that was considered in Fig. 2. Define the maximum step size for the network, $\Delta_{\max}$, as follows. Let $\Delta_k = r_k - r_{k-1}$, where $r_0 = 0$. Then Δ_k is the step size of the kth level or DL^k. Let r_{net} be the radius of the network. Then m OLAs are required for successful broadcast if $r_{m-1} < r_{net} \le r_m$. Then $\Delta_{\max} = \max_{k\in\{1,\ldots,m\}} \Delta_k$. Usually, $\Delta_{\max} = \Delta_m$. Fig. 3 shows the step size as a function of ε_2 and γ. The contours generally decrease with decreasing ε_2 and γ, however, there are some exceptions, e.g. at $\varepsilon_2 \cong 1.28$ and $\gamma = 0$, that are explained as follows. Suppose $\Delta_{\max} = \Delta_4$ for some certain ε_2 and ε_3. As ε_2 and ε_3 smoothly decrease, so will Δ_4. However, when $r_4 < r_{net}$, then $\Delta_{\max}$ switches to Δ_5, which is larger than Δ_4 at the time of the switch. As in Fig. 2, the white space in the lower left corner of Fig. 3 corresponds to parameters for which the broadcast fails to reach the edge of the network.

There are several observations we can make. First, step size reduction is possible through control of transmission threshold parameters. Second, if minimizing the step size is the objective, then the network should be operated near the point of broadcast failure. Third, by comparing Figs. 2 and 3, we see that the network becomes more energy efficient as the transmission threshold (and therefore step size) is reduced. Threshold and step size are dependent; large steps with low thresholds are not possible.

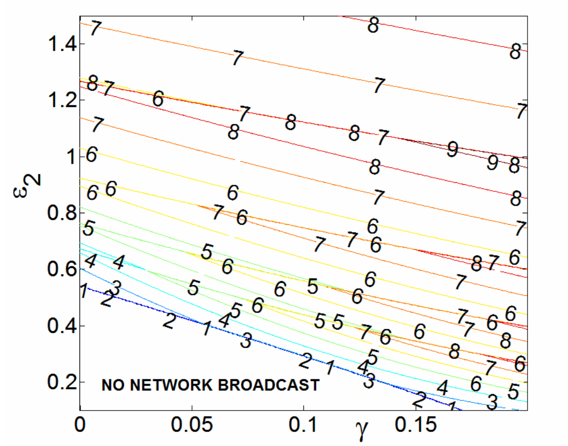

Figure 3. Maximum step size of OLA-T that corresponds to successful broadcast over a disk-shaped network of radius 22, as a function of transmit threshold parameters.

V. Simulation Results

Closed form analytical results are possible for the downstream broadcast scenario because of the simple geometry. However, the same is not true for the upstream using OLACRA and its variations because of the generally irregular shapes of the upstream OLAs. At the time of this writing, only Monte Carlo simulation is available to demonstrate the validity and explore the properties of the OLACRA protocol.

Each Monte Carlo trial had 2000 nodes in a square area $[0,30]\times[0,30]$, with the sink in the center at (15, 15). For the downstream, the source power was 3 and the relay power was 0.5. For all results in this section, $\tau_d = 1$ and 400 Monte Carlo trials were performed.

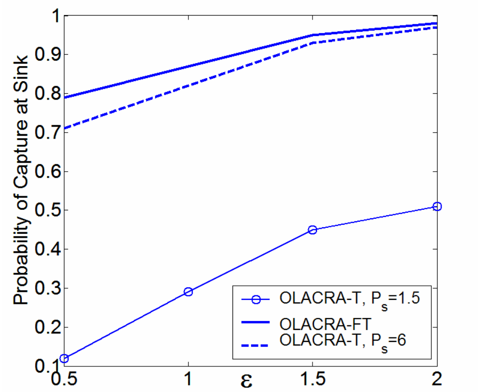

Figure 4. Probability of successful message delivery for three versions of OLACRA.

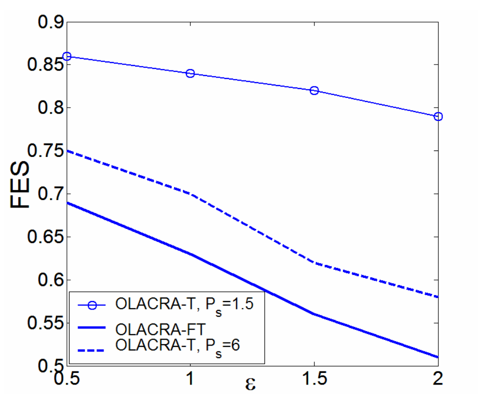

Figure 5. FES for three versions of OLACRA.

Figs. 4 and 5 address the upstream connectivity issue discussed in Section IV.C. To initialize the network, OLA-T was used with $\varepsilon_k = \varepsilon = 1.5$. A relay power of 1 was assumed for upstream routing. The source node was at (25.5, 25.5), which places it at the outer edge of DL^7. Fig. 4 shows the probability that the message successfully reached the sink as a function of ε, assuming that the same value of ε was used for all levels in OLACRA-T. The top curve represents OLACRA-FT, for which, in this example, a low source power of $P_s = 1.5$ was used and three OLAs of flooding were required to recruit forward boundary nodes. The downstream transmission boundary is also used in the first upstream level so only significant nodes in the extended source transmit. $\varepsilon = 2$ was used just for the flooding stage and the ε on the horizontal axis was used for the other upstream levels. For $P_s = 1.5$, OLACRA-T (no flooding), the probability at $\varepsilon = 1.5$ is poor at 0.47, but increases to 0.94 for the high source power of $P_s = 6$.

Fig. 5 indicates the FES for each of the same varieties of OLACRA that were considered in Fig. 4. We observe that OLACRA-T with $P_s = 1.5$ appears to have a great FES (about 83%) at $\varepsilon = 1.5$, but recall that the probability of reaching the sink is poor. On the other hand, OLACRA-FT has a lower FES of about 55% at $\varepsilon = 1.5$.

The fact that 55% FES was achieved with OLACRA-FT on the upstream and 51% FES was achieved by OLA-T on the downstream may seem to imply that the simpler algorithm OLA-T should be used on the uplink instead of OLACRA-FT. However, we point out that the OLA-T result has double the source power, which is OK for the downstream, but is not desirable for the upstream.

VI. CONCLUSIONS

Two energy-saving schemes were proposed in this paper for general and upstream transmissions, respectively, in ad hoc multi-hop networks that use opportunistic large arrays (OLAs). For the general case, the transmission threshold scheme (OLA-T) saves over 50% of the energy of an OLA flood, with no overhead and no central control. For upstream transmissions in wireless sensor networking topologies, the OLA Concentric Routing Algorithm (OLACRA), combined with first-level only flooding and OLA-T, yields over 50% saving in transmission energy relative to OLA flooding, without requiring that nodes know their location and without requiring high transmit power on the source node. Limiting the maximum downstream step size was explored as a potential way to reduce the first-level flooding in upstream transmission, while keeping high the probability of successfully delivering the message to the sink.

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