Energy-Efficient Strategies for Cooperative Communications in Wireless Sensor Networks

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Abstract

An opportunistic large array (OLA) is a group of simple, inexpensive relays or forwarding nodes that operate without any mutual coordination, but naturally fire together in response to energy received from a single source or another OLA. Therefore, OLAs do a form of cooperative transmission. OLAs, when used for broadcasting, form concentric rings around the source, and have been shown to use less energy than conventional multi-hop protocols. This paper proposes two energy efficient schemes: OLA-T for general OLA transmission and OLACRA for upstream routing in the topology of wireless sensor networks. OLA-T uses a transmission threshold to suppress nodes that would make weak contributions. OLA Concentric Routing Algorithm (OLACRA) exploits the concentric ring shapes of broadcast OLAs to limit flooding on the upstream connection. OLACRA-T is OLACRA with a transmission threshold. OLACRA-T and other variations of OLACRA are evaluated in terms of energy savings relative to a full flooding approach and probability of successful upstream routing. OLA-T and OLACRA-T are shown to save over 50% and 75%, respectively, of the energy relative to OLA flooding.

1. Introduction

An Opportunistic Large Array (OLA) [1] is a collection of nodes that behave without coordination between each other, but they naturally transmit or fire together in response to energy received from a single source or another OLA. OLAs do a form of cooperative transmission that has been shown to have an advantage in terms of energy for wireless sensor networks (WSNs) [2]. Each node has just one antenna, however because the nodes are separated in space, they collectively provide diversity protection from multi-path fading [1, 3, 4]. OLAs reduce the need for contention-based, energy-consuming MAC and routing protocols for ad hoc networks [2, 5].

This paper proposes two simple strategies to reduce the energy consumed by OLAs [1]. The first method, OLA-Threshold (OLA-T), is generally applicable to all OLA transmissions. The main result of this scheme, which is applicable for broadcast, is a closed-form expression for the total transmission energy for OLA-T. The second method, the OLA Concentric Routing Algorithm (OLACRA), is an upstream routing method that is appropriate for wireless sensor networks (WSNs) that use OLA transmission. Several variations of OLACRA are explored.

Many solutions have been proposed to replace the inefficient whole network flood by intentionally limiting the flood. In the Neighbor Elimination Scheme (NES) proposed in [6], a relay node does not retransmit immediately but waits for a given period of time. If during this period all its neighbors have been covered by other transmissions, it won't retransmit. The disadvantage to this scheme is that the overhead goes up with network density. Also it is difficult to ensure that this deletion won't jeopardize the broadcast coverage. RNG Relay Subset [7] is a modification to NES that keeps the overhead constant with increasing node density and also ensures broadcast. But both these methods require the nodes to be aware of their distance with all their neighbors, which would require Global Positioning System (GPS) or some other location sensing mechanism [6, 7]. Another method to limit the flood by making the transmissions propagate in a strip was proposed in [8], where also the flood was limited by exploiting GPS information. Limitations in cost and the need for energy efficiency may make GPS undesirable.

Unlike the network flooding approach previously proposed for OLAs [9], OLACRA uses only a fraction of the network nodes on the uplink, by exploiting the natural ring structure of OLAs formed in an initialization broadcast to guide a message up to the sink. Furthermore, the OLACRA approach inherits scalability with node density from the OLA transmission method and it does not require GPS information. We show energy savings as much as 50% and 75% for the OLA-T and OLACRA approaches respectively, relative to a full flooding approach [9].

2. General Network Model

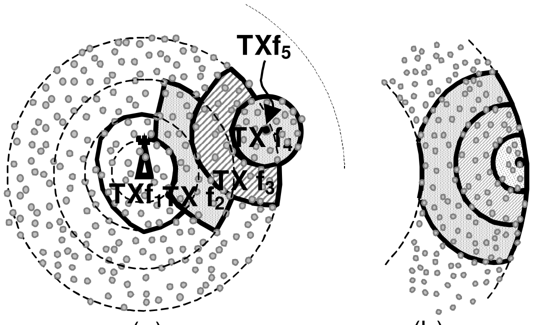
Half-duplex nodes are assumed to be distributed uniformly and randomly over a continuous area with average density ρ. The '*deterministic model*' [9] is assumed, which means that the power received at a node is the sum of the powers from each of the node transmissions. This model implies node transmissions are orthogonal. However, because non-orthogonal transmissions also produce similarly shaped OLAs [9], OLA-T and OLACRA should work in principle for them as well.

We assume a node can "decode and forward" (D&F) a message without error when its received signal-to-noise ratio (SNR) is greater than or equal to a modulation-dependent threshold τ_d [9]. Assumption of unit noise variance transforms SNR criterion to a received power criterion and τ_d becomes a power threshold. Let the source power be P_s and the relay transmit power be denoted P_r, and let the relay transmit power per unit area be denoted $\overline{P}_r = \rho P_r$. For a fixed $\overline{P}_r$, there exists a maximum threshold value such that the relayed signal will be propagated in a sustained manner by concentric OLAs [9]. Borders of such downstream OLAs are illustrated by dashed circles in Fig. 1a, where the nodes are grey dots and the sink is in the center.

3. 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 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. We note that with OLA-T, the front and rear boundaries delineate sets of transmitting nodes; these sets are generally only subsets of the set of all decoding nodes.



(a) (b)

Figure 1. (a) OLA flooding and OLACRA; (b) limited upstream flooding (OLACRA-FT)

We note that the OLA-T concept was discovered recently and independently by the authors of [10], however it was not analyzed in [10].

3.1. Analysis of OLA-T Broadcast

In the remainder of this section, we provide some analytical results that show the energy savings of 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 deterministic continuum approach in [9], which assumes $\rho \to \infty$, while $\overline{P}_r$ is held constant.

The relationship between the two SNR thresholds is given by $\tau_b - \tau_d = \varepsilon$. Let $l(x, y) = (x^2 + y^2)^{-1}$ be the squared-path-loss function, where (x, y) are normalized coordinates of a receiver. As in [4], 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 $p_r = \min(p/d^2, p)$ [9]. Also as in [9], we define the aggregate path-loss from a circular disc of radius x to a point p as

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

Let $r_{d,k}$ and $r_{b,k}$ denote the forward and rear boundaries, respectively, of the k^{th} OLA-T ring. These boundaries can be found recursively using

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

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

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

$$r_{j,k}^2 = \frac{\beta(\tau_j) r_{d,k-1}^2 - r_{b,k-1}^2}{\beta(\tau_j) - 1}, j \in \{b,d\},$$

where $\beta(\tau) = \exp\left(\tau / (\pi \overline{P}_r)\right)$.

Next, the recursive problem is cast as difference equation as follows:

$$\begin{pmatrix} r_{d,k+1}^2 \\ r_{b,k+1}^2 \end{pmatrix} = \begin{pmatrix} \alpha(\tau_d)+1 & -\alpha(\tau_d) \\ \alpha(\tau_b)+1 & -\alpha(\tau_b) \end{pmatrix} \begin{pmatrix} r_{d,k}^2 \\ r_{b,k}^2 \end{pmatrix},$$

where $\alpha(\tau) = [\beta(\tau) - 1]^{-1}$.

The solution is obtained by solving this first-order difference equation using Z-transforms. The closed-form expression for OLA-T radii is given by

$$r_{j,k}^2 = \frac{1}{A_1 - A_2}(\Delta_1 - \Delta_2),$$

$j \in \{b,d\}$, $\Delta_{1,2} \in \{\eta_{1,2}^k, \varsigma_{1,2}^k\}$, for $k > 0$, with the following definitions,

$$\alpha(\tau_d) - \alpha(\tau_b) = \Psi,$$

$$A_{1,2} = \frac{\Psi + 1 \pm \sqrt{(\Psi+1)^2 - 4(\Psi)}}{2},$$

$$\eta_i^k = \left\{ [A_i + \alpha(\tau_b)] \frac{P_s}{\tau_d} - \alpha(\tau_d) \frac{P_s}{\tau_b} \right\} A_i^{k-1}, i \in \{1,2\},$$

$$\varsigma_i^k = \left\{ [1 + \alpha(\tau_b)] \frac{P_s}{\tau_d} + [A_i - \alpha(\tau_d) - 1] \frac{P_s}{\tau_b} \right\} A_i^{k-1}.$$

From the derived expressions, it can be observed that the OLA-T radii depend on the ratio of the powers (P_s, P_r) to the thresholds (τ_b, τ_d).

The total relay transmission power in the deterministic continuum model can be expressed as $\xi^L = \overline{P}_r \sum_{k=1}^{L} \pi \left(r_{d,k}^2 - r_{b,k}^2 \right)$, where the L OLAs fill a given network area. Substituting for the radii, the total transmit power is

$$\xi^L = \frac{\pi}{A_1 - A_2} \left(\frac{P_s}{\tau_d} - \frac{P_s}{\tau_b} \right) \sum_{k=1}^{L} \sum_{i=1}^{2} (-1)^{i-1} (A_i - 1) A_i^{k-1}.$$

3.2. Energy Comparison for OLA and OLA-T

Since essentially all nodes transmit once under the original OLA protocol when conditions for broadcast are satisfied [9], we can define a metric for the energy saved with OLA-T relative to the original OLA protocol by simply using the ratio of the sum of areas of OLA-T rings to the area of the disk corresponding to the largest outer boundary of the OLA-T network. The Fraction of Energy Saved (FES) using the OLA-T relative to the OLA flooding, for the continuum network model, is given by

$$FES = 1 - \frac{\sum_{k=1}^{L} \pi \left(r_{d,k}^2 - r_{b,k}^2 \right)}{\pi r_L^2},$$

where L is the number of rings or levels considered. Fig. 2 shows FES versus epsilon for various values of relay power density $\overline{P}_r$. FES is computed for a set of ε for a fixed number of levels (10 in this case), and for different choices of $\overline{P}_r$. If the OLAs fail to propagate (i.e. if broadcast is not achieved), then FES is set to zero. The "cliff" in the curves indicates that excessively small values of ε cause broadcast failure. The choice for ε that yields the maximum FES value happens to be the one that just barely achieves broadcast. Fig. 2 also shows that FES increases with $\overline{P}_r$. For large ε (e.g. for ε>0.6, in Fig. 2) the improvements are small. However for small ε, higher values of $\overline{P}_r$ enable broadcast, and correspond to energy savings as high as 75%.

4. Energy Efficient Upstream Routing

4.1. OLACRA

OLACRA depends on an 'initialization phase' to help nodes decide if they should relay an upstream transmission or not. In the initialization phase, the sink transmits with waveform or preamble W_1 with power P_{sink}. Like OLA, "Downstream Level 1" or DL^1 nodes are those that can D&F the sink transmitted message, but unlike OLA, they retransmit the message using a different waveform W_2. For example the relayed message could use a different center frequency, a different spreading code, or simply change a field in the preamble. This change of the waveform distinguishes our approach from previous OLA works.

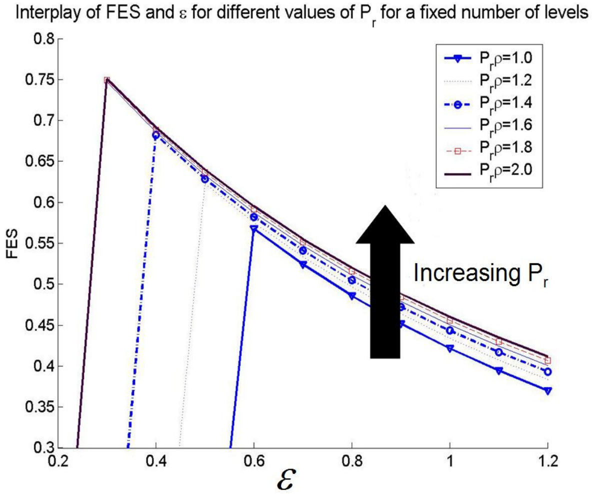


Figure 2. OLA-T vs. OLA: variation of FES with $\overline{P}_r$ and threshold difference ε for 10 levels.

Sensor nodes that can D&F the signal at W_2 and which have not relayed this message before will repeat the message with waveform W_3 and join DL^2. This continues until each node is indexed or identified with a particular level. We note that changing the waveform by shifting its center frequency has the advantage that simple filtering and energy detection is all that is needed to route the message. We also note that the waveforms can be reused after a few levels.

For upstream communication, a source node in DL^{n-1} transmits using W_n. Any node that can D&F at W_n will repeat at W_{n-1} *if it is identified with the proper level(s)* and 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 [9]. For a given message, to ensure that OLA propagation goes upstream or downstream as desired, but not both, a preamble bit is required. 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}.

4.2. 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.

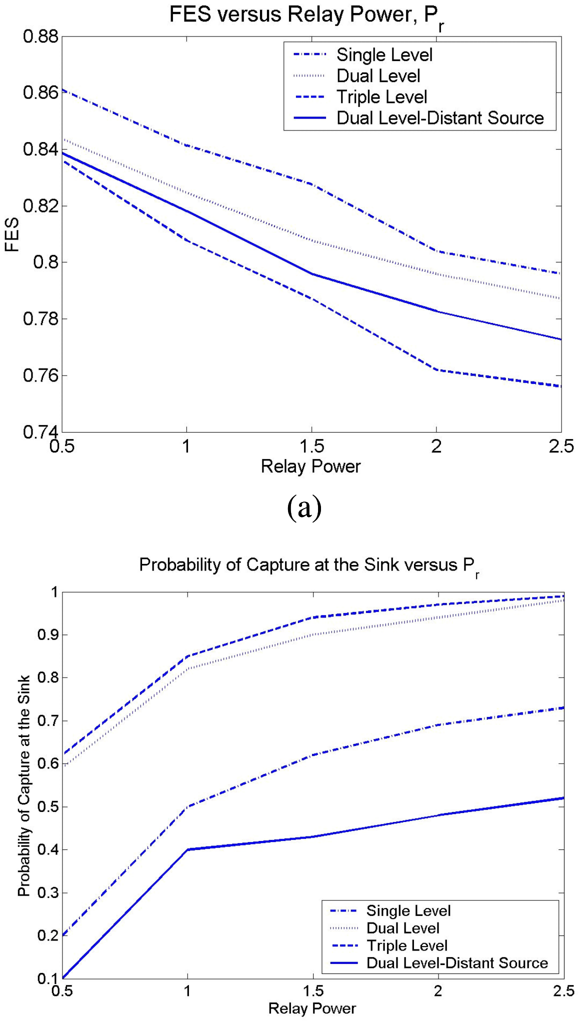
4.3. Enhancing Upstream Connectivity in OLACRA and OLACRA-T

It is a characteristic of an OLA broadcast that the thickness of the ring or level grows with the level index. This 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 can happen when there is a large gap between the forward and rear boundaries of DL^n, where DL^n contains the source. The following are some possible remedies to this problem.

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. A similar effect can be obtained by reducing the required decoding threshold, which in turn, reduces the data rate.

2) Limit the step-sizes (i.e r_{dk}-r_{dk-1}) of the downstream OLAs: We observe that the step size in OLA-T depends on the ratio P_r/τ_d and ε. Therefore the increase in step-size with level index can be limited by (1) reducing relay power, P_r, (2) increasing decoding threshold, τ_d, or (3) reducing epsilon, ε. Reduced step size means more levels are required to cover the same network area. So this method would be unsuitable for delay intolerant traffic. 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.

3) 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. It is noted that the worst case number of



(a)

(b)

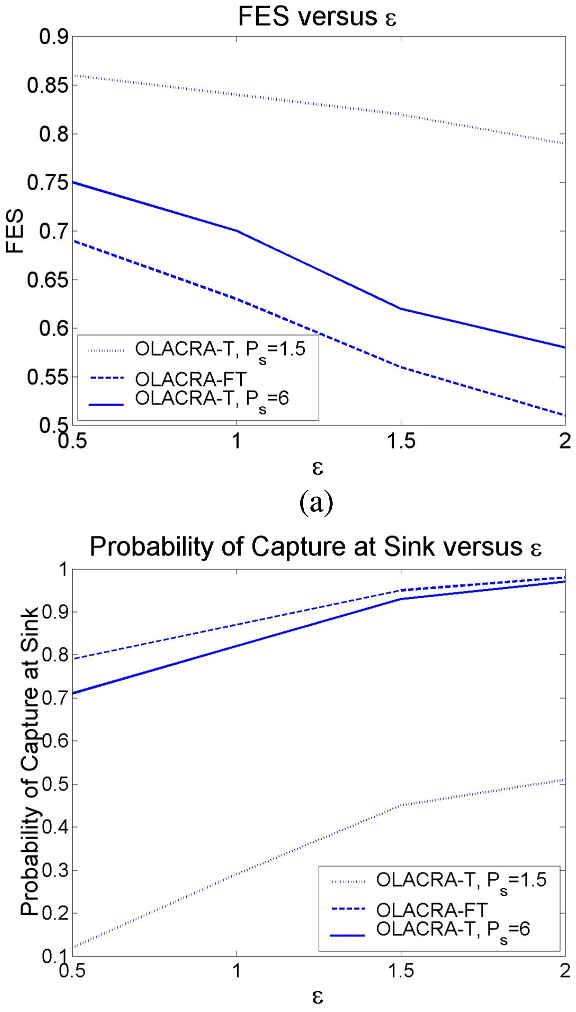
Figure 3. Effect of multiple-level ganging on OLACRA-T for (a) FES, and (b) probability of reaching the sink. $\varepsilon = 1.5$.

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 waveform, 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 different waveform is used, similar to the network initialization phase of OLACRA, 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.

4.4. Simulation Results

This section compares the different versions of OLACRA in terms of FES and probability of successful broadcast. Each Monte Carlo trial had 2000 nodes randomly distributed in a circular field of radius 17 with the Sink located at the center. The levels were established in the downstream with source power 3 and relay power 0.5. For upstream routing, the source power was 1.5 and the decoding threshold was 1. For the results in this section, 400 Monte Carlo trials were performed. The Upstream source node was located at a radius of 14 for the Dual Level Distant Source (DLDS) case and at a radius of 5 for all the other cases considered. These two cases were considered to show the variations of FES and probability of capture with distance of the upstream source node from the Sink. FES, in this section, calculates the fraction of energy saved using OLACRA-T compared to whole network flood.

Fig. 3a shows the FES under OLACRA-T, for different values of relay power and different level ganging strategies. Fig. 3b shows the probability that the message reached the sink, also versus relay power. We observe the single-level case had the highest FES for all values of relay power; however, the probability of reaching the sink was very low. Dual Level and Triple Level had much higher probabilities of capture, with only a small degradation of FES relative to Single Level. The use of the transmission threshold is probably what made the degradation small and not large. Though the FES values of Dual Level when the source was close to the Sink was comparable to the Dual Level Distant Source (DLDS) case, the probability of capture at the sink is rather low for DLDS. The reason is the distant source was in a downstream level that is so thick that the dual level upstream ganging was not enough to reach the upstream forward boundary.



(a)

(b)

Figure 4. FES (a), and Probability of Successful Message Delivery at the Sink (b), for OLACRA-T and OLACRA-FT

Figs. 4a and b compare OLACRA-FT and OLACRA-T for two different values of source power. We observe that OLACRA-T with $P_s = 1.5$ had the highest FES. But the probability of reaching the sink was less than 0.5 for all ε values considered. On the other hand, OLACRA-FT had an FES of 0.57 at $\varepsilon = 1.5$, with a high probability of reaching the sink of 0.9. OLACRA-T with the much higher power of $P_s = 6$ does only slightly better, showing that OLACRA-FT is effective.

6. Conclusions

Novel energy-efficient strategies were proposed in this paper for general and upstream transmissions in multi-hop wireless networks that use opportunistic large arrays, without requiring knowledge of the node locations and high source transmit power. Applying an upper threshold on received power as a criterion for transmission saves more that 50% of energy relative to OLA flooding, in uplink and downlink transmissions, with no additional overhead and no central control. The ratios of the powers to the decoding thresholds govern the broadcast performance strongly. For upstream transmissions in WSN topologies, using OLACRA with optimal ganging of levels yields significant gains of over 75% in terms of transmission energy relative to OLA flooding. It was also shown that allowing some flooding in just the first upstream level can significantly enhance connectivity with a minor energy penalty.

7. References

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