Power Allocation and Self-Scheduling for Cooperative Transmission Using Opportunistic Large Arrays

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Abstract*—This paper introduces methods for broadcasting and upstream routing in ad hoc networks that use a form of cooperative diversity called opportunistic large arrays (OLAs). By "limiting the flood," each method saves more than half the energy compared to OLA-flooding, without requiring GPS, individual node addressing, or inter-node interaction. OLAs form in "levels," and we present a simple, distributed way for a node to learn its level. In the broadcast method, called OLA-T, a node compares its received power to a prescribed threshold to decide if it should forward. A more energy-efficient variation, OLA-VT, optimizes the thresholds as a function of level. The upstream routing method applies to the wireless sensor network topology. The OLA concentric routing algorithm (OLACRA) exploits the concentric shapes of the OLAs to guide the message upstream to the collection node. Enhancements to OLACRA are considered to further improve energy savings and reliability.

I. Introduction

The requirement for energy efficiency in battery-powered wireless terminals is of paramount importance and pervades all aspects of the system design. Energy management solutions, which can be adopted at the different layers of the protocol stack to enhance energy efficiency of the system, can be broadly categorized into battery management, transmission power management and system power management [1]. This paper presents a distributed cross-layer approach to transmission power management, based on a physical layer that uses cooperative transmission.

Cooperative transmissions have diversity benefits that increase received SNR and save energy [2]. In [10], significant energy savings were leveraged as a result of a type of cooperative transmission called *Opportunistic Large Array (OLA)*. In an OLA setup, nodes behave without coordination between each other, but they naturally fire together in response to energy received from a single source or another OLA [6]. Each node has just one antenna, however because the nodes are separated in space, they collectively provide diversity protection from multi-path fading.

In [13], a centralized OLA broadcasting scheme is proposed that requires knowledge of the individual channel gains and that uses power allocation and scheduling to minimize total power consumption. For a dense network though, this requirement vanishes. The authors in [13] found an optimal *trivial schedule* for a dense OLA network that allocates power and order of transmission according to node distance from the source.

In [11], a node is assumed to know its geographical location to limit node participation. In the Relative Neighbor Graph (RNG) Relay Subset Protocol [16], only a subset of nodes relay the message from the source. Pairs of nodes are assumed to be able to evaluate the distance between them with integration of a positioning system or a signal strength measure. As a result, the network overhead goes up with the network density for this protocol. In [7], a couple of nodes are initially configured to transmit beacons to estimate node locations. This algorithm doesn't require Global Position System (GPS) information. Connectivity-based location estimation schemes have been developed for wireless ad hoc networks that gather neighborhood relations by each user through message exchanges over a wireless ad hoc network to estimate the locations of hosts [8].

Two simple strategies are proposed in our paper to reduce the energy consumption for OLA transmissions. These strategies achieve energy efficiency by only letting a subset of the total nodes in a level transmit and

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this subset determination requires no central control and coordination between nodes; in other words, the nodes *self-select* themselves for relaying. The first strategy, OLA-Threshold (OLA-T), is generally applicable to all OLA transmissions and achieves energy savings of about 50% compared to the OLA-flooding described in [9]. An OLA-T approach with level-dependent self-selection criteria, called the OLA-Variable Threshold (OLA-VT) which yields further energy savings, is also introduced in this paper. OLA-T and OLA-VT can both be shown to be suboptimal trivial schedules [13], with the virtues of simple implementation and good performance. While the OLA-T strategies are applicable to all OLA transmissions, a second strategy called the OLA Concentric Routing Algorithm (OLACRA) is an upstream routing method that is appropriate for wireless sensor networks (WSNs) that use OLA transmission. OLACRA 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. OLACRA requires only that a node remembers its OLA index from a previous down link transmission and that it relays any packet at most once. Variants of OLACRA that greatly enhance the upstream connectivity called OLACRA-FT and OLACRA-VFT are also presented. Like OLA-T, OLACRA and its variants require neither centralized control nor coordination among nodes to decide which node will relay.

Finally, an important feature that all the proposed schemes inherit from basic OLA is that no individual nodes are addressed. This makes the protocols scalable with node density.

II. System Model

Half-duplex nodes are assumed to be distributed uniformly and randomly over a continuous area with average density ρ. For simplicity, 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 for them as well. We assume a node can *decode and forward* (DF) a message without error when its received signal-to-noise ratio (SNR) is greater than or equal to a modulation-dependent threshold [9]. Assumption of unit noise variance transforms the SNR threshold to a received power criterion, which is denoted as the decoding threshold τ_d. 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 by $\overline{P_r} = \rho P_r$. For a fixed $\overline{P_r}$, there exists a maximum value of τ_d such that the relayed signal will be propagated in a sustained manner by concentric OLAs [9].

The loss function in cartesian coordinates is given by $l(x, y) = (x^2 + y^2)^{-1}$, where (x, y) are the normalized coordinates at the receiver. As in [9], distance d is normalized by a reference distance. Transmit power p is the received power at $d = 1$. Received power from a node distance away is $p_r = \min(\frac{p}{d^2}, p)$ [9]. The aggregate path-loss from a circular disc of radius x at an arbitrary point p is given by $f(x,p) = \int_0^x \int_0^{2\pi} l(p - r\cos\theta, r\sin\theta) r dr d\theta$ [9].

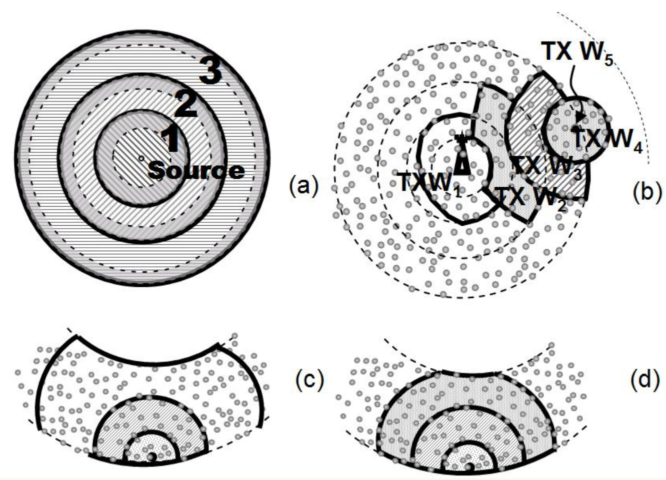

Fig. 1. *(a) OLA-T; (b) OLA flooding and OLACRA; (c) limited upstream flooding (OLACRA-FT); (d) OLACRA-VFT (Upstream Source in DL^{n-1})*

III. Energy-Efficient Broadcast for the Downlink

A. OLA-T

Energy efficiency of OLAs can be improved preventing the nodes whose transmissions have a negligible effect on the formation of the next OLA from participating in the relaying. 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. The difference between the two thresholds is given by $\tau_b - \tau_d = \epsilon$.

B. Analysis of OLA-T Broadcast

Formation of the downstream OLAs are a result of the transmitting strips in Fig. 1(a), where the nodes in each level are represented by hatched regions while the grey shaded regions refer to the subset of transmitting nodes at each level. The source is assumed to be at the center. The behavior of the OLA radii and energy consumption as a function of the OLA level, k are analyzed using the closed-form expressions for the OLA-T boundaries for the squared-distance path-loss model have been derived for the broadcast scenario, by slightly modifying the continuum approach in [9], which assumes relay transmissions are orthogonal and not faded.

Let the outer radius and inner boundary radius for the k-th OLA ring be denoted as $r_{d,k}$ and $r_{b,k}$. The boundaries can be found recursively using

$$\overline{P_r}\left[f(r_{d,k}, r_{j,k+1}) - f(r_{b,k}, r_{j,k+1})\right] = \tau_j,\ j \in \{b, d\}.$$

The problem is then cast as a difference equation. From [18], using the initial conditions, $r_0 = 0$, $r_{d,1} = \sqrt{\frac{P_s}{\tau_d}}$, and $r_{b,1} = \sqrt{\frac{P_s}{\tau_b}}$; the definitions for the k-th OLA are given by

$$r_{d,k}^2 = \frac{\eta_1^k - \eta_2^k}{A_1 - A_2},\ r_{b,k}^2 = \frac{\zeta_1^k - \zeta_2^k}{A_1 - A_2}, \tag{1}$$

where a few more terms as a function of α, β, and the initial conditions are introduced and given by

$$A_1 = \alpha - \beta, \quad A_2 = 1,$$

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

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

where

$$\alpha = exp\left(\frac{\tau_d}{\pi\overline{P_r}}\right),\ \beta = exp\left(\frac{\tau_b}{\pi\overline{P_r}}\right).$$

The radii for the OLAs have been plotted in Fig.2. as functions of the downstream OLA index given by (1). One can see that in the scenario where network broadcast fails, the radii converge to a value, as does the sequence of the square of the radii. On the other hand, where network broadcast is achieved, the radii has a highest value that is level-dependent or k-dependent. Note that this figure is on logarithmic scale. The *no-broadcast* case

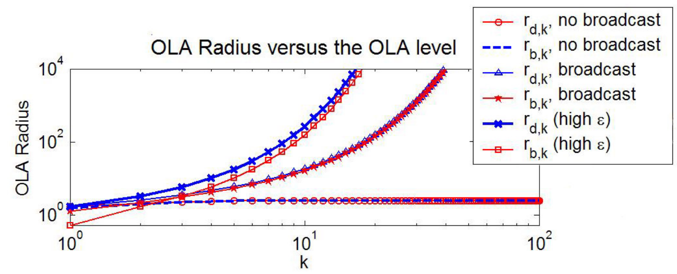

Fig. 2. $r_{d,k}, r_{b,k}$ *Versus* k

refers to a choice of $\epsilon = 0.2$ and the broadcast case corresponds to an $\epsilon = 0.8$.

The energy consumed by the first L levels in relaying the message in this multi-hop wireless network for a continuum case is mathematically expressed, in energy units, as $\xi^L = \overline{P_r}T_s\sum_{k=1}^{L}\pi(r_{d,k}^2 - r_{b,k}^2)$, where T_s is the length of the message in time units. Substituting for the radii, we have

$$\xi^L = \overline{P_r}T_s\left[\frac{\xi^1}{A_1 - A_2}\right]\sum_{k=1}^{L}\sum_{i=1}^{2}(-1)^{i-1}(A_i - 1)A_i^{k-1}. \tag{2}$$

As $\tau_b \to \infty$ (or high values of ϵ), the transmitting strip grows in thickness and the energy consumption asymptotically approaches the Basic OLA described in [9]. Thus, the energy consumption increases with increasing ϵ. On the other hand, as $\tau_b \to \tau_d$, one would expect the transmitting strips to start *thinning out*. In other words, for lower values of ϵ, the two thresholds become close and the set of boundary nodes that transmit decreases. And with a little bit of analysis, it follows from (2) that $\xi^L \to 0$, which is indicative of OLA formations dying out and a failure in the network broadcast operation.

We can express the fraction of transmission energy saved (FES) for OLA-T relative to Basic OLA as

$$FES = 1 - \frac{\sum_{k=1}^{L}\left(r_{d,k}^2 - r_{b,k}^2\right)}{r_{d,L}^2}. \tag{3}$$

C. OLA-VT

The approach till now has involved just a single *fixed* ϵ for the whole wireless system. A drawback of this approach is that the radii growth is polynomial and the OLA rings keep growing bigger, expending more energy than is needed, to cover a given network area. In this section, a level-dependent threshold that maximizes the FES achieving network broadcast is introduced and will be referred to as OLA-Variable Threshold (OLA-VT).

The Genetic Algorithm (GA) is adopted to determine the $\{\epsilon_k\}$ that yields the maximum FES and their corresponding optimal FES values are contrasted to those of fixed-ϵ systems. The input to the GA is a specification of the number of OLA levels (length of the $\{\epsilon_k\}$ sequence). The problem statement then becomes one of maximizing the FES for the fixed network subject to covering the network. Depending on the objective (and the definition of the penalty function in the GA) the choices for $\{\epsilon_k\}$ changes.

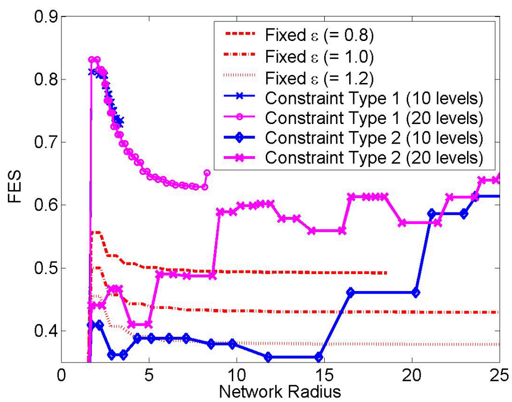

Fig. 3. *FES Comparisons for Variable ϵ_k Versus Fixed ϵ*

1) Constraint Type 1: Double Difference Criterion: The behavior of the radii with respect to the OLA index suggest that a negative second derivative can be used to detect a broadcast failure. In fact, it can be shown that the radii for both OLA and OLA-T successful broadcasts have a faster than linear growth with OLA index. We define double difference (DD) which as $(r_{d,k+2} - r_{d,k+1}) - (r_{d,k+1} - r_{d,k})$ and Constraint Type 1 is that this double difference is not negative for any k value under consideration. Fig.3 plots the FES as a function of network radius. For each curve, consecutive symbols correspond to the radii sequence $\{r_{d,1}, r_{b,2}, r_{d,2}, r_{b,3}, \ldots\}$. Since the FES is a function of whole levels and not partial levels, we just define the FES for $r_{b,i}$ to be equal to the FES for $r_{d,(i-1)}$. The first point thus represents the energy at $r_{d,1}$, since the FES at $r_{b,1}$ is zero. This enables us to see the step sizes and OLA widths for these network examples. The top 2 curves, which nearly overlay with each other, correspond to the variable epsilon case. The parameter for these two curves is the total number of levels. We observe that the step sizes are small and a higher number of levels corresponds to a larger network, for example, 20 levels corresponds to a network of radius approximately equal to 9, while 10 levels has a radius of only about 5. We also observe that the FES varies from 0.6 to 0.85 depending on network size. The bottom three curves correspond to the case of $\epsilon_k = \epsilon$ for all k. These curves also correspond to the number of steps fixed at 10. We observe that the step size starts large and decreases with network radius. The fixed-epsilon cases clearly have lower FES values than the variable epsilon cases, and lower values of epsilon have higher FES. One also notes that for large networks (theoretically, as network radius $\rightarrow \infty$), the FES gains saturate.

2) Constraint Type 2: Barely Broadcasting: While Constraint Type 1 was tailor-made for a very large network (an infinite network, in theory), Constraint Type 2 guarantees that a fixed-size network is just barely flooded with a high system FES. The key difference is that the algorithm checks if the radius of the last OLA level is greater than the specified network radius. To generate this plot, a network size of 25 was assumed. As an example, for the 20-level case, the algorithm maximized the system FES with the constraint that $r_{d,20} > 25$.

3) Discussion: The GA gives a sequence of $\{\epsilon_k\}$ that maximizes FES while flooding the given network. Having a level-dependent parameter yields significant energy savings compared to the OLA-flood. With Constraint Type 1, the FES versus network radius plot is a decreasing function. This behavior is expected as the smaller the steps one would take, higher would be the FES for the system. A shortcoming with this approach would be the time required (or the number of steps required) to achieve broadcast over a network. With Constraint Type 2, the objective was to just barely flood a given network while maximizing the system FES. So the GA picks an optimum combination of $\{\epsilon_k\}$ that achieves this goal. A general trend with this method is little steps initially followed by big steps as it reaches the network boundary. This explains the dips in the curves for Constraint Type 2 in Fig.3. From Fig.3, it can also be inferred that as ϵ increases FES decreases. Also, as the number of *steps* increases the FES for the system increases, for a fixed network radius. That is why the energy savings are higher for a network with 20 steps compared to just 10 steps.

IV. Energy-Efficient Upstream Routing

A. OLACRA

For upstream transmission in WSNs which use OLA transmission, the state of art routing protocols is flooding. But this is not energy efficient as most of the upstream traffic is not broadcast and is intended to be received only at the Sink. A method to limit the flood by making the transmissions propagate in a strip was proposed in [11], where the flood was limited by exploiting Global Position System (GPS) information, which might not be possible in Sensors. In [17], [18], the OLACRA algorithm was proposed by the authors as a way to limit the flood and save energy, without requiring GPS information. In this section, we review OLACRA and its variant OLACRA-FT. Then we introduce a more energy efficient version, OLACRA-VFT, which uses a variable relay power.

OLACRA depends on an *initialization phase* to help nodes decide if they should relay an upstream transmission. In the *initialization phase*, the sink transmits with waveforms or preambles W_1 with power P_{sink}. *Downstream Level 1* or DL^1 nodes are those that can DF the sink transmission, except they retransmit using a different waveform W_2. This change of waveform distinguishes our approach from previous OLA works. Sensor nodes that can DF 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. Routing information may be signaled purely by frequency modulation, which has the advantage that a simple filtering and energy detection is all that is needed to route the message. We also note that the waveforms, frequencies or preambles could be reused after a few levels.

For upstream communication, a source node in DL^{n-1} transmits using W_n. Any node that can DF at W_n will repeat at W_{n-1} if (1) *it is identified to be in DL^n or DL^{n-1}*, and (2) *it has not repeated the message before*. The authors had considered alternate lower performing schemes in [17], [18] where ganging of: (1) Single-level (DL^n), and (2) Three levels (DL^n, DL^{n-1}, DL^{n-2}) were studied. 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}.

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. Limitations of OLACRA and OLACRA-T

The protocols might fail in the upstream if the upstream source node is located far away from the Sink. This is because the thickness of the ring grows with the level index as shown Fig.2. The problem happens when there is a large gap between the boundary of UL^1 and the downstream rear boundary of DL^{n-1}. The following are the possible ways to enhance the upstream connectivity.

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. Similar effect can be obtained by reducing the required decoding threshold i.e data rate. This technique would not be suitable for communication systems that have strict delay requirements.

2) Limit the step-size of the downstream OLAs: We observe that the step size in OLA-T depends on the ratio $\frac{P_r}{\tau}$ 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 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) OLACRA-FT: Allow OLA or OLA-T flooding in just the first upstream level (i.e; allow all nodes in DL^{n-1} that can decode a message to forward the message if they haven't forwarded that message before) until an OLA meets the downstream rear boundary of DL^{n-1}. We call this variation OLACRA-FT. The worst case number of broadcast OLAs required to meet the downstream rear boundary of DL^{n-1} can be known a priori as a function of the downstream level index. For example, in Fig.1(c), three upstream broadcast OLAs are needed to meet the downstream rear boundary of DL^{n-1}. The union of the upstream decoding nodes (e.g. all three shaded areas in Fig.1(c)) in DL^{n-1}, 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. 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. 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.

D. OLACRA-VFT

The energy efficiency of OLACRA-FT can be enhanced by optimizing the relay power of the initial OLA flood levels in the upstream (OLACRA-FT with variable relay power: OLACRA-VFT). Consider the case in Fig.1(c) where the boundary of the third OLA flood level is just before the downstream rear boundary of DL^{n-1} . Here the upstream source node would do an OLA flood for 3 levels as required by OLACRA-FT making the width of the *extended source* really large, thereby making the scheme energy inefficient. The *skinniest* strip width which corresponds to the largest energy savings is obtained when the boundary of the last OLA upstream flood level is just above the downstream rear boundary of DL^{n-1} as in Fig.1(d). Since the radii depends on relay power, this can be achieved by varying the relay power of the initial OLA flooding stages, P_{rf}, to have the last upstream OLA flood boundary be as close to the downstream rear boundary of DL^{n-1} as possible. Similar result can be obtained by varying the transmission threshold, τ_f, or by using a combination of both.

While both methods try to vary the radii of the flood levels, they achieve it in different ways. While reducing relay power increases the number of levels required to reach DL^{n-1} thereby making more number of nodes transmit at a lower power, decreasing transmission threshold would decrease the number of nodes transmitting but the transmission is at a higher power relative to the former. OLACRA-VFT has been done 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 in the upstream transmission 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 the OLACRA levels in upstream use relay power P_r as defined in earlier sections.

E. 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 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 of the OLACRA protocol and its variants.

Each Monte Carlo trial had 2000 nodes uniformly and randomly distributed in a circular field of radius 17 with the Sink located at the center. The downstream levels were established using OLA-T with source power $P_s = 3$, relay power $P_r = 0.5$ and $\epsilon_k = \epsilon = 1.5$. For upstream routing using OLACRA, the source node was located at a radius 13 with $P_s = 1.5$. A relay power of 1 was assumed for upstream routing. $\epsilon = 1.5$ was just used for the flooding stage and the ϵ on the horizontal axis was used for the other upstream levels. The relay power for the flooding stage in OLACRA-VFT, P_{rf} was 0.6. For all the results in this section, the decoding threshold was 1 and 400 Monte Carlo trials were performed.

In Fig.4 the *right* Y-axis corresponds to the FES under OLACRA, for different values of ϵ while the *left* Y-axis shows the probability that the message has been successfully decoded at the Sink, also versus ϵ. We observed a maximum FES of around 0.86 for OLACRA-T(no flooding) with $P_s = 1.5$ for $\epsilon = 0.5$; however, the probability of reaching the sink was less than 0.5 for all values of ϵ. OLACRA-FT had the highest probability of successful message decoding at the Sink for all values of ϵ but the FES was only 0.55 for $\epsilon = 1.5$. OLACRA-T with the high source power of 6 and OLACRA-VFT had probability of successful message decoding at the Sink comparable to OLACRA-FT, and at the same time had a higher FES than OLACRA-FT. OLACRA-T with the high source power had an FES of 0.61 and the probability of successful message decoding at the Sink was close to 0.9 for $\epsilon = 1.5$. OLACRA-VFT performs similarly (FES=0.66 and probability of successful message decoding at the Sink of about 0.9 for $\epsilon = 1.5$) but it achieved this with a much lower $P_s = 1.5$. We observe that though OLACRA-VFT had a high probability of successful message decoding at the Sink, it was not as high as OLACRA-FT or OLACRA-T with $P_s = 6$. This was because OLACRA-VFT achieved a higher energy efficiency by making the step sizes in the flood levels smaller, but there was a possibility that the node occupancy in the flood level might be so low that message might not propagate.

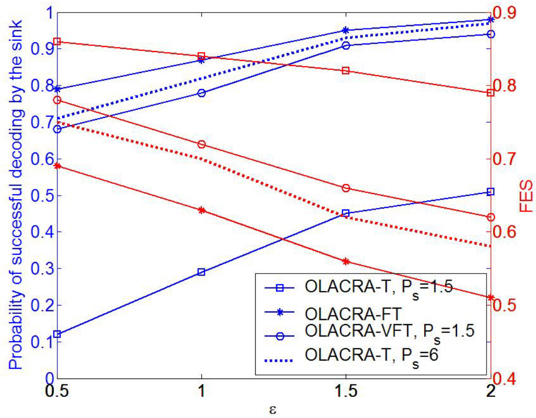

Fig. 4. *Right: FES versus ϵ (decreasing graph), Left: Probability of successful message decoding at the Sink versus ϵ (increasing graph)*

V. Conclusion

In this paper, we proposed and analyzed some optimizations to novel energy-efficient strategies that leverage the cooperative advantage in multi-hop wireless networks. OLA-T which has applications to the uplink as well as the downlink saves over 50% of the energy of an OLA flood, and OLA-VT results in energy savings as high as 80%, with no overhead and no central control. The trade-offs between the FES and the time to broadcast over a given network size were discussed using the OLA-VT. For upstream transmissions in WSN topologies, the OLACRA, combined with first-level only flooding and OLA-T, yields significant gains in terms of transmission energy of about 85% relative to OLA flooding. Upstream connectivity can be further enhanced by schemes such as OLACRA-FT and OLACRA-VFT which have energy savings of 65% and 78% each relative to whole network flooding. The inter-play between the system FES that can be achieved and the probability of successful message reception at the sink has been studied for the proposed upstream schemes.

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