Alternating Cooperative Transmission for Energy-Efficient Broadcasting

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***Abstract*—We propose a broadcast protocol that is based on a form of cooperative diversity called the Opportunistic Large Array (OLA). In the initial broadcast, an SNR ("transmission") threshold is used to define mutually exclusive sets of OLAs, such that the union of the sets includes all the nodes in the network. The broadcast protocol then basically alternates the transmitting set of nodes (or OLAs) during each broadcast cycle and is called Alternating OLA with Transmission Threshold (A-OLA-T). Under A-OLA-T, broadcasting drains the energies of the nodes in the network efficiently and uniformly, extending the network life relative to broadcasts that use simple OLA or non-alternating OLAs with a transmission threshold. In this paper, we optimize the A-OLA-T protocol under the continuum assumption (very high node density).**

I. Introduction

BROADCASTING is a significant operation, especially in multi-hop networks [1]. *Energy-aware* broadcast protocols either minimize the energy consumption [3]-[5] or maximize network lifetime [6]-[7]. The objective of minimizing energy may not be the most efficient for a fixed source because if all the data packets are routed through the same minimum energy path, batteries along the path will drain the batteries quickly, while the remaining nodes in the network will remain intact. During broadcast, the network life can be maximized by the routing the data packets such that the energy consumption is balanced among the nodes in the network. There are *cooperative* and *non-cooperative* algorithms that extend network life. Most broadcast algorithms in the current literature are non-cooperative and indirectly attempt to optimize groups of broadcasts to meet this objective. In this paper, we present broadcast strategies for multihop ad hoc and sensor networks that use cooperative transmission and explicitly optimize groups of broadcasts to increase the network longevity.

Cooperative transmission strategies provide spatial diversity, which enables dramatic reduction of the fade margins (i.e., the transmit powers) in a multipath fading environment, thereby saving energy [8], [9]. In [10], a simple cooperative transmission technique called the *Opportunistic Large Array* (OLA) was proposed, in which nodes behave without coordination between each other, but they naturally fire at approximately the same time in response to energy received from a single source or another OLA [11]. All the transmissions within an OLA are repeats of the same waveform; therefore the signal received from an OLA has the same model as a multipath channel. Small time offsets (because of different distances and computation times) and small frequency offsets (because each node has a different oscillator frequency) are like excess delays and Doppler shifts, respectively. As long as the receiver, such as a RAKE receiver, can tolerate the effective delay and Doppler spreads of the received signal and extract the diversity, decoding can proceed normally. Even though many nodes may participate in an OLA transmission, energy can still be saved because all nodes can reduce their transmit powers dramatically and large fade margins are not needed.

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OLA transmission has been proposed for energy-efficient broadcasting [11], [10], [13]-[15]. [11] and [10] propose what we refer to in this paper as Basic OLA. In Basic OLA, the first OLA comprises all nodes that can decode the transmission from the originating node; then the first OLA transmits and all nodes that can decode that transmission and that haven't decoded that message before, form the second OLA, and so forth.

The energy efficiency of OLAs can be improved by preventing those nodes from relaying, whose transmissions have a negligible effect on the formation of the next OLA. A node that receives much more power than is necessary for decoding is more likely to be near the source of the message. OLA with Transmission Threshold (OLA-T) method is simply Basic OLA with the additional transmission criterion that the node's received SNR must be *less* than a *user-specified* transmission threshold [18], [19], [21]. For a fixed source, such as the fusion node in a WSN, and for a static network, OLA-T causes the same subset of nodes to participate in all broadcasts. If we define network lifetime to be the length of time before the first node dies ("death" happens when the batteries die), and we assume that broadcasts are the only transmissions, then we observe that OLA-T has no advantage over Basic OLA in terms of network lifetime even though it consumes less total energy in a single broadcast.

The new broadcast scheme presented in this paper, which we call Alternating OLA With a Transmission Threshold (A-OLA-T), is an extension of OLA-T [18], [19], [21]. Unlike the OLA-based schemes above, our proposed strategy optimizes groups of broadcasts instead of a single broadcast. The key parameter is the *transmission* or SNR threshold, which controls the OLA sizes. The optimization involves minimizing the

OLA sizes while utilizing mutually exclusive sets of OLAs on consecutive broadcasts, thereby balancing the broadcast load across the network. An important feature that A-OLA-T inherits from Basic OLA is that no individual nodes are addressed. This makes this protocol scalable with node density.

II. System Model

For our analysis, we adopt the notation and assumptions of [15]. Half-duplex nodes are assumed to be distributed uniformly and randomly over a continuous area with average node density ρ. The originating node is assumed to be a point source at the center of the given network area. We assume a node can *decode and forward* (DF) a message without error when its received signal-to-noise ratio (SNR) is greater than or equal to a modulation-dependent threshold [15]. Assumption of unit noise variance transforms the SNR threshold to a received power criterion, which is denoted as the decoding threshold τ_d. We note that the decoding threshold τ_d is not explicitly used in real receiver operations. A real receiver always just tries to decode a message. If no errors are detected, and the message was decoded properly, then it is assumed that the receiver power must have exceeded τ_d. In contrast, the Transmission Threshold that we will introduce later is used explicitly in the receiver to compare against the received SNR.

For simplicity, the *deterministic model* [15] is assumed, which means that the power received at a node is the sum of the powers from each of the node transmissions. This implies that signals received from different nodes are orthogonal. The orthogonality can be approximated for example, with Direct Sequence Spread Spectrum (DSSS) modulation, RAKE receivers, and by allowing transmitting nodes to delay their transmission by a random number of chips [16], [20]. Let the source power be denoted P_s, the relay transmit power be denoted P_r, and the relay transmit power per unit area be denoted by $\overline{P_r} = \rho P_r$. We assume a continuum of nodes in the network, which means that the we let the node density ρ become very large ($\rho \to \infty$) while $\overline{P_r}$ is kept fixed. Continuing to follow [15], we assume a non-fading environment. 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 [15], distance d is normalized by a reference distance. Received power P_{rx}, from a node distance d away is $P_{\text{rx}} = \frac{P_0}{d^2}$ [15], where P_0 is the power at $d = 1$. The aggregate path-loss from a circular disc of radius x at an arbitrary point q is given by $f(x, q) = \int_0^x \int_0^{2\pi} l(q - r\cos\theta, r\sin\theta) r dr d\theta$ [15]. The received power at a point q, P_q, is given by

$$P_q = \overline{P_r} \int_0^x \int_0^{2\pi} l(q - r\cos\theta, r\sin\theta) r dr d\theta. \quad (1)$$

We note that non-orthogonal transmissions in fading channels produce similarly shaped OLAs [15], therefore the A-OLA-T concept should work for them as well, although the theoretical results would have to be modified.

III. Alternating OLA-T (A-OLA-T)

In this Section, we propose the Alternating OLA-T (A-OLA-T), which improves the network lifetime compared to Basic OLA and OLA-T. In A-OLA-T, broadcasts are grouped. Any number of broadcasts may be grouped under the continuum assumption; with finite node density, smaller group sizes are expected to be the best to ensure that the OLAs are populated with a sufficient number of nodes. In this paper, we consider just two groups, called *Broadcast 1* and *Broadcast 2*.

The idea of A-OLA-T is that the nodes that do not participate in one broadcast make up the OLAs in the next broadcast. To ensure that the sets of OLAs during each broadcast are mutually exclusive, the OLA boundaries should not change during the two broadcasts. It remains to determine if there exist OLA radii for A-OLA-T such that both Broadcasts 1 and 2 are successful, where success means that the broadcasted message propagates to the edge of the network. Since the boundaries don't change, our approach will be to first review the sufficient condition for Broadcast 1 to be successful. This condition takes the form of a lower bound on ϵ. An ϵ that satisfies this bound fixes the boundaries. Next, we derive a necessary and sufficient condition for Broadcast 2 to also be successful given these boundaries. The second condition is an upper bound on ϵ.

A. Broadcast 1 (OLA-T) [18]

Broadcast 1 is just OLA-T from previous work [18], which is summarized as follows.

Let the radii sequences $\{r_{d,k}\}$ and $\{r_{b,k}\}$ denote the outer and inner boundary radii sequences, respectively, for the k-th OLA ring formed during the Broadcast 1, as shown in the upper half of Fig. 1(a) (OLAs are indicated with blue shading). The boundaries can be found recursively using

$$\overline{P_r} \left[f(r_{d,k}, r_{j,k+1}) - f(r_{b,k}, r_{j,k+1}) \right] = \tau_j, \ j \in \{b, d\}. \quad (2)$$

Using the initial conditions, $r_{d,1} = \sqrt{\frac{P_s}{\tau_d}}$ and $r_{b,1} = \sqrt{\frac{P_s}{\tau_b}}$, the definitions for the k-th OLA using a recursive formula are given by

$$r_{d,k}^2 = \frac{\beta(\tau_d) r_{d,k-1}^2 - r_{b,k-1}^2}{\beta(\tau_d) - 1}, \ r_{b,k}^2 = \frac{\beta(\tau_b) r_{d,k-1}^2 - r_{b,k-1}^2}{\beta(\tau_b) - 1}. \quad (3)$$

From [18], the closed-form expressions for OLA-T radii are given by

$$r_{d,k}^2 = \frac{\eta_1 A_1^{k-1} - \eta_2 A_2^{k-1}}{A_1 - A_2}, \ r_{b,k}^2 = \frac{\zeta_1 A_1^{k-1} - \zeta_2 A_2^{k-1}}{A_1 - A_2}, \quad (4)$$

where

$$A_1 = \alpha(\tau_d) - \alpha(\tau_b), \quad A_2 = 1, \quad (5)$$

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

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

$$\alpha(\tau) = [\beta(\tau) - 1]^{-1}, \ \beta(\tau) = \exp\left[\tau / (\pi \overline{P_r})\right],$$

$$i \in \{1, 2\}, \text{ and } A_1 - A_2 \neq 0.$$

From [21], a sufficient condition to achieve infinite network broadcast with a constant transmission threshold was derived, which takes the form of the following lower bound for ϵ

$$\epsilon_{\text{lower bound}} = (-1)\left\{\overline{P_r}\pi \ln\left[2 - \exp\left(\frac{\tau_d}{\overline{P_r}\pi}\right)\right] + \tau_d\right\}. \quad (6)$$

B. Necessary and Sufficient Condition for Broadcast 2 Success

During Broadcast 2, the set of nodes that transmitted during Broadcast 1 will not transmit and the nodes that did not participate during the the first broadcast will transmit. In the previous Section, we presented a lower bound on ϵ. In this Section, we show that an upper bound on ϵ is required for a successful Broadcast 2.

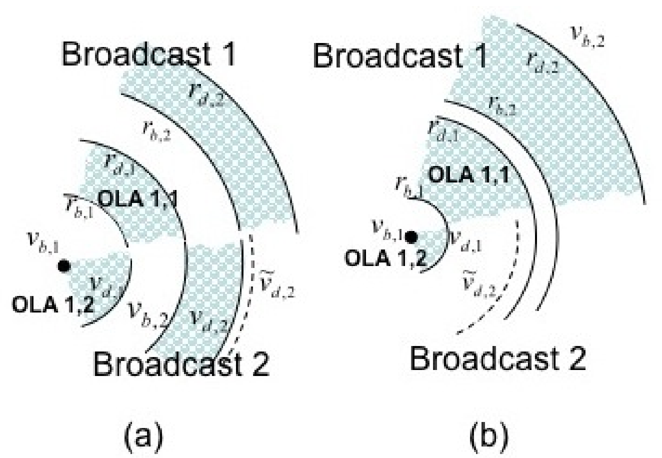

Fig. 1. *Illustration of the A-OLA-T Algorithm with (a) admissible ϵ, (b) inadmissible ϵ.*

Fig. 1(a) and (b) illustrate how it is possible to design OLAs for Broadcasts 1 and 2, to ensure that their propagation is sustained. The upper part of both drawings corresponds to Broadcast 1 and the radii are labeled according to (3). The lower parts of both drawings correspond to Broadcast 2. In Fig. 1(a) the OLA radii are relabeled $\{v_{d,k}\}$ and $\{v_{b,k}\}$, to denote the outer and inner boundary radii sequences, respectively for the k-th OLA ring formed during the Broadcast 2. The initial conditions for the second broadcast are $v_{b,1} = 0$, and $v_{d,1} = \sqrt{\frac{P_s}{\tau_b}}$. In Fig. 1(a), the first OLA during Broadcast 1 is denoted by *OLA 1,1* and is defined by the radii pair, $\{r_{b,1}\}$ and $\{r_{d,1}\}$. On the other hand, the first OLA during Broadcast 2 is denoted by by *OLA 1,2* and is the circular disk of radius $\{v_{d,1}\}$. Let $\widetilde{v}_{d,2}$ be the decoding range of *OLA 1,2* during Broadcast 2. The key idea is that $\widetilde{v}_{d,2}$ must be greater than $r_{b,2}$. In Fig. 1(a), this inequality is satisfied, while in Fig. 1(b), it is not. More generally, the network designer just needs to check that the decoding range, $\widetilde{v}_{d,k+1}$, of the k-th OLA in Broadcast 2 is always greater than $r_{b,k+1}$, for all k. Alternatively, we can compute the received power at $r_{b,k+1}$ and confirm that it is greater than the minimum. Mathematically, we express this as

$$\overline{P_r}\left[f(v_{d,k}, r_{b,k+1}) - f(v_{b,k}, r_{b,k+1})\right] \geq \tau_d. \quad (7)$$

We then substitute $r_{b,k} = v_{d,k}$ and $r_{d,k-1} = v_{b,k}$.

Intuitively, we observe that as ϵ becomes very large, the OLAs during Broadcast 1 become larger and the OLAs of Broadcast 2 become relatively smaller, as shown in Fig. 1(b). As a result, the sets of nodes that did not transmit during Broadcast 1 (or the OLAs during Broadcast 2), eventually become so small that their decoding range (indicated by the dashed line in Fig. 1(b)) cannot reach the next Broadcast 2 OLA to sustain propagation. In other words, for a very high value of ϵ, the k-th OLA in Broadcast 2 may be so weak that some nodes between $v_{b,2}$ and $v_{d,2}$ cannot decode the signal. When this happens, OLA formations die off during Broadcast 2 and A-OLA-T fails to achieve network broadcast. Thus, it makes sense for ϵ to have an upper bound. In the remainder of this section, we provide highlights of a derivation that guarantees a successful Broadcast 2. The complete derivation is in [22].

Substituting $r_{b,k} = v_{d,k}$ and $r_{d,k-1} = v_{b,k}$ into (7), and using the same approach as in [18] we can rewrite (7) as follows.

$$\begin{aligned} r_{b,k+1}^2 &\leq \frac{\beta(\tau_d)v_{d,k}^2 - v_{b,k}^2}{\beta(\tau_d) - 1} = \frac{\beta(\tau_d)r_{b,k}^2 - r_{d,k-1}^2}{\beta(\tau_d) - 1}, \\ \Rightarrow 0 &\leq \frac{\beta(\tau_d)r_{b,k}^2 - r_{d,k-1}^2 - (\beta(\tau_d) - 1)\, r_{b,k+1}^2}{\beta(\tau_d) - 1}. \end{aligned}$$

Next, we substitute the expressions for $r_{d,k}$ and $r_{b,k}$ from (4). Using the relation (6), collecting the A_1 and A_2 terms and re-arranging, we get

$$\begin{aligned} 0 \leq \Bigg\{ & A_1^{k-1}\left[\Big(\alpha(\tau_d) + 1\Big)\zeta_1 - \alpha(\tau_d)\eta_1 A_1^{-1} - \zeta_1 A_1\right] \\ & - A_2^{k-1}\left[\Big(\alpha(\tau_d) + 1\Big)\zeta_2 - \alpha(\tau_d)\eta_2 A_2^{-1} - \zeta_2 A_2\right]\Bigg\}. \end{aligned}$$

Next, we re-write this as shown below.

$$A_1^{k-1}\Omega - A_2^{k-1}\Pi \geq 0. \quad (8)$$

where

$$\Omega = \Big(\alpha(\tau_d) + 1\Big)\zeta_1 - \alpha(\tau_d)\eta_1 A_1^{-1} - \zeta_1 A_1, \text{ and}$$

$$\Pi = \Big(\alpha(\tau_d) + 1\Big)\zeta_2 - \alpha(\tau_d)\eta_2 A_2^{-1} - \zeta_2 A_2.$$

Using $A_2 = 1$ from (5), we get $\Pi = \zeta_2 - \eta_2 = 0$, which, when applied to (8) along with $A_1 > 1$ (proved in [22]), (8) may be simplified to $\Omega \geq 0$.

The inequality in (8) implies an upper bound on ϵ, the closed-form expression for which has been derived in [22] and is given by

$$\epsilon_{\text{upper bound}} = \overline{P_r}\pi \ln(r_1) - \tau_d, \quad (9)$$

where

$$r_1 = \frac{\beta(\tau_d) + 1 + \sqrt{\Big(\beta(\tau_d) + 1\Big)^2 - 4}}{2}.$$

We remark that it is not necessary to assume the same constant ϵ for both broadcasts or even for a single broadcast [19]. With the flexibility of variable transmission thresholds (τ_b^k or level-dependent ϵ_k), a designer may be able to make the decoding ranges in Broadcast 2 match up with the boundaries in Broadcast 1.

C. Relationship Between the Bounds and Relay Power

Fig. 2 is a plot of the upper and lower bounds for ϵ as a function of $\overline{P_r}$ and τ_d. First, we observe that as $\overline{P_r}$ increases, the difference between the upper and lower bounds increases. In other words, the range of ϵ over which A-OLA-T would be successful increases. This has two reasons. Increasing the $\overline{P_r}$ makes Broadcast 1 successful for more slender OLAs, which corresponds to a decrease of the lower bound. Higher $\overline{P_r}$ makes it easier for the OLAs during Broadcast 2 to reach across the next pair of boundaries and so this increases the upper bound. As an example, consider the curves for $\tau_d = 1$. As we increase $\overline{P_r}$ from 1 to 1.5, the range of ϵ increases from $[0.5, 0.8]$ to $[0.3, 1.3]$. Next, we consider the effect of varying τ_d for a fixed $\overline{P_r}$. Increasing τ_d increases both the upper and lower bounds. This is because a higher value of τ_d corresponds to a higher SNR requirement at the receiving node, and so in order to meet this power requirement, the OLAs must include more nodes. This is achieved by increasing ϵ. As an example, for $\overline{P_r} = 1$, the lower bound for ϵ increases from 0.2 to 0.5 when τ_d increases from 0.5 to 1. The upper bound for the same value of $\overline{P_r}$ also changes from 0.75 to 0.80 as τ_d is increased.

We also observe from Fig. 2 that the upper and lower bounds converge as $\overline{P_r}$ decreases. This implies a minimum value of $\overline{P_r}$, which we will denote as $\overline{P_r}_{(\mathrm{AO})}$, where the bounds meet. We observe that $\overline{P_r}_{(\mathrm{AO})}$ is a function of τ_d. The specific dependence is difficult to find analytically, so we find it numerically in this paper. However, by setting the upper bound equal to the lower bound, and by doing a little algebra, we can at least show that $\overline{P_r}_{(\mathrm{AO})}$ and τ_d are linearly related:

$$\epsilon_{\text{upper bound}} = \epsilon_{\text{lower bound}},$$

$$\overline{P_r}_{(\mathrm{AO})}\pi \ln(r_1) - \tau_d = (-1)\left\{\overline{P_r}_{(\mathrm{AO})}\pi \ln\left[2 - \exp\left(\frac{\tau_d}{\overline{P_r}_{(\mathrm{AO})}\pi}\right)\right] + \tau_d\right\}. \quad (10)$$

Simplification yields $r_1\left[2 - \exp\left(\frac{\tau_d}{\overline{P_r}_{(\mathrm{AO})}\pi}\right)\right] = 1$. We observe that τ_d appears only in ratio with $\overline{P_r}_{(\mathrm{AO})}$. Therefore, when a solution to the ratio $\frac{\overline{P_r}_{(\mathrm{AO})}}{\tau_d}$ exists, we know that $\overline{P_r}_{(\mathrm{AO})}$ must vary linearly with τ_d; i.e., $\frac{\overline{P_r}_{(\mathrm{AO})}}{\tau_d} = \gamma$, for some $\gamma > 0$.

For Basic OLA, the minimum $\overline{P_r}$ as a function of τ_d can be found directly from [15], and is denoted by $\overline{P_r}_{(\mathrm{O})}$. For example, substituting the $\tau_d = 1$ gives $\overline{P_r}_{(\mathrm{O})} = 0.4592$, which corresponds to the lowest $\overline{P_r}$ that would guarantee successful broadcast using Basic OLA.

Fig. 3 compares $\overline{P_r}_{(\mathrm{O})}$ and $\overline{P_r}_{(\mathrm{AO})}$ as functions of τ_d. As expected, the two curves are straight lines and $\overline{P_r}_{(\mathrm{AO})}$ has a higher slope than $\overline{P_r}_{(\mathrm{O})}$, implying that for a given τ_d, A-OLA-T requires a higher minimum $\overline{P_r}$ in order to achieve network broadcast compared to Basic OLA.

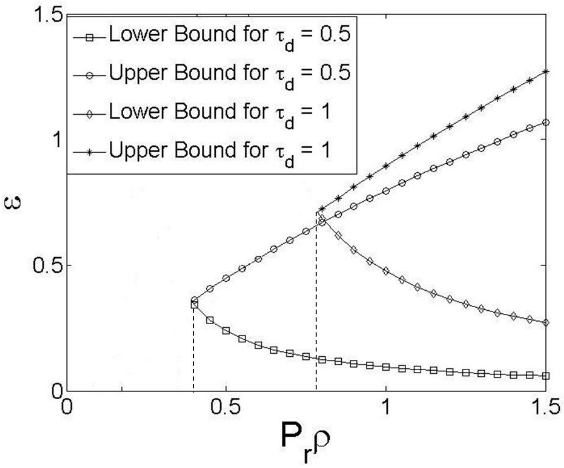

Fig. 2. ϵ *Versus* $\overline{P_r}$.

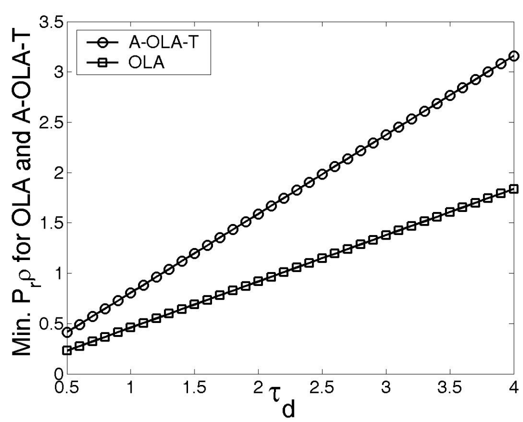

Fig. 3. $\overline{P_r}_{min}$ *for OLA and A-OLA-T to achieve network broadcast Versus* τ_d.

Next, we compare the network life extension resulting from A-OLA-T relative to Basic OLA. At a first glance, it would seem that A-OLA-T doubles the battery life of the sensors in the network compared to Basic OLA. This is true if A-OLA-T and Basic OLA use the same $\overline{P_r}$. However, this would not be a fair comparison since Basic OLA can achieve successful broadcast at a lower $\overline{P_r}$ according to [15]. Hence, we need to compare these two protocols at their respective minimum relay powers for a fixed value of τ_d. Since all nodes in both protocols use the same amount of power in broadcasts, we assume the *broadcast life* of the network is inversely proportional to the time-averaged power transmitted by each node. For Basic OLA, the time-averaged minimum power is $\overline{P_r}_{(\mathrm{O})}$. For A-OLA-T with two sets, the time-averaged minimum power is $\frac{\overline{P_r}_{(\mathrm{AO})}}{2}$, since each node transmits only every other broadcast. The ratio of broadcast lives of Basic OLA to A-OLA-T is therefore $2\frac{\overline{P_{r(\text{O})}}}{\overline{P_{r(\text{AO})}}}$, and the *Fraction of Life Extension* may be defined as

$$FLE = 2\frac{\overline{P_{r(\text{O})}}}{\overline{P_{r(\text{AO})}}} - 1.$$

Fig. 4 shows the FLE that is achievable for different values of τ_d. It is observed as τ_d increases the FLE increases and approaches a limit. That the limit exists is motivated by Fig. 3. It follows that as $\tau_d \rightarrow \infty$, the FLE approaches twice the ratio of the two slopes minus one, which is about 0.17. Recalling that τ_d is the SNR required for decoding, FLE will be close to its maximum for τ_d values between 4–10 (6–10 dB). Therefore, A-OLA-T extends network life by about 17% compared to Basic OLA in a minimum power configuration.

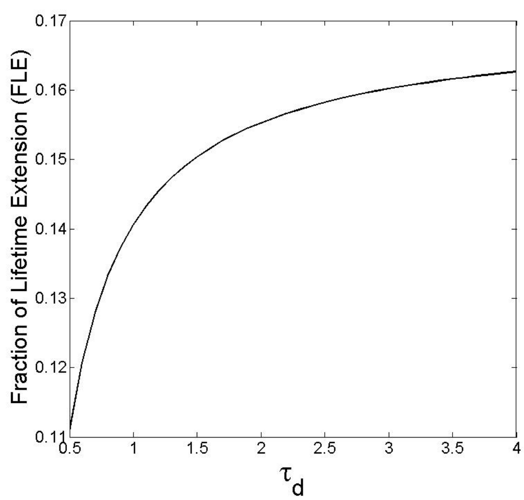

Fig. 4. *Fraction of Lifetime Extension (FLE) for A-OLA-T relative to Basic OLA as a function of the minimum required SNR for decoding,* τ_d.

IV. Conclusions

In this paper, we proposed and analyzed a novel same-source broadcast strategy that extends the life of a wireless ad hoc or sensor network by alternating between two mutually exclusive sets of opportunistic large arrays (OLAs) in pairs of broadcasts. We showed that A-OLA-T extends the network life by a maximum of 17% relative to the Basic OLA. Further, when A-OLA-T is compared to OLA-T, the battery-life of the nodes is doubled. The key parameter is the transmission threshold, which was assumed constant for the whole network. Plans for future work include an analysis of A-OLA-T for finite densities of nodes, other path-loss exponents, and fading environments, and a consideration of the limitations of practical synchronization.

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