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Equitable Energy Consumption During Repeated Transmissions in a Multihop Wireless Network

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***Abstract*—This paper addresses the issue of network life during repeated broadcasts originating from the same source in large, strip-shaped wireless sensor networks. The proposed technique would also apply to a unicast over a strip-shaped cooperative route within a network. The proposed medium access control (MAC)-free "alternating sets" transmission strategy is based on a very low-overhead form of cooperative diversity called the opportunistic large array (OLA). The proposed alternating OLA with transmission threshold (A-OLA-T) uses a received power-based threshold to define mutually exclusive sets of nodes, such that the union of the sets includes all the nodes in the network or cooperative route during the initial broadcast. A-OLA-T alternates the set of cooperators (or OLAs) during successive transmissions to reduce the energy consumption and the duty cycles of nodes (measured in terms of the percentage time a node is on and transmitting), thereby avoiding the formation of "hot spots" (regions of overuse, high energy consumption, and traffic) in the network. Under the continuum assumption (very high node density) for two-dimensional strip networks (or routes), we obtain lower bounds (as a function of the number of alternating sets, m) on the node degree for achieving optimal load balancing in the network, and, consequently, prolonging the network life.**

***Index Terms*—Broadcast, cooperative diversity, energy efficiency, life extension, multihop networks, opportunistic large arrays, sensor networks**

I. Introduction

In this paper, we investigate the alternating opportunistic large array with transmission threshold (A-OLA-T) for two-dimensional strip-shaped networks, and establish the conditions for optimal performance. A-OLA-T would be particularly useful for load balancing in broadcasts or along cooperative routes (defined as a sequence of clusters of nodes; nodes in each cluster being "geographically close" for cooperation) in which large number of packets follow the same route. Rectangular strips model sensor networks for some applications such as structural health monitoring (e.g., sensor strip along a bridge), detection of disruptive or dangerous events along a edge (e.g., a chemical spill), livestock monitoring during strip grazing, just to name a few.

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A. Background of OLA-Based Broadcast Protocols

Cooperative Transmission (CT)-based strategies leverage the spatial diversity in a network by having multiple nodes transmit the same message, and offers signal-to-noise ratio (SNR) advantage in a multipath fading environment that can be used to lower total transmission power expended in the network, achieve range extension, etc., [9], [10]. The opportunistic large array (OLA) is a simple form of CT wherein a group of nodes autonomously fire the transmit diversity waveforms in response to energy received from a single source or another OLA [6]. OLA transmission time synchronization with the root mean square transmit time delay spreads less than 100 ns have been demonstrated [11]. One simple, power amplifier-friendly way to achieve transmit diversity is to transmit on-off-shift keying (OOK) or frequency-shift keying (FSK) on orthogonal carriers, with a simple energy detectors in the receiver [11]. Even though many nodes may participate in an OLA transmission with diversity, total transmission energy can still be saved because all nodes can reduce their transmit powers dramatically and large fade margins are not needed.

"Basic OLA," during network broadcasts, uses nodes that haven't repeated the message before, subject to a condition on relay power and receiver sensitivity.

In a strip network, the message "propagates," forming rectangular OLAs that will eventually include all nodes in the network [6]. OLA with transmission threshold (OLA-T) applies a received signal power-based threshold to form an OLA comprising the nodes at the edge of the decoding range [1], [7]. However, for a fixed source in a static network, repeated use of the same sets of nodes in every broadcast drain their batteries first, resulting in *network holes*.

Two-set A-OLA-T was proposed in [8] to avert this situation in disc- and strip-shaped networks, respectively. This paper extends the two-set case to m-sets ($m > 2$) for strip-shaped networks. In A-OLA-T, a simple, decentralized algorithm, the transmission threshold is used to divide all the nodes in the network into many mutually exclusive sets of OLAs. For example, in the 2-set A-OLA-T, the network is divided into two mutually exclusive sets. The first set is used in the initial OLA-T broadcast, while the second set is used in the second broadcast. Each succeeding broadcast alternates between the two sets, thereby saving transmit energy via OLA-T, but also draining the batteries uniformly across the network.

B. Related Work

Dividing the nodes in the network into disjoint sets and activating them successively one set at a time to carry out network functions (e.g., monitoring, target tracking, etc.) has been investigated for non-cooperative wireless networks [2]–[4]. In [2]–[3], the network is divided into sets with the objective of maximizing the coverage (in terms of sensing area or targets-tracking) of each set, and the centralized algorithms activate these sets, one at a time, using only the sensors from the current active set for monitoring all targets and for transmitting the collected data to a sink. More recently, [5] explored combining and alternating between two non-cooperative routes (formed using multipath routing and spanning tree algorithms) to prolong the operation lifetime of nodes in a sensor network. Compared to the aforementioned non-cooperative strategies, in A-OLA-T, the sets are formed proactively based on the received signal power.

II. Analytical Framework

For our analysis, we adopt the notation and assumptions of [1], some of which were used earlier in [12]. Half-duplex nodes are assumed to be distributed randomly and uniformly over a continuous strip defined by $\mathbb{S} = \{(x, y) : |y| \leq \frac{W}{2},\ 0 \leq x \leq L\}$ with average node density ρ, width W, and length L. The originating source (assumed to be a point source) and the destination are assumed to be at the opposite ends of the network strip.

We assume a node can *decode and forward* (DF) a packet without error when its received signal-to-noise ratio (SNR) is greater than or equal to a modulation-dependent 'lower' threshold, τ_l [7]. In practice, there is no explicit SNR threshold; nodes DF only if they pass CRC check. In contrast, the 'transmission' or 'upper' threshold, τ_u is used explicitly in the receiver to compare against the received SNR. This additional criterion for relaying limits the number of nodes in each hop because a node would relay only if its received SNR is *less* than τ_u. This is in contrast to MAC CT schemes that require the SNR at the relays to be greater than a threshold [14]. Assumption of unit noise variance transform τ_l and τ_u to received powers, which define a range of received powers that correspond to the "significant" boundary nodes, which form the OLA. We define the relative transmission threshold (RTT) as $\mathcal{R} = \frac{\tau_u}{\tau_l}$.

For simplicity, the *deterministic model* [12] 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. Techniques to *induce* orthogonality in the node transmissions by randomly delaying the firing times (such as in [13]) or transmitting on orthogonal carriers (frequency division multiplexing) will work as long as the receivers can extract the multipath diversity from the wireless channel.

Following the Continuum Model for a strip network from [12], we assume a non-fading environment and a path-loss exponent of 2. The path-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 [7], distance d is normalized by a reference distance, d_0. Let the normalized source and relay transmit powers be denoted by P_s and P_r, respectively, and the relay transmit power per unit area be denoted by $\overline{P_r} = \rho P_r$. The normalization is such that P_s and P_r are actually the SNRs at a receiver d_0 away from the transmitter [7]. Since we assume a continuum of nodes in the network, we let the node density ρ become very large ($\rho \to \infty$) while $\overline{P_r}$ is kept fixed. Under the continuum assumption, A-OLA-T can have an *arbitrary* number of broadcast groups; however, 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. Our results are parameterized by $\mathcal{R}$ and node degree, $\mathcal{K}$, which for any finite node density, can be expressed as $\mathcal{K} = \pi\overline{P_r}/\tau_l$ [1]. Table I give some example values of our key parameters, and the receiver sensitivity in all the

TABLE I
EXAMPLES OF UN-NORMALIZED VARIABLES

Ex.	P_r (dBm)	Node Density (nodes/area)	$\mathcal{K}$	$\mathcal{R}$ (dB)	W
1	-48.00	3 nodes/m^2	12.56	1.2	10 m
2	-30.00	5 nodes/m^2	11	3	3 m
3	-20.97	2.5 nodes/m^2	6	2	4 m
5	-20.97	5 nodes/200m^2	14	3.5	6 m

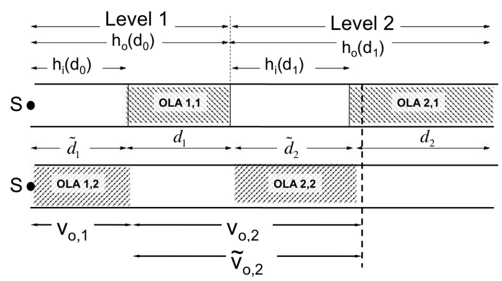

Fig. 1. *Illustration of the A-OLA-T with an admissible $\mathcal{R}$.*

examples was assumed to be -90 dBm.

III. ALTERNATING OLA WITH A TRANSMISSION THRESHOLD (A-OLA-T)

First, we review A-OLA-T with just two mutually exclusive sets (i.e., $m = 2$) during consecutive broadcasts, which was analyzed in [16]. Next, we consider A-OLA-T for m alternating sets, and derive conditions for optimal performance.

A. Review of 2-set A-OLA-T [16]

Figure 1 illustrates the basic concept of the A-OLA-T with 2 alternating sets. Let S be the originating node. The upper part of Fig. 1 corresponds to Broadcast 1, and the sequences $\{h_o(d_k)\}$ and $\{h_i(d_k)\}$ denote the outer and inner boundaries, respectively, relative to the previous OLA outer boundary. The boundaries depend on the OLA length, d_k, defined as $d_k = h_o(d_{k-1}) - h_i(d_{k-1})\ \forall\ k$. Furthermore, the boundaries, $h_\Omega(d_{k-1})$, $\Omega \in \{i, o\}$, are computed iteratively as the unique solutions of $\int_{h_\Omega(d_{k-1})}^{h_\Omega(d_{k-1})+d_{k-1}} \frac{2\overline{P}_r}{u} \arctan\left(\frac{W}{2u}\right) du = \tau_\Gamma$, where $\Gamma = u$ when $\Omega = i$ and $\Gamma = l$ when $\Omega = o$. The lower part of Fig. 1 corresponds to Broadcast 2, and the OLA radii are relabeled $\{v_{o,k}\}$ and $\{v_{i,k}\}$, to denote the outer and inner boundary sequences, respectively for the k-th OLA ring formed during the Broadcast 2. The initial conditions for the second broadcast are $v_{i,1} = 0$, and $v_{o,1} = h_i(d_0) = \sqrt{\frac{P_s}{\tau_u}}$.

Because Broadcast 1 is just OLA-T, the necessary and sufficient condition for a successful OLA-T broadcast, given by $2 \geq \exp\left(\frac{1}{\mathcal{K}}\right) + \exp\left(\frac{-\mathcal{R}}{\mathcal{K}}\right)$ [1], is also the Broadcast 1 condition, which reduces to the condition for a successful Basic OLA broadcast (as in [15]) when $\mathcal{R} \to \infty$:

$$2 \geq \exp\left(\frac{1}{\mathcal{K}}\right). \quad (1)$$

The aforementioned condition for OLA-T takes the form of a lower bound on $\mathcal{R}$, and is given by $\mathcal{R}_{\text{lower bound}} = -\mathcal{K} \ln\left[2 - \exp\left(\frac{1}{\mathcal{K}}\right)\right]$. In [16], it was shown that an upper bound on $\mathcal{R}$ is required for a successful Broadcast 2, and is given by $\mathcal{R}_{\text{upper bound}} = \mathcal{K} \ln\left[2\exp\left(\frac{1}{\mathcal{K}}\right) - 1\right]$. It was shown in [16] that two-set A-OLA-T extends the life of a strip-shaped network by about 141% relative to Basic OLA when both protocols were optimized.

During propagation down a strip, it was observed in [17] that after a transient period, a "steady state" is attained in which the OLA lengths (or step sizes) become uniform, i.e., independent of the index, k. Stating it differently, the lengths of adjacent OLAs from successive broadcasts become equal, and the ratio of adjacent areas converge to ≈ 1. Mathematically, the ratio of the total area of the Broadcast 1 OLAs to the total area of the network (for the first N levels), $\tilde{\Psi}$, expressed as $(1/r_{\text{strip}}) \sum_{k=1}^{N} d_k$, where $r_{\text{strip}} = \sum_{k=1}^{N} h_o(d_k)$, was shown to equal 1/2 for the $m = 2$ case at the minimum node degree, $\mathcal{K}_{(\text{A,min})}$.

IV. PERFORMANCE OF m-SET A-OLA-T ($m > 2$)

To analyze the performance of the A-OLA-T with m alternating sets for a strip-shaped route or network, we proceed as follows. For m-A-OLA-T, it is conjectured that $\tilde{\Psi}$ would be $1/m$ for all m broadcasts, and we have verified this numerically for $m = 4$. This phenomenon is illustrated in Fig. 2, which shows the steady state OLA propagation when alternating between four mutually exclusive sets of cooperating nodes. The k-th OLA during the Broadcast m is denoted by *OLA k,m*. In the steady state, (Refer to Fig. 2) the OLA lengths (or step sizes) become constant, and are denoted by d_∞. So, in the case of 4-set A-OLA-T, during each broadcast, the network designer just needs to ensure that the decoding range of the k-th rectangular OLA is at least greater than $4d_\infty$ to ensure enough nodes in the $(k+1)$-st OLA for sustaining OLA propagation. More generally, assuming steady state OLA propagation, satisfying $h_o(d_\infty) \geq m d_\infty$ will guarantee a successful

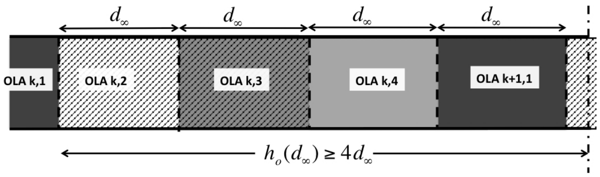

Fig. 2. Steady state OLA propagation for $m = 4$.

A-OLA-T broadcast, i.e., exercise mutually exclusive sets of nodes during successive broadcasts.

The optimum m-set A-OLA-T broadcast is achieved when (1) becomes an equality when $\mathcal{K} = \mathcal{K}_{(\text{A,min})}$. A closed-form expression for $\mathcal{K}_{(\text{A,min})}$ is derived as follows: Consider $h_o(d_\infty) = md_\infty$. Taking derivatives on both sides with respect to d_∞, substituting $d_k = 0$ (because closed-form expressions exist for $h_o^{'}(0)$ from [12]), we get $h_o^{'}(0) = m, \Rightarrow \frac{1}{\exp\left(\frac{1}{\mathcal{K}_{(\text{A,min})}}\right)-1} = m$. Simplifying further, we get

$$\mathcal{K}_{(\text{A,min})} = \left[\ln\left(\frac{m+1}{m}\right)\right]^{-1}, \qquad (2)$$

the same as that for a disc-shaped network (given by (2) in [18]).

A. Factor of Life Extension

We compute the "broadcast life" extension of A-OLA-T compared to Basic OLA when both protocols are operating in their minimum energy configurations. By broadcast life, we mean the lifetime of the network if only broadcasts were transmitted. Noting that every broadcast is an OLA-T broadcast, and in order to absorb the energy savings resulting from using strip-shaped networks (as demonstrated in [1]), we proceed as follows. We define the 'factor of life extension' (FLE) [1] achieved by A-OLA-T relative to Basic OLA as FLE $= 1/(1-\text{FES})$, where FES is the fraction of energy saved by OLA-T relative to Basic OLA [7]:

$$\text{FES} \;=\; 1 - \frac{\overline{P_r}_{(\text{OLA-T})}}{\overline{P_r}_{(\text{O})}} \frac{\Big(\text{Area used}\Big)_{\text{OLA-T}}}{\Big(\text{Area used}\Big)_{\text{Basic OLA}}},$$

where $\overline{P_r}_{(\text{O})}$ and $\overline{P_r}_{(\text{OLA-T})}$ denote the powers for each protocol.

We recall from (1) the minimum $\mathcal{K}$ for Basic OLA: $\mathcal{K}_{(\text{O,min})} = 1/\ln(2) \approx 1.44$. So, when the minimum powers are substituted, and using $\mathcal{K}_{\min} = \pi\overline{P_r}_{\min}/\tau_l$, we have $\widehat{\text{FLE}} = 1/(1-\widehat{\text{FES}})$, where $\widehat{\text{FLE}}$ represents the FLE achieved by A-OLA-T relative to Basic OLA, and $\widehat{\text{FES}}$ represents the FES achieved by A-OLA-T (per broadcast) relative to Basic OLA, when both protocols operate in their minimum power configurations.

Asymptotically (i.e., $m \to \infty$), considering (2), and the FES results for a strip-shaped network from [1], it is found that maximum $\widehat{\text{FES}} \approx 0.64$, yielding a maximum life extension of $\widehat{\text{FLE}} = 2.78$. In other words, A-OLA-T when deployed in a strip-shaped network can extend the operation life of sensors by 278% when both protocols are optimized, 88% higher than the lifetime extension obtained in a disc-shaped network from [18]. However, high enough network life extensions can be realized using reasonable values of m. For example, using $m = 3, 4$, and 12 yielded an $\widehat{\text{FLE}} \approx 1.61, 1.81$, and 2.63.

[1]We note that this performance metric is different from the *fraction* of life extension considered in [1], [8], [18].

V. Limiting OLA lengths, d_∞

Figure 3 is a plot of h versus the OLA length, d, for different values of m when the m-set A-OLA-T is operating in its minimum power configuration. The value on the abscissa corresponding to the intersection point of the line, $h(d) = md$ with the curve $h(d)$ is the limiting OLA length (or step size), i.e., when the OLA propagations have attained their steady state. It can be observed that with increasing m, the limiting OLA length decreases. When m is increased from 2 to 3, the limiting OLA length, d_∞ decreases from ≈ 0.3 to 0.2 units. This is because as the number of alternating sets increases, the OLA-T strips become narrower resulting in steady state OLAs of shorter lengths. It is remarked that Fig. 3 is plotted at the minimum permissible node degree, $\mathcal{K}_{(\text{A,min})}$ for the different values of m. It was also observed (not shown here) that operating A-OLA-T at higher node degrees increased the limiting OLA lengths, and lowered the lifetime extension relative to Basic OLA.

It is not possible to obtain a closed-form expression for the limiting OLA length, d_∞. Using the results from [12] ($r_{o,\infty} + d_\infty \leq W\mathcal{K}/\pi$), we are able provide an upper bound for d_∞, and outline the derivation. Noting that $r_{i,\infty} + d_\infty \leq \frac{W\mathcal{K}}{\pi\mathcal{R}} \Rightarrow r_{i,\infty} \leq \frac{W\mathcal{K}}{\pi\mathcal{R}}$ (since $d_\infty \geq 0$), it follows that $2d_\infty \leq \text{LUB}\left[\frac{W\mathcal{K}}{\pi} - r_{i,\infty}\right]$, where LUB is the least upper bound. So, $\text{LUB}\left[\frac{W\mathcal{K}}{\pi} - r_{i,\infty}\right] = \frac{W\mathcal{K}}{\pi} - \frac{W\mathcal{K}}{\pi\mathcal{R}}$, which results in

$$d_\infty \leq \frac{W\mathcal{K}}{2\pi} - \frac{W\mathcal{K}}{2\pi\mathcal{R}}.$$

It can be seen that the upper bound for $d_\infty \to$ upper

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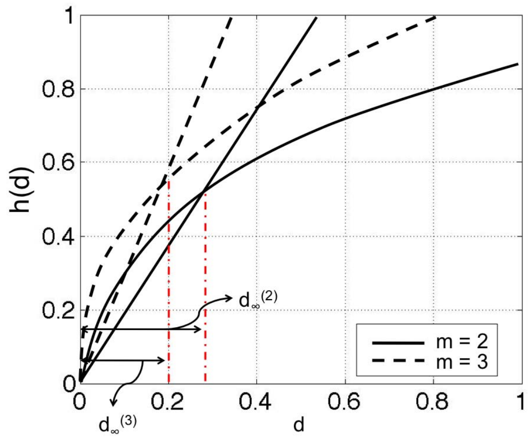

Fig. 3. Numerical evaluation of the limiting OLA lengths for different m at the minimum node degree, $\mathcal{K}_{(\mathrm{A,min})}$.

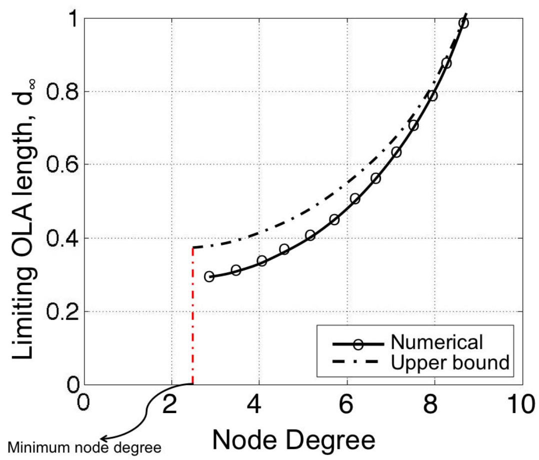

Fig. 4. The limiting OLA length, d_∞, versus node degree, $\mathcal{K}$.

bound for $r_{o,\infty}$ (as in [12]) when $\mathcal{R} \to \infty$. Figure 4 shows a comparison of the analytical bound with the numerical d_∞ for $m = 2$. It is seen from the figure that the upper bound becomes very tight at high node degrees away from the minimum node degree.

VI. Conclusions

A-OLA-T drains the batteries efficiently and equitably across the network, thereby avoiding hotspots in static networks. Unlike OLA-T and other OLA-based schemes, A-OLA-T optimizes groups of broadcasts instead of a single broadcast. A-OLA-T with m sets, $m >> 1$ extends the network life by a maximum of 278% relative to the Basic OLA when both protocols are operated in their minimum energy configuration. Future work includes a consideration of different path-loss exponents and practical effects such as finite node density.

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