

OPPORTUNISTIC LARGE ARRAY CONCENTRIC ROUTING ALGORITHM (OLACRA) OVER WIRELESS FADING CHANNELS

Lakshmi V. Thanayankizil, and Mary Ann Ingram
School of Electrical and Computer Engineering, Georgia Institute of Technology
{lakshmi, mai}@ece.gatech.edu

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 simple form of cooperative transmission. The Opportunistic Large Array Concentric Routing Algorithm (OLACRA) is an energy efficient upstream routing algorithm that has been proposed for OLA-based networks and has been shown to save over 70 percent of the energy in comparison to whole network OLA flooding for the non-faded channel. This paper analyzes the performance of OLACRA over the Rayleigh flat-fading channel. Distributed delay diversity using direct sequence spread spectrum (DSSS) waveforms is proposed to obtain diversity in such channels. Each node in an OLA chooses its transmission time randomly from a limited set of choices, thereby creating a limited set of orthogonal channels, which are then combined with RAKE receivers. Performance comparison is made with orthogonal non-faded channels. Simulations results demonstrate that the performance of OLACRA over the flat-fading channel approaches the performance of the deterministic channel for a diversity order of 4.

1. Introduction

Channel degradation due to signal fading arising from multipath is a critical performance bottleneck in wireless ad hoc networks. Diversity techniques are generally used to combat the detrimental effects of channel fading. A new kind of diversity called cooperative diversity [4] has been proposed that enables single antenna nodes in a multi-node environment to share their resources and generate a virtual array that allows them to achieve diversity. Energy efficient cooperative diversity protocols were introduced in [4,5] to combat the effects of channel impairment caused by multipath fading. These aforementioned schemes assume orthogonal channel allocations.

The authors gratefully acknowledge the support for this research from the Georgia Tech Broadband Institute (GTBI) and the National Science Foundation under grant # CNS-0721296.

Lately, a particularly simple and energy-efficient form of cooperative transmission, the opportunistic large array (OLA), has been proposed for broadcasting in WSNs [1]. An OLA is a large group of simple, inexpensive relays or forwarding nodes operate without mutual coordination, and transmit the same message at approximately the same time [6]. In addition to providing resistance to fading, OLAs have been shown to save over 20 percent of the energy in comparison with existing multihop broadcast schemes [2]. If the OLA nodes transmit the same message at exactly the same time in the same channel, then the OLA provides only array gain (a sum of the average powers), but no diversity gain (a reduction in the fade margin). Since diversity gain can enable transmit power reductions of 15 dB and higher, ensuring diversity gain is critical to the energy efficiency of OLAs.

In fading channels, an OLA can provide spatial diversity if the waveforms transmitted by the different nodes in the OLA are orthogonal and the receivers can receive on those orthogonal dimensions and do diversity combining. The authors in [6] considered the case when all nodes' transmissions were orthogonal to each other and the receivers could separate all transmissions and do optimal diversity combining.

Delay dithering schemes to orthogonalize transmissions were proposed in [7,8]. Wei et al. considered a limited orthogonal scheme in [8], where every relay node delays its transmission by a random 'artificial delay' selected from a pool of artificial delays $\{0, T, 2T, \dots\}$. This scheme converts the channel into m orthogonal channels which can be combined at the receiver. $m < n$ where n is the total number of transmitting nodes. Another work was done in [9] where space-time codes were used to orthogonalize channels of nodes in OLA based networks.

The authors in [6] also considered a case when all nodes transmitted on the same channel (*non-orthogonal*). Although most authors make node transmissions orthogonal to improve performance, authors in [6] showed that *non-orthogonal transmissions* outperformed the *orthogonal* case. This is because in a dense node deployment, although the probability of having a good fading realization is very small, there is always a fraction of nodes that experience them and they boost the overall performance of the system.

In this paper, we investigate the performance of OLACRA over Rayleigh flat fading channels. OLACRA is an energy efficient upstream routing protocol that has been proposed for Wireless Sensor Networks that use OLA-based

transmission. OLACRA was proposed in [8] for deterministic channels where nodes transmit in non-faded orthogonal channels. In this paper we extend OLACRA to fading non-orthogonal channels. In order to get diversity at the receiver we extend the scheme proposed in [8] to OLACRA. The relays transmit direct sequence spread spectrum (DSSS) waveforms in a flat-fading environment. We ensure m^{th} - order diversity gain by having each relay choose at random its transmission time from a time window m chips long. Therefore, for a large enough node density and a spreading code that has good autocorrelation properties (ideally, an impulse autocorrelation function), this strategy implies that a RAKE receiver with m fingers will achieve approximately equal average power per finger and therefore, with maximal ratio combining of the fingers, achieve full m^{th} order diversity gain.

2. Description of OLACRA

We consider a network where half-duplex nodes are assumed to be distributed uniformly and randomly over a continuous area with average density ρ . All antennas are assumed to be omni-directional. We assume a node can “decode and forward” (D&F) a message without error when its received signal-to-noise ratio (SNR) at the output of the RAKE combiner is greater than or equal to a modulation-dependent threshold τ_d . In the downlink, the sink transmits with waveform $W1$ with power P_{sink} . “Downstream Level 1” or DL^1 nodes are those that can D&F the sink transmitted message. Only the nodes in DL^1 whose received power is less than the “transmission threshold, τ_b , form DL_r^1 and relay the message using a different waveform $W2$.

The τ_b condition ensures that only nodes near the boundary relay the transmission, thereby saving energy. The relationship between the two SNR thresholds is given by $\tau_b - \tau_d = \mathcal{E}$. “OLA-T,” or the OLA algorithm that uses the τ_b condition, has been analyzed previously for the non-faded channel in [10]. When $\mathcal{E} \rightarrow \infty$, OLA-T becomes the OLA flooding approach in [6].

The DL_r^1 nodes transmit a waveform, denoted W_2 , that carries the original message, but the waveform can be distinguished from the source transmission, for example, by using a different preamble or spreading code. This difference enables nodes that can decode the W_2 waveform and which have not relayed this message before to know that they are members of a new decoding level, DL^2 . A DL^2 node with received SNR less than τ_b forms DL_r^2 and relays using a different waveform W_3 . This continues until each node is

indexed with a particular level.

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 DL^{n-1} and has not repeated the message before. 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.

3. Signal Models for Fading Channels

The signal model is explained in the context of the OLA-T downstream communication [3]. The spreading codes are assumed to be ideal. The Sink power is P_s , the relay transmit power is denoted as P_r , and the relay transmit power per unit area is denoted $\bar{P}_r = \rho P_r$. For a fixed \bar{P}_r , there exists a maximum threshold value such that the relayed signal will be propagated in a sustained manner by concentric OLAs [6].

Let the Sink start its transmission at $t=0$ by transmitting $W1$. Let the time at the which a node l receives the source transmission be t_r^l , where

$$t_r^{(l, \text{Sink})} = d(l, \text{Sink})/c$$

where c is the velocity of light and $d(a, b)$ is the distance between nodes a and b .

Following [6], the average power received by node l is

$$\bar{P}_l^1 = \begin{cases} \bar{P}_o \left(\frac{d_o}{d(l, \text{Sink})} \right)^n & d_o < d(l, \text{Sink}) \\ \bar{P}_o & \text{otherwise} \end{cases},$$

where n is the path loss exponent and \bar{P}_o is power received at a reference distance. n is chosen to be 2 in this work. We use normalized variables in our simulation. We let distance be normalized by the reference distance, and power be normalized by the path gain at the reference distance. Therefore, the average received power model becomes

$$\bar{P}_l^1 = \begin{cases} \frac{P_s}{d(l, \text{Sink})^2} & 1 < d(l, \text{Sink}) \\ P_s & \text{otherwise} \end{cases}$$

where \bar{P}_l^1 and $d(l, \text{Sink})$ are now considered normalized quantities.

Every node has a RAKE receiver with m fingers. However for the Sink transmission, the received power will be concentrated in the first finger. To model the Rayleigh fading, the received power, P_r^l at node l is an exponentially

$$t_t^l = t_r^{(l, Sink)} + T_c^j \quad \text{where} \quad T_c^j = jT_c.$$

T_c is the chip time of the DSSS signal transmitted, and $j \in \{0, 1, 2, \dots, m-1\}$, where m is the numbers of RAKE fingers at the receiver. This intentional delay dithering is done to create diversity as explained in Section 3.1.

Our idealized model for the power received by a RAKE finger is explained as follows. Consider a hypothetical node H that receives transmissions from all the nodes in DL_T^1 . The time when H receives the transmission from a node $P \in DL_T^1$ is given as

$$t_r^{(H,P)} = t_t^P + \frac{d(H,P)}{c},$$

where $d(H,P)$ is the distance between nodes H and P .

Let $\bar{P}_{r,k}^H$ be the *average* power received at the k^{th} RAKE finger of node H . We make the ideal assumption that $\bar{P}_{r,k}^H$ is the sum of average powers of all the signals that arrive at H within the k^{th} “delay bin,” which means that their arrival times $t_r(H, :)$ are such that $(k-1)T_c \leq t_r(H, :) \leq kT_c$.

Then $P_{r,k}^H$, which denotes the faded power received at the k^{th} RAKE finger of node H , is modeled as an exponential random variable with mean $\bar{P}_{r,k}^H$.

Furthermore, we assume a flat-fading channel, which means that without the intentional delay dithering, all transmissions from a single OLA will fall into one delay bin. This assumption is consistent with MICAZ motes in a limited indoor environment. MICAZ’s chip width is 500ns. Typical indoor delay spreads are less than 100ns and a signal propagates 150 m in 500 ns. So a network diameter less than 100 m will support this assumption.

Assuming maximal ratio combining, the total received power, P_r^H at H from the transmissions of all nodes in DL_T^1 is the sum of the powers of the RAKE fingers.

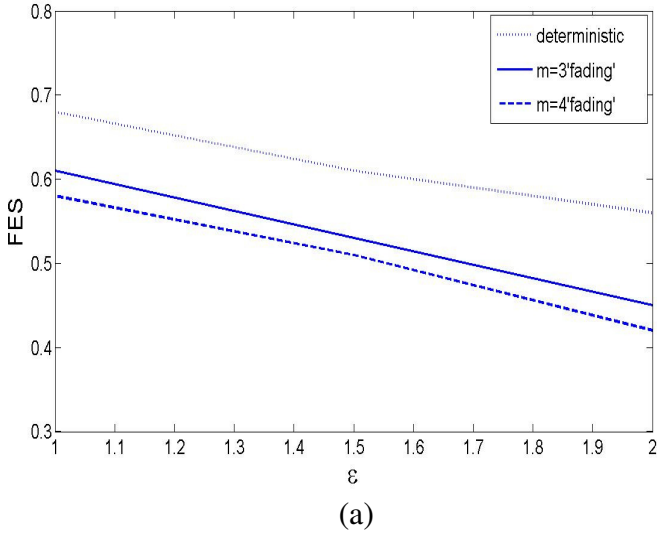
$$P_r^H = \sum_{k=1}^m P_{r,k}^H.$$

If $P_r^H \geq \tau_d$, the node joins DL^2 . This is continued till all nodes are indexed with a particular downlink level.

The signal model for the deterministic case is the same except P_r^H is replaced by \bar{P}_r^H .

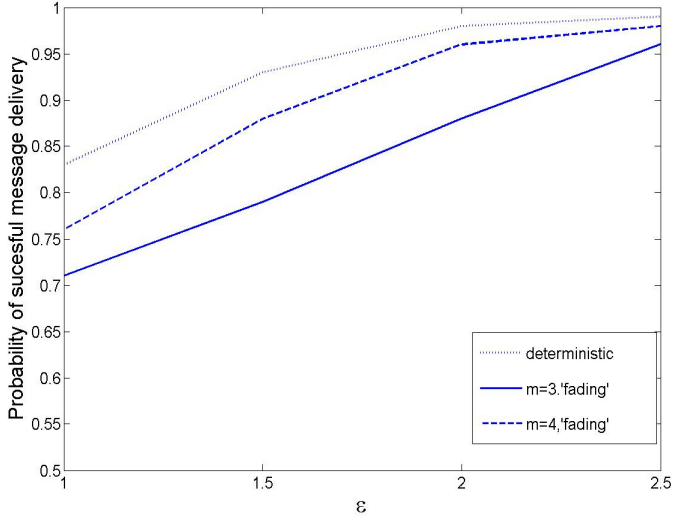
The Fraction of Energy Saved (FES) is a performance metric used to analyze the energy efficiency of OLACRA over a full network flood using OLA, which is the state of the art for OLA transmission if geographical location is not exploited. Since in a full OLA flood, every node transmits once, FES is defined as

FES v/s ε for OLACRA



(a)

Probability of succesful message delivery at the Sink v/s ε for OLACRA



(b)

Figure 1. Effect higher order diversity on (a) FES, and (b) probability of reaching the sink.

distributed random variable with mean equal to \bar{P}_l^1 .

A node l joins DL^1 if $P_r^l > \tau_d$ where τ_d is the decoding threshold. Now as described in Section 3 all nodes in DL_T^1 would repeat the message using a different waveform W_2 . The transmit times of these nodes in modeled as

$$FES = \frac{\text{Number of nodes that do not relay}}{\text{Total number of nodes}}$$

Even though the probability of outage due to multipath can be reduced by exploiting diversity through delay dithering, low source power is a critical bottleneck for upstream connectivity in OLA networks. Since any node can be a source node, the upstream source transmission would be at a relatively low power. Because of this there is a chance that there might not be enough nodes in its vicinity and OLA transmissions would never kick off. We call this problem the ‘initial bottleneck’.

We do a little analysis of this initial bottleneck. Let A be the event that there are no nodes within the decoding range of the source, and let B be the event that the message fails to get to the sink. Then $A \subseteq B$ and $P(A) \leq P(B)$. It is straightforward to calculate $P(A)$. We will show these two probabilities in the next section.

4. Simulation and Results

Monte Carlo simulations with 400 trials were conducted to test the OLACRA algorithm. Each trial had 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 $P_r = 1$ and $\epsilon = 3$. For upstream routing using OLACRA, the source node was located at a radius 13 with $P_s = 2$. A relay power of 1 was used for the upstream levels. For all the results in this section, the decoding threshold was 1. Each node randomly selected the transmission time from a time window m chips long.

Fig 1 (a) compares the FES under OLACRA under the *deterministic* channel model and *random* channel model, for different values of epsilon, while Fig 1 (b) shows the probability that the message is successfully decoded at the Sink, also versus epsilon. In each trial, the fading results for diversity orders 3 and 4 are compared to the deterministic case. We observe that for $m=3$ (third order diversity) FES is 0.61 at $\epsilon = 1$, whereas the FES for the deterministic case for the same value of ϵ is 0.68. Similarly the probability of message delivery at the Sink is only 0.71 for the $m=3$ case at $\epsilon = 1$, whereas the probability of success for the deterministic case is much higher at 0.835 for the same ϵ . Also even for a high value of $\epsilon = 2$, the probability of success is only 0.83 for $m=3$. But when the diversity order is 4 ($m=4$), the performance characteristics of the fading channel gets closer to the deterministic case. For $m=4$ the probability is about 0.94 for an epsilon of 2, when the deterministic case has

a probability of 0.96. It should also be noted that the FES performance of $m=4$ case is not very different from the $m=3$ case, meaning that the higher probability of message reception obtained by having an additional rake finger is not at the cost of energy.

Fig. 2 captures the variation of the probability that the message is not decoded by the Sink versus ϵ for different values of m (diversity order). The curve labeled ‘initial bottleneck’ shows the probability that there are no nodes in the first level in UL¹. At $m=1$, which corresponds to the ‘no diversity case’, we observe that the probability of failure is 1 for $\rho < 1.2$. Even at a much higher density, $\rho = 2$, the probability of failure drops only to 0.58. That it drops with increasing density is consistent with the claim in [6] regarding non-orthogonal transmissions. However when $m=2$, the probability of failure tends to zero at a node density of 2.2. When $m=3$, probability of failure drops to 0.01 at a node density of 1.1. It should be observed that the $m=3$ and ‘initial bottleneck’ lines are very close for $\rho \geq 1.1$, implying that at $m=3$, the probability of failure is dominated by the probability that there are no nodes in the first level (‘initial bottleneck’) since the probability of outage due to fading tends to zero.

Fig. 3 shows the power delay profile of a node located in UL³ at a radius of 7. m was chosen to be 3. The three vertical lines correspond to the power received at each of the RAKE fingers. It was observed that the total received power at each of the RAKE fingers converged to about 2, thereby

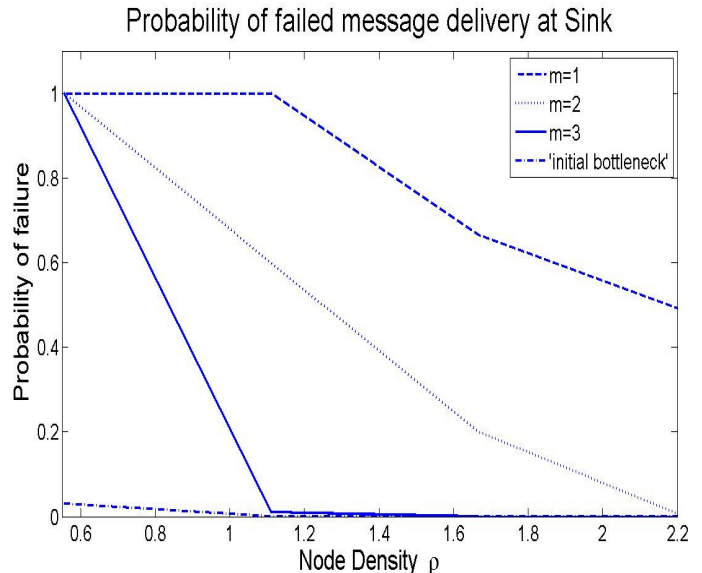


Fig. 2 (epsilon=3) Probability of failure v/s node density in OLACRA.

giving full ‘third order diversity’. Thus it can be inferred that by intentionally delaying the source transmissions we can orthogonalize the channel into m orthogonal flat fading channels with approximate equal power.

5. Conclusion

OLACRA is a simple routing scheme requires no centralized control and no knowledge of geographical location by the nodes. This paper has shown that OLACRA can work on flat fading channels when spread spectrum waveforms are used with sufficient dithering of the relay times to create delay diversity. At higher diversity orders the performance on such channels is shown to approach that of the ‘deterministic channel’ where transmissions are on orthogonal non-faded channels. In future work, we will explore the behavior of these networks when non-ideal spreading codes are used and for other network topologies.

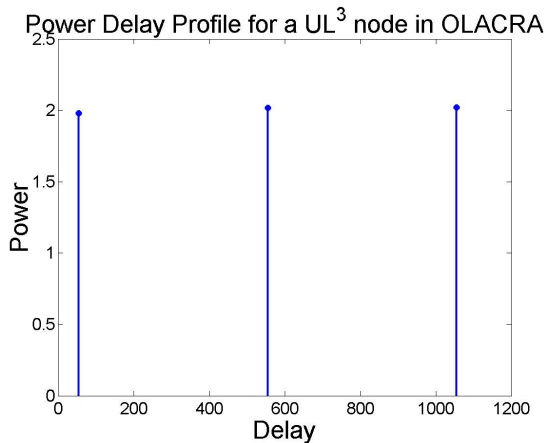


Fig.3 Power Delay Profile ($\mathcal{E} = 3$)

6. References

- [1] A. Scaglione, and Y. W. Hong, "Opportunistic large arrays: cooperative transmission in wireless multihop adhoc networks to reach far distances," *IEEE Transactions on Signal Processing*, Vol. 51, No. 8, pp. 2082-92, Aug. 2003.
- [2] Y.-W. Hong and A. Scaglione, "Energy-efficient broadcasting with cooperative transmissions in wireless sensor networks," *IEEE Trans. Wireless Comm.*, Vol. 5, No. 10, pp. 2844-2855.
- [3] L. Thanayankizil and A. Kailas and M.A. Ingram, "Energy-Efficient Strategies for Cooperative Communications in Wireless Sensor Networks," in *proceedings of IEEE Sensorcomm*, Oct 10-14, 2007.
- [4] N. Laneman, D. N. C. Tse and G. W. Wornell, "Cooperative Diversity in Wireless Networks: Efficient Protocols and Outage Behavior," submitted to *IEEE Transactions of Information Theory*, Vol. 49 pp. 2415-2425, Oct 2003.
- [5] T. Hunter, and A. Nosratinia, "Coded cooperation under slow fading, fast fading, and power control," in *Proc. Asilomar Conf. Signals, Systems. and, Computers*, Pacific Grove, CA, November 2002 .
- [6] B. Sirkeci-Mergen, A. Scaglione, G. Mergen, "Asymptotic analysis of multi-stage cooperative broadcast in wireless networks," in *Joint special issue*

of the IEEE Transactions on Information Theory and IEEE/ACM Trans On Networking, Vol. 52, No. 6, pp. 2531-50, Jun. 2006.

[7] R. Mudumbai, G. Barriac, and U. Madhow, "Spread-spectrum techniques for distributed space-time communication in sensor networks," *Proc. of Thirty-Eighth Asilomar Conference Signals, Systems and Computers*, Vol.1, pp. 908 - 912, Nov. 2004.

[8] S. Wei, D.L. Goeckel, and M. Valenti, "Asynchronous cooperative diversity," *Proc. of CISS*, Mar. 2004.

[9] A. Khisti, U. Erez, and G.W. Wornell, "A Capacity Theorem for Cooperative Multicasting in Large Wireless Networks," *Proc. Allerton Conf. Commun., Contr., and Computing*, (Illinois), Oct. 2004.

[10] L. Thanayankizil and A. Kailas and M.A. Ingram, "Two energy saving schemes for cooperative transmission with Opportunistic large Arrays," in *proceedings of IEEE Globecom*, Nov 26-30, 2007.