OPPORTUNISTIC LARGE ARRAY CONCENTRIC ROUTING ALGORITHM (OLACRA) FOR UPSTREAM ROUTING IN WIRELESS SENSOR NETWORKS

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OPPORTUNISTIC LARGE ARRAY CONCENTRIC ROUTING ALGORITHM (OLACRA) FOR UPSTREAM ROUTING IN WIRELESS SENSOR NETWORKS

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To my husband,

for his relentless support!

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SUMMARY

An opportunistic large array (OLA) is a form of cooperative diversity in which a large group of simple, inexpensive relays or forwarding nodes operate without any mutual coordination, but naturally fire together in response to energy received from a single source or another OLA. When used for broadcast, OLAs form concentric rings around the source, and have been shown to use less energy than conventional multi-hop protocols. This simple broadcasting scheme, which is already known, is called Basic OLA. The OLA Concentric Routing Algorithm (OLACRA), which is our contribution, takes advantage of the concentric ring structure of broadcast OLAs to limit flooding on the upstream connection. By limiting the node participation, OLACRA saves over 80% of the energy compared to Basic OLA, without requiring GPS, individual node addressing, or inter-node interaction. This thesis analyzes the performance of OLACRA over 'deterministic channels' where transmissions are on non-faded orthogonal channels and on 'diversity channels' where transmissions are on Rayleigh flat fading limited orthogonal channels. The performance of diversity channels is shown to approach the deterministic channel at moderate orders of diversity. Enhancements to OLACRA to further improve its efficiency by flooding in the initial upstream level and limiting the downlink 'step sizes' are also considered. The protocols are tested using Monte Carlo evaluation.

CHAPTER 1

INTRODUCTION

Recent years have witnessed a huge rise in the number of applications of Wireless Sensor Networks(WSNs). Usually WSNs would consist of a large number of low computational capacity resource-constrained nodes that are densely and randomly deployed on the fly for unattended operation. Since these devices are battery powered, one of the main design issues for a sensor network is conservation of energy available at each node, requiring WSNs to have energy efficient routing schemes and transmission algorithms. This thesis presents an energy efficient routing algorithm that is based on a physical layer that uses cooperative transmission.

Cooperative transmission (CT) is the strategy wherein one user helps another user transmit multiple copies or versions of the same message through independently faded channels to ultimately be received by a destination node [1, 2]. By sharing information this way, the users can create a "virtual array" and achieve spatial array and diversity gain. Because of the diversity gain, all users can reduce their fade margins (i.e. their transmit power) by as much as 12-15 dB, thereby reducing the energy consumed by each transmitter [3]. Because of the array gain (the simple summing of average powers from each antenna), the required transmission power for a link can be divided across multiple radios; this provides a convenient mechanism for applications in which each node has extreme transmit power constraints or heat restrictions. A particularly simple form of CT called the Opportunistic Large Array (OLA) [4] doesn't require predetermining or individually addressing relay nodes and is therefore scalable with node density and suitable for highly mobile networks. An OLA is formed when nodes transmit the same message, without coordination between each other, but at approximately the same time in response to energy received from a single source or another OLA [5, 6]. The signal received from an OLA has the same model as a multi-path channel [5]. Small time offsets (because of different distances and processing delays) 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 decoding can proceed normally. To induce orthogonalization of the diversity channels, nodes with RAKE receivers can intentionally delay their transmissions by certain fractions of a symbol period (to emulate a frequency selective channel) [7] or nodes with Orthogonal Frequency Division Multiplexing (OFDM) transmitters can choose different sub-carriers. Alternatively, Space-time Block Coding (STBC) can be implemented [8], where nodes can randomly choose which part of the STBC code they will transmit. Even though many nodes may participate in an OLA transmission, energy is saved relative to single-node transmissions because all nodes can reduce their transmit powers dramatically and large fade margins are not needed. Further in [6], the Basic OLA algorithm was shown to yield an energy savings of over 5dB compared with the Broadcast Incremental Protocol (BIP) algorithm [9].

This thesis presents the OLA Concentric Routing Algorithm (OLACRA), which is an upstream routing method that is appropriate for wireless sensor networks (WSNs) that use OLA based cooperative transmission and which are characterized by a Sink, or fusion node in the center of a large, dense deployment of energy-constrained nodes [10].

OLACRA exploits the natural concentric structure of OLAs that are naturally created in the previous broadcast to limit the size of the upstream OLAs and guide them back to the Sink. OLACRA requires neither location knowledge nor centralized control for pre-computing of routes. Further energy can be saved though the use of a transmission threshold [11] to save over 80% of energy in transmission relative to Basic OLA broadcast for the upstream [12]. This variant of OLACRA is called OLACRA-T (OLACRA with Transmission threshold). 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.

Variants of OLACRA-T that enhance the upstream connectivity called OLACRA-FT (OLACRA with Flooding and Threshold) and OLACRA-VFT (OLACRA-FT with variable relay power) are also presented [13]. The downlink transmission is optimized to obtain fixed step sizes in OLACRA-SC and energy savings of over 90% relative to Basic OLA is reported in this scheme. These are analyzed for *deterministic channels* [11], where node propagations are on orthogonal non faded channels and on *diversity channels* where transmissions are on faded limited orthogonal channels. Intentional delay dithering with RAKE receivers is done at the transmitter nodes to provide diversity gain at the receiver in *diversity channels* [14]. The algorithms presented are analyzed using Monte Carlo simulations.

CHAPTER 2

LITERATURE REVIEW

WSNs are inherently multi-hop because the range of highly energy-constrained low power nodes is small compared to the areas usually requiring coverage. A common approach at the network layer to the energy efficiency problem is energy aware routing. The objective of these protocols has been either minimizing the energy consumption or maximizing network lifetime. The aim of minimum energy routing [15, 16, 17] is to minimize the total consumed energy to reach the destination, which in turn minimizes the energy consumed per unit flow. This method is not the most efficient as if all the traffic is routed through the same minimum energy path it will drain the batteries quickly, while the remaining nodes will remain intact. On the other hand the objective of the maximum network lifetime scheme [18, 19, 20, 21] has been to increase the time to network partition. It turns out that to maximize the network lifetime, the traffic should be routed such that the energy consumption is balanced among the nodes in proportion to their energy reserves [18]. However the above-mentioned protocols do not consider cooperation among nodes.

Lately cooperative transmission has been extended to multi-hop networks to further enhance the energy savings. Several works in this area assume that a conventional multi-hop route exists and assign and allocate power to nodes along the route or near the route to assist with cooperative transmission [22, 23, 24]; the corresponding routing metric is the total path power. A particularly well-developed example is proposed by Jakllari et al. [25]. They propose a protocol that selects relays from among the nodes in a conventional route (the “primary path”), and uses cooperative transmission to take longer hops along that same route. [24] considers a sequence of node clusters between the source and destination (presumably along a predetermined route) and selects one relay from each cluster to minimize the probability of outage, either hop-by-hop, or end-to-end. One disadvantage of using these schemes is that they require coordination and addressing of relay nodes which OLA based schemes don’t entail.

In OLA based networks, routing is generally established using flooding [26], which is not energy-efficient for upstream routing. The only work other than OLACRA that limits flood in the upstream was done in [27] where the nodes are assumed to be aware of their location, which is obtained using a Global Positioning System (GPS). However this assumption might not be practical in sensor network scenarios. OLACRA on other hand does not require location information.

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 [5] 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, 28]. Wei et al. considered a limited orthogonal scheme in [28], where every relay node delays its transmission by a random ‘artificial delay’ selected from a pool of artificial delays {0, T, 2T, …}. 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 [8] where space-time codes were used to orthogonalize channels of

nodes in OLA based networks.

The authors in [5] 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 [5] 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.

CHAPTER 3

OLACRA

3.1 SYSTEM MODEL

Half-duplex nodes are assumed. For the purpose of analysis, the nodes are assumed to be distributed uniformly and randomly over a continuous area with average density ρ. We assume a node can decode and forward a message without error if its received Signal to Noise ratio (SNR) is greater than or equal to a modulation dependant threshold [4]. Assumption of unit noise variance transforms the SNR threshold to a received power criterion, which is denoted by 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, then it is assumed that the receiver power must have exceeded τ_d. In contrast, the proposed transmission threshold would be explicitly compared to an estimate of the received SNR.

Let the normalized source power relay transmit power and the relay transmit power per unit area be denoted as P_s, P_r and $\overline{P}_r = P_r\rho$ respectively. We consider two network models, the *Deterministic* model and the *Diversity Channel* model. In the *Deterministic* model, the power received at a node is the sum of the powers received from each of the node transmissions. This model implies that node transmissions occur on orthogonal non-faded channels. In the *Diversity Channel* model, node transmissions are assumed to be on limited number of orthogonal Rayleigh faded channels. The path-loss function in Cartesian coordinates is given by $l(x, y) = \left(x^2 + y^2\right)^{-1}$, where (x, y) are the normalized coordinates at the receiver. As in [5], distance d is normalized by a reference distance d_o. Let power P_o be the received power at d_o. The received power from a node distance d away is $P_{rec} = \min(\frac{P_o}{d^2}, P_o)$. For modeling the received power of simultaneously transmitted signals we use the approach is [5].

In the deterministic channel model, it is assumed that if a set of relay nodes (say L_n) transmits simultaneously, the node j with normalized coordinates (x_o, y_o) receives with power

$$P_{rec}^{J} = P \sum_{(x,y)\in L_n} l(x - x_o, y - y_o) \qquad (1)$$

where P is the normalized transmit power given by

$P = \frac{P_t G_T G_R}{\sigma_n^2}\left(\frac{\lambda}{4\pi d_0}\right)^2$, where P_t is the relay transmission power in mW, G_t and G_r are the transmit and receive antenna gains, σ_n^2 is the thermal noise power and λ is the wavelength in meters. Following [5], for ease of analysis we assume a continuum of nodes, which means that we let the node density ρ become large $(\rho \to \infty)$ while $\overline{P_r}$ is fixed. Then (1) simplifies to

$$P_{rec}^{J} = P \int_x \int_y l(x - x_0, y - y_o)\,dxdy \qquad (2)$$

For the Diversity Channel model [14], the received power is given by

$$P_{rec}^{J} = \sum_{k=1}^{m} \gamma_k P_{rec,k}^{J} \qquad (3)$$

where m is the number of limited orthogonal channels and $P^{J}_{rec,k}$ is the average power received at the k^{th} orthogonal channel and γ_k is a zero mean, unit variance exponential random variable (since squared Rayleigh is Exponential).

The efficiency of OLA based networks depend on the optimum choice of the two independent parameters $\frac{\overline{P}_r}{\tau_d}$ and $\frac{\tau_b}{\tau_d}$ [13]. We give the ratio $\frac{\tau_d}{\overline{P}_r}$ the name Decoding ratio (DR), because it can be shown to be the ratio of the receiver sensitivity (i.e. minimum power to be decoding at a given rate) to the power received from a single relay at the distance to the nearest neighbor, $d_{nn} = 1/\sqrt{\rho}$. If ρ is a perfect square, then d_{nn} would be the minimum distance between the nearest neighbors if the nodes were arranged in a uniform square grid and τ_b / τ_d is defined as RTT.

3.2 OLACRA DESCRIPTION

The OLA Concentric Routing Algorithm (OLACRA) has two phases. In the first phase, the Sink initializes the network by flooding the whole network using OLA-T or Basic OLA [7, 14]. In OLA-T, the Sink transmits waveform W_1 with power P_{sink}. "Downstream Level 1" or DL^1 nodes are those that can Decode and Forward (D&F) the Sink-transmitted message. Only the nodes in DL^1 whose received power is *less* than τ_b form the downlink OLA O_{D1}. The O_{D1} nodes transmit a waveform, denoted by W_2, which carries the original message, but the waveform can be distinguished from the source transmission, for example, by using a different preamble, spreading code or center frequency. This difference enables nodes that can decode the W_2 waveform and which

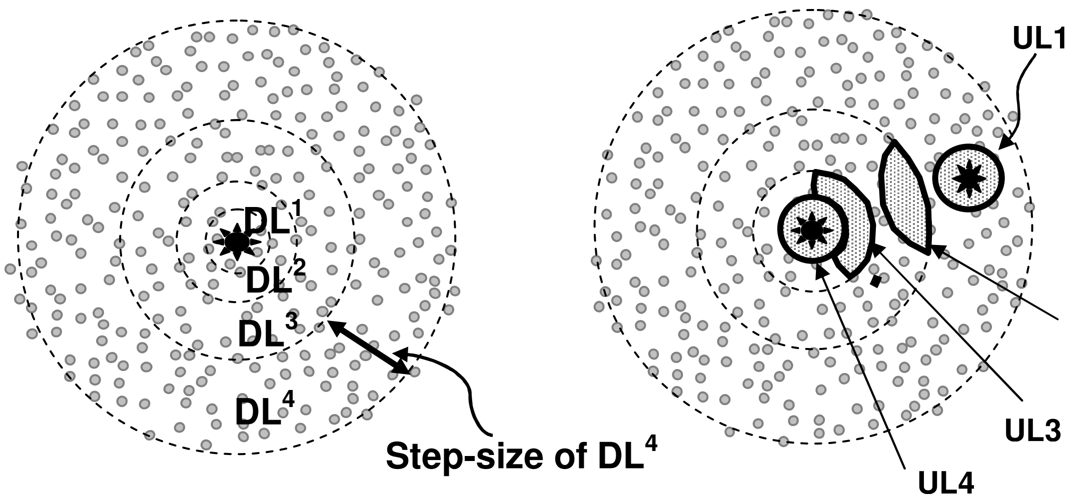


Figure 1: Illustration of OLACRA. (a) Phase 1 (b) and Upstream phase.

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 the second OLA O_{D2}, and relays using a different waveform W_3. This continues until each node is indexed with a particular level. The levels form concentric rings as shown in Figure 1(a). A feature shared by Basic OLA and OLA-T algorithms is that the distance between outer boundaries of consecutive downstream OLAs, also called the “step size” [7], grows with the downstream OLA index. For example, the step-size of DL^4 is shown in Figure 1(a). In other words, the rings that are farther from the Sink are thicker.

The second phase of OLACRA is upstream communication. 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 if it has not repeated the message before. Downstream OLA boundaries formed in the initialization phase are shown by the

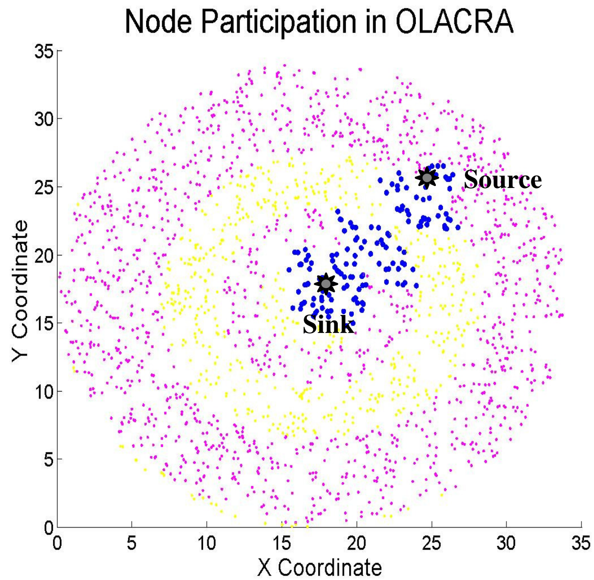


Figure 2: Node participation in Single Level

dotted circles in Figure 1(a). Upstream OLAs formed are illustrated by the solid boundaries in Figure 1(b). Since each upstream OLA is associated with just one downstream level, OLACRA as defined above, is also referred to as *Single-Level* OLACRA to differentiate it from the other multi-level ganging variations discussed later. We shall refer to the n^{th} upstream OLA as UL^n, where UL^1 contains the source transmitter. In Figure 1(b) for example, UL^1 is indicated by the solid circle and UL^4 contains the Sink. 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}. For a given message, to ensure that OLA propagation goes upstream or downstream as desired, but not both, a preamble bit is required. As in OLA-T, energy can be saved in OLACRA if the transmission threshold criterion is applied (That is only the nodes near the upstream forward boundary are allowed to transmit). In this case O_{Uk} and UL^K would denote the transmitting set and decoding sets respectively for the k^{th} upstream level. We call this variant as OLACRA-T. O_{Uk} and UL^{K} are the same in OLACRA without transmission threshold as shown in Figure 1(b). A simulation example in Figure 2 illustrates OLACRA when the upstream source node is in DL^{5}. To indicate the level membership, downlink level nodes are shown using circles with contrasting shades (magenta circles for even indices and yellow circles for odd indices in the figure) and the upstream nodes are denoted using darker shades (blue circles in the figure). This simulation plot is only for illustration purposes; the performance of OLACRA and its variants will be evaluated in Chapter 5.

The two important performance issues in wireless networks in general and WSNs in particular are energy efficiency and maintaining reliability. We define two metrics to measure these in the context of OLACRA:

- The Fraction of Energy Saved (FES) compares the transmit energy consumed by OLACRA in the upstream direction with that of Basic OLA. FES is defined as

$$FES = 1 - \frac{\text{Total transmit energy consumed in the network in OLACRA}}{\text{Total transmit energy consumed in the network in Basic OLA}}$$

  where the transmit powers are chosen to be the minimum transmit power required for a 'successful transmission'; where successful transmission implies sustained propagation for Basic OLA and successful reception at the Sink in the case of OLACRA. This modification makes the comparison fair. Both OLACRA and Basic OLA were assumed to use the same transmit power (which was the minimum power required in OLACRA). We also note that Basic OLA, unlike OLACRA, doesn't have a mechanism to limit transmission beyond the Sink or to limit flooding. Because of this, the minimum power that is required to reach the Sink in Basic OLA is the same as the minimum power required to broadcast the whole network.

- The Packet Delivery Ratio (PDR) is the probability that a packet transmitted by the upstream source node is successfully decoded at the Sink.

CHAPTER 4

ENHANCING OLACRA EFFICIENCY

4.1 UPSTREAM CONNECTIVITY ISSUES IN OLACRA

If the upstream source node is located far away from the Sink, and also far away from the forward boundary of UL^1, then the decoding range of the upstream source node

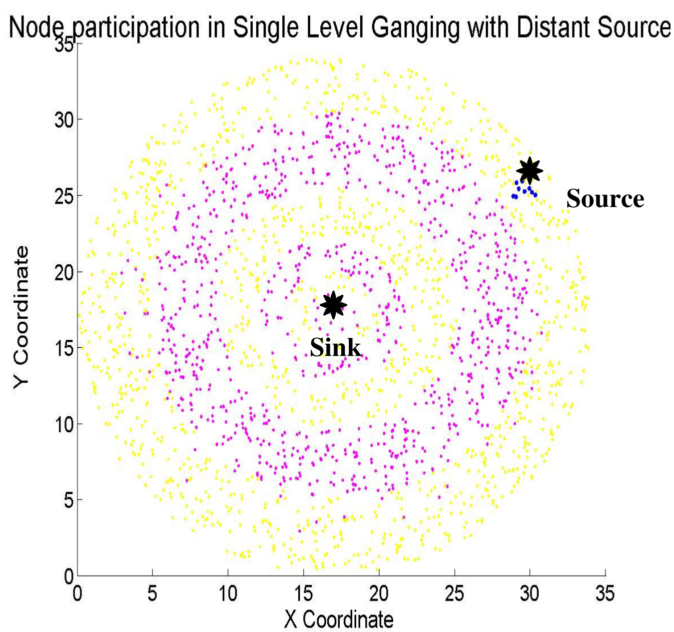


Figure 3: Node participation with Distant Source.

may be too short and UL^2 may not form. This is shown in Figure 3, where the upstream source node is present away from the reverse boundary of DL^6 and we observe that the upstream transmission does not get to the Sink. This can happen for an OLACRA upstream transmission when the source node is many, e.g. 7, steps away from the Sink, because downlink levels of higher index are thicker. This causes the PDR to fall, and motivates the need to explore new methods to improve the upstream connectivity/reliability of OLACRA. We are interested in methods that enhance the upstream connectivity and conserve energy. Some of the solutions we considered are as follows.

4.1.1 Ganging of levels in the upstream

Ganging of levels can be done in the upstream to increase the number of nodes participating in the upstream and hence increase the PDR. We consider two types of ganging: *Dual Level* and *Triple Level*. When a 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 has not repeated the message before and if it is identified with (1) DL^n or DL^{n-1} for *Dual Level Ganging* and (2) DL^n, DL^{n-1} or DL^{n-2} for *Triple Level Ganging*. As we will show in Chapter 5, Single-Level OLACRA is effective when combined with techniques explored below, and hence we use Single-Level OLACRA as the nominal configuration for all our simulations/protocol variations.

4.1.2 Increase the power of the source node for the upstream transmission

While effective, the simple approach of just having the upstream source node transmit with a higher power is not practical because any node could be a source, therefore all nodes would require the expensive capability of higher power transmission.

4.1.3 OLA or OLA-T flooding in just the first upstream level

This scheme allows all nodes in DL^n that can decode a message to forward the message if they haven't forwarded that message before until an OLA meets the upstream

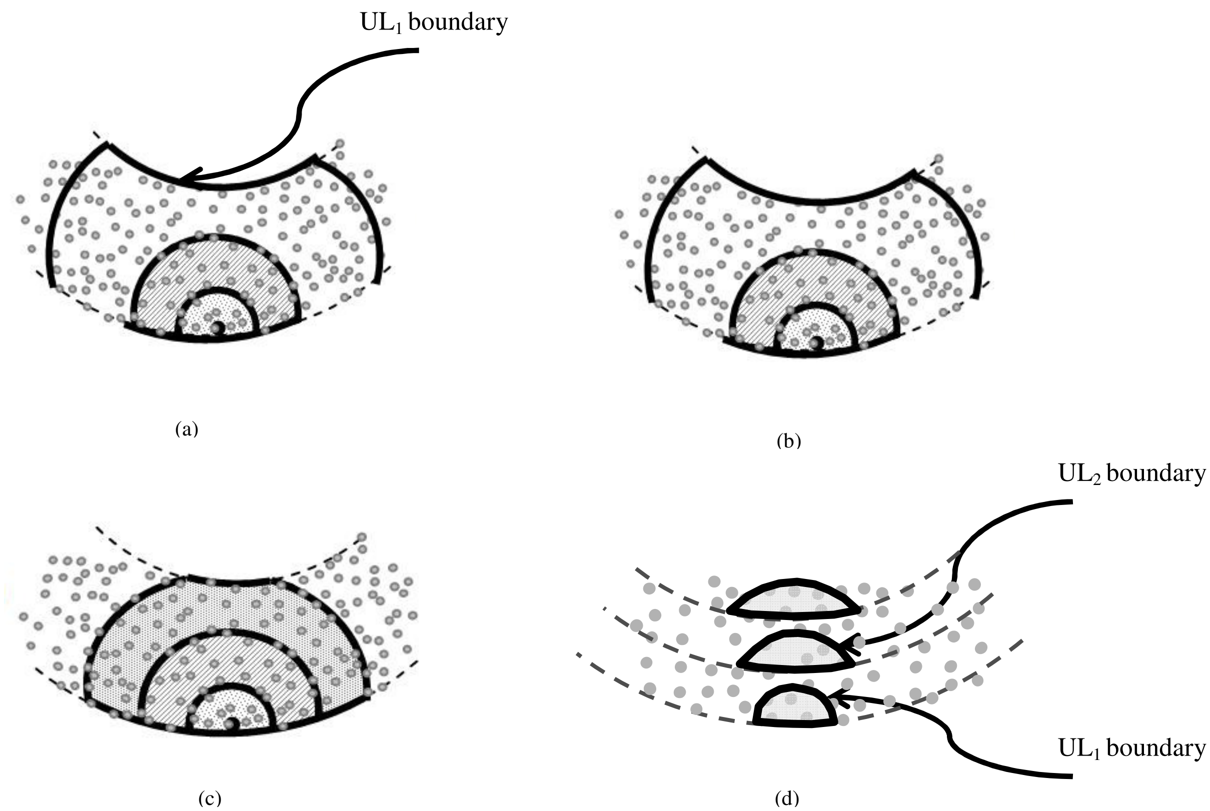


Figure 4: Extended Source formation (a) UL1 flooding (b) boundary nodes in extended source (c) UL1 flooding in OLACRA-VFT and (d) OLACRA-SC.

forward boundary of DL^n. Then all nodes in DL^n that have decoded the upstream message will transmit at the same time as an “extended source”. We consider the following variations of this: OLACRA-FT and OLACRA-VFT.

4.1.3.1 OLACRA-T with Limited Flooding (OLACRA-FT)

The worst case number of broadcast OLAs required to meet the upstream forward boundary of DL^n can be known a priori as a function of the downstream level index. For example, in Figure 4(a), three upstream broadcast OLAs are needed to meet the upstream forward boundary of DL^n. The union of the upstream decoding nodes (e.g. all three shaded areas in Figure 4(a) in DL^n, are then considered the 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 preamble as would a source node under the OLACRA protocol. In order for the nodes to know when it is time to transmit as an extended source, a OLA waveform distinction (example: different preamble bit), similar to the network initialization phase of OLACRA, must be used in this upstream flooding phase. To save energy, the nodes in the extended source that transmitted in the downstream transmission could be commanded to not transmit in the extended source transmission; in other words, those nodes that were near the forward boundary in the downstream would be near the rear boundary in the upstream, and therefore will not make a significant contribution in forming the next upstream OLA. This is shown in Figure 4(b). Figure 5(a) shows a simulation result illustrating node participation in OLACRA-FT.

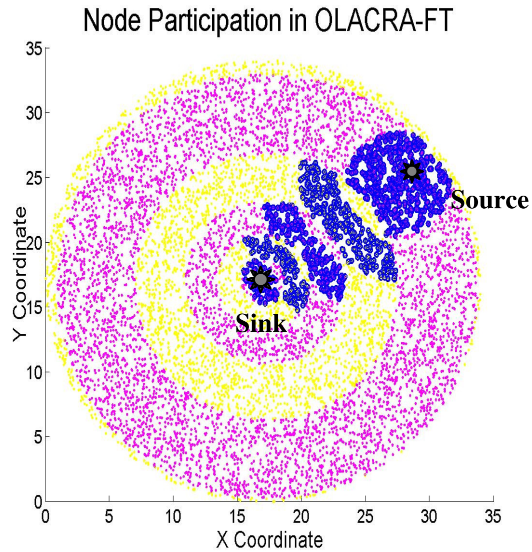
4.1.3.2 OLACRA-FT with variable relay power (OLACRA-VFT)

Even though the extended source gets to the reverse boundary of the downlink level that has the upstream source in OLACRA-FT, its width is very large, making it energy inefficient. This can be seen in Figure 4(a). In order to make this scheme more effective, we desire the smallest extended source that also gets to the downlink reverse boundary. In OLACRA-VFT, the transmit powers in these upstream flooding steps are reduced relative to OLACRA-FT, to reduce the size of the extended source, as shown in Fig. 4(c). Energy can be saved further by commanding the nodes that participated in the downlink OLA-T to not transmit as in OLACRA-FT. Instead of varying the relay power, we could also very the transmission threshold , τ_f , or a combination of both to obtain similar results.

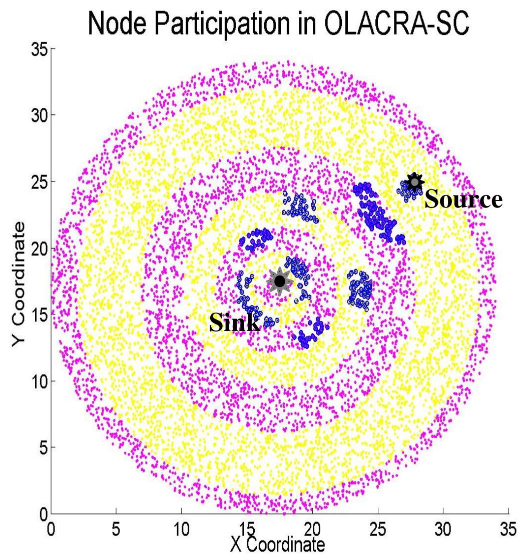
While both methods, varying transmission threshold and varying relay power in the flooding level, try to vary the size of the extended source, they achieve it in different ways. While reducing relay power increases the number of levels required to reach DL^{n-1} thereby making more number of nodes transmit at a lower power, decreasing the transmission threshold decreases the number of nodes transmitting but the transmission is at a higher power. OLACRA-VFT has been simulated in this thesis by optimizing the relay power of the flood levels, P_{rf} . Note that the transmission threshold for the initial OLA flooding stages 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 OLACRA levels in upstream use relay power P_r as defined in earlier chapters.

4.1.4 OLACRA with Step-Size Control (OLACRA-SC)

As will be shown in Chapter 6, OLACRA-FT and OLACRA-VFT have high reliability (high PDR), but their energy efficiency is very low as they make a large number of nodes participate in the transmission. So we consider another alternative to enhance upstream connectivity, while at the same time conserving energy. OLACRA-SC simply aims to reduce the downlink step-size, so that there are enough nodes in UL^2 to carry on the transmission. The downlink radii depend on the downlink transmission threshold and relay power [14]. Thus step-sizes in the downlink can be controlled by optimizing the transmission threshold or relay power on the downlink to have smaller



(a)



(b)

Figure 5: Node participation in (a) OLACRA-FT (b) OLACRA-SC.

fixed downlink step-sizes. Unlike OLACRA-FT and OLACRA-VFT, the goal here is not to make the extended source touch the downlink reverse boundary, but to make the extended source strong enough to reach a sufficient number of nodes in UL^2 to carry the transmission back to the Sink as can be seen in Figure 4(d). A simulation example for this case is also shown in Figure 5(b). In this figure, to further increase the energy savings, only the nodes that participated in the downlink OLA-T are allowed to relay the message in the upstream. This is in contrast to OLACRA-FT where energy was saved in the extended source by commanding the nodes that didn't relay in the downlink OLA-T to transmit in the upstream. Even though the scheme in OLACRA-FT is more efficient it is not possible in OLACRA-SC as there is a high possibility that the nodes that relayed in OLA-T would not be taking part in the upstream OLACRA-SC transmission. This is the case in Figure 5(b). Please note that the discontinuous OLAs in Figure 5(b) is because of the use of a transmission threshold in the upstream that prevents some nodes from transmitting.

4.2 EFFECT OF NODE DENSITY ON UPSTREAM CONNECTIVITY

Because the number and placement of the nodes is random, there is a chance that there might not be enough nodes in the vicinity of the source to form an OLA when the node density is low. If this happens, there are no relays, and the packet won't be delivered. We do a little analysis of this problem, which we call the '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 $P(A)$. $P(A)$ will be evaluated in Chapter 5.

CHAPTER 5

PERFORMANCE RESULTS

Closed form analytical results are difficult to obtain for the upstream using OLACRA and its variations because of the generally irregular shapes of the upstream OLAs. Hence Monte Carlo simulation is done to demonstrate the validity of and explore the properties of the OLACRA protocol. First we evaluate the variations of OLACRA over the Deterministic Channel, with *step-size* control considered separately from the other variations. Next, we consider the Diversity Channel followed by some examples of practical parameter values that correspond to the normalized values we have analyzed.

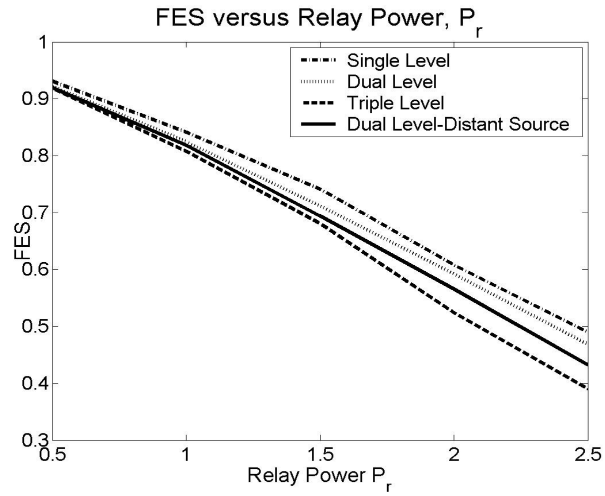
5.1 DETERMINISTIC CHANNELS

Each Monte Carlo trial has nodes randomly distributed in a circular area of radius 17 with the Sink located at the center. For all results in this section, $\tau_d = 1$ and 400 Monte Carlo trials are performed. The downstream levels are established using OLA-T with source power P_s=3.

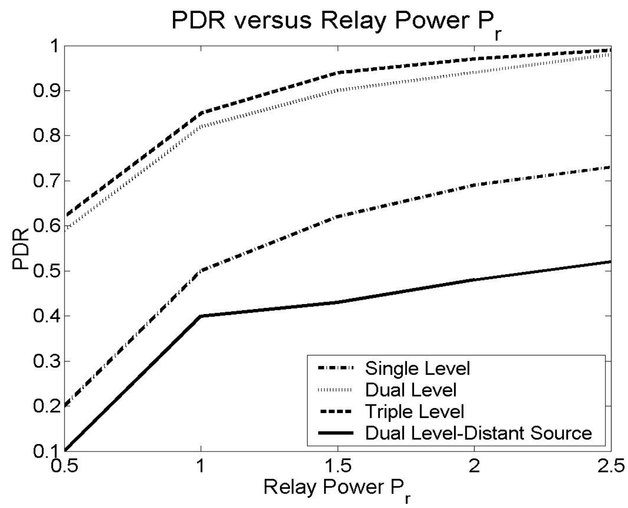
5.1.1 WITHOUT STEP-SIZE CONTROL

A node density of 2.2 is considered in these simulations. A fixed RTT of 4 and a $\bar{P}_r$ of 1.1 are used for the downstream.

Figures 6 (a) and (b) compare different versions of OLACRA in terms of FES and PDR versus relay power. The upstream source node is located at a radius of 15 for the dual-level distant source (DLDS) and at a radius of 5 for the other cases. These two



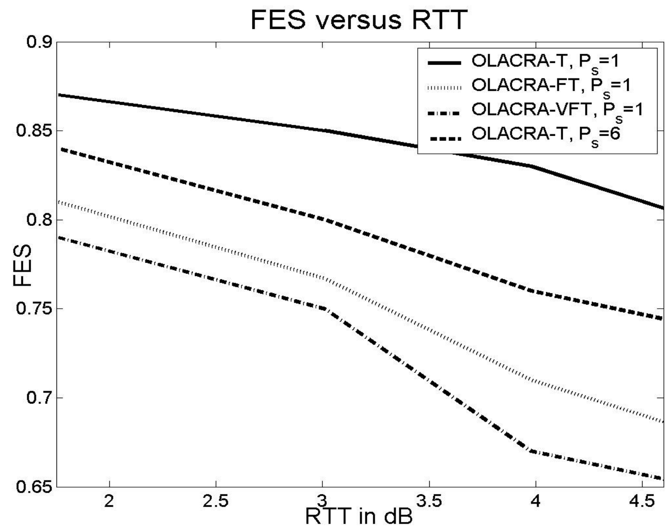
(a)



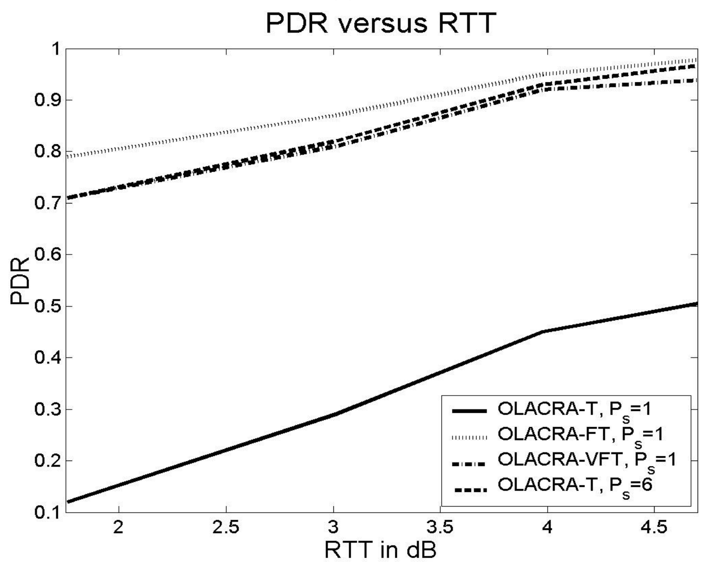
(b)

Figure 6: (a) FES and (b) PDR versus Relay power for different variants of OLACRA.

radii are considered to show the variations of FES and PDR with distance from the Sink. We observe that the Single Level case has the highest FES for all values of relay power; however the PDR is very low. The Dual Level and Triple Level cases have higher PDRs, with only a small degradation of FES relative to Single Level. Though the FES value of Dual Level when the source is close to the Sink (radius 5) was comparable to Dual-Level Distant Source (DLDS) case, the PDR is very low for DLDS. The reason is that the



(a)



(b)

Figure 7: (a) FES and (b) PDR versus RTT for different versions of OLACRA.

distant source is in a downstream level so thick that the dual level upstream ganging is not enough to reach the upstream forward boundary.

Figures 7 (a) and (b) compare the performances of the different variants of OLACRA in terms of their FES and PDR versus RTT in dB. The upstream source node is located at a radius of 15. $\bar{P}_r$ of 2.2 is assumed for upstream routing. The relay power for the flooding stage in OLACRA-VFT P_{rf} is 0.6. OLACRA-T with a source power of 1 has the highest FES of 0.87 at RTT of 1.76 dB; however the PDR at this RTT is very low = 0.12. The FES of OLACRA-FT is only slightly lower than OLACRA-T with source power = 1, but the PDR for this case is very high. A further improvement in FES of OLACRA-FT is obtained with OLACRA-VFT. We also see that OLACRA-T with a source power of 6 performs similarly to OLACRA-FT, which shows that the upstream source power requirement will be very high to achieve similar performance.

5.1.2 WITH STEP-SIZE CONTROL (OLACRA-SC)

For results in this section, a much higher density of 10 is considered. Downlink levels are established at $\bar{P}_r$ = 1.1. As described earlier, the radius of a level depends on the RTT value and hence downlink step-sizes can be controlled by varying RTT. For results in this section the RTT values in the downlink are chosen as the continuum predicted RTT values that give fixed step-sizes [12]. Upstream $\bar{P}_r$ is 1.1. Two step-sizes are considered: $0.8rd1$ and $rd1$ where $rd1$ denotes the first downlink radius.

Figures 8 (a) and (b) compare the FES and PDR performances of $0.8rd1$ and $rd1$. The $0.8rd1$ has a very high FES of 0.928 at a RTT of 1.76 dB, however the PDR at this RTT is very low. This is because of the low value of RTT. A lower value of RTT suppresses a large number of nodes thereby reducing the PDR. This effect is more pronounced in the fixed step size case compared to the general OLACRA, because the small step-size alone prevents a large number of nodes from participation. Use of RTT removes a substantial amount of nodes from a set that already did not have many nodes to begin with. As RTT is increased to 4.5 dB, the PDR improved to about 0.927. Compared

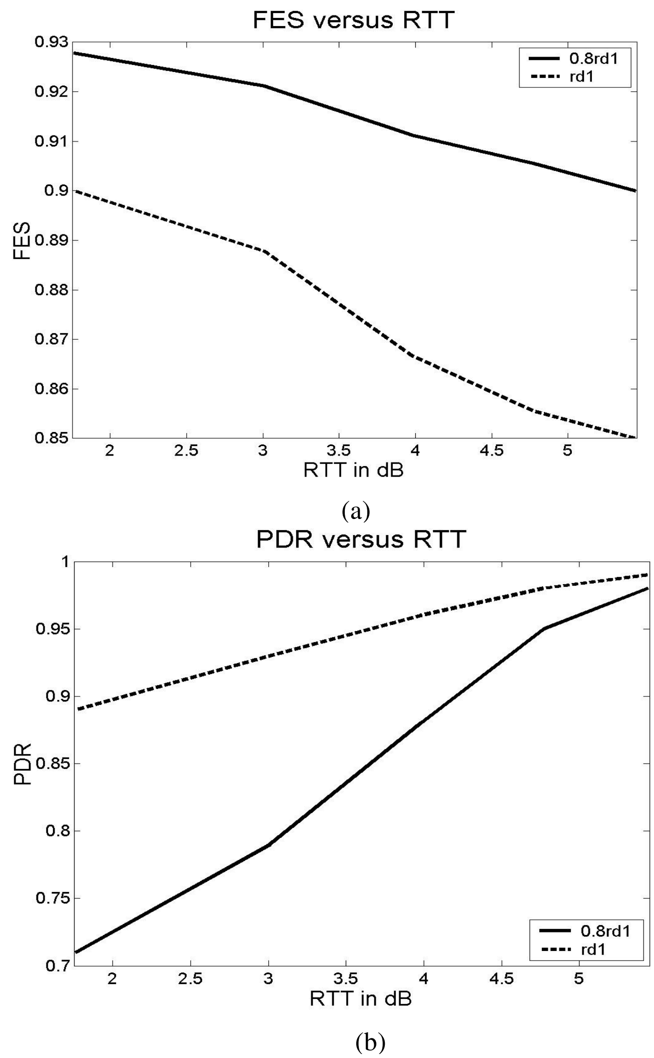


Figure 8: (a) FES and (b) PDR versus RTT for OLACRA-SC.

to the $0.8rd1$ case, the $rd1$ case has a lower FES and a higher PDR. But even the FES for the $rd1$ case is much higher than the FES observed for a general OLACRA or OLACRA-FT.

Fig 9 shows the variation of FES with distance from the Sink for a fixed network size. Step-Size optimization is done for the downlink to obtain fixed step-sizes of $0.8rd1$ and all other parameters are chosen as in the previous result. We observe that the FES has a general decreasing trend as the distance of the source from the Sink increases. This

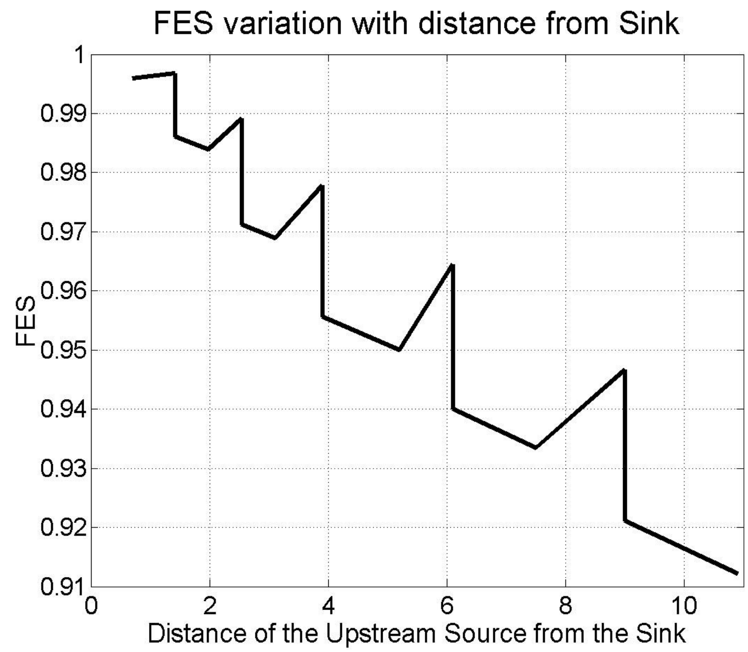


Figure 9: FES variation with distance of the Upstream Source from the Sink.

is very intuitive, as more nodes in OLACRA have to take part when the source is at a greater distance from the Sink, while Basic OLA always broadcasts to the whole network. We also observe that FES has a saw- tooth variation within a level. Within a level, the highest FES was observed close to downlink forward boundary. This was because when the upstream source is at this location, minimum numbers of nodes are activated in the next upstream level, whereas when the upstream source node is closer to the downlink forward boundary it activates maximum number of nodes in the next upstream level. The sharp saw-tooth fall of FES happens because of the change in level of the node. That is a node at 1.414 was a part of downstream level 1 and hence was 1 hop away from the Sink, whereas a node at 1.4141 was in Downstream level 2 and was 2 hops away and hence activates many more nodes.

The distance between two saw-tooth peaks in Figure 9 corresponds to the downlink step-size. We can see that the step-size strays away from fixed values as the distance from Sink increases. This is because our RTT values in the downlink were chosen using the continuum approach as described earlier. The continuum tool is valid at very high densities, however the validity of continuum prediction falls at lower densities. Even though higher densities (density of 10) were chosen for the step-size control section compared to our other results, the continuum prediction is not accurate even at this density.

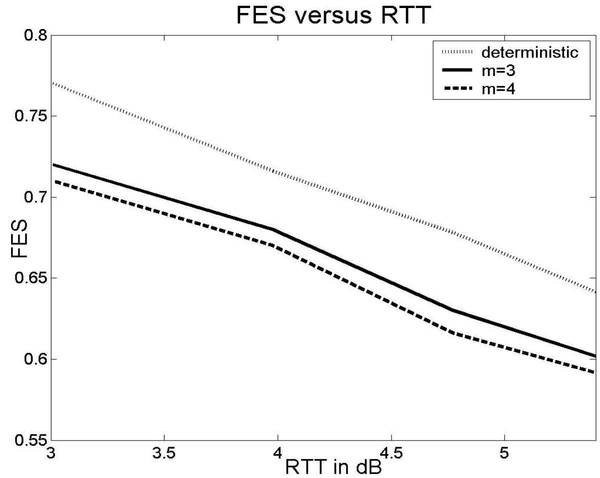
5.2 DIVERSITY CHANNELS

Our results so far have considered networks where transmissions occur on orthogonal and non-faded channels (*deterministic channel*). In this section we extend our simulations to *diversity channel model* where transmissions are on quasi-orthogonal Rayleigh faded channels. The relays transmit Direct Sequence Spread Spectrum (DSSS) signal. To ensure m^{th} order diversity gain we let each relay delay its transmission by a random 'artificial' delay selected from a pool of artificial delays $\{0, T_C, 2T_C, \ldots(m-1)T_C\}$, where T_C is the chip time of the DSSS signal [7]. To extract this diversity at the receiver, every node has a RAKE receiver with *m* fingers. Assuming maximal ratio combining, the total received power at each node is taken to be the sum of the received powers at each of its RAKE fingers. To model Rayleigh fading, the received power at a RAKE finger is modeled as an exponential random variable with mean equal to the *average* power received at that finger. We make the ideal assumption that the *average* power at the k^{th} finger is the sum of powers of all the signals that arrive at that node within the k^{th} "delay bin", which means their excess delay times t_r are such that $(k-1)T_c \le t_r \le kT_c$.

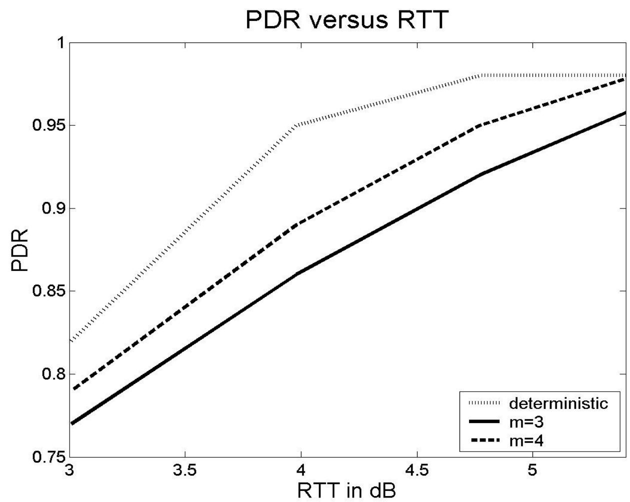
Each trial has 2000 nodes randomly distributed in the circular field of radius 17 giving $\rho = 2.2$. The downstream levels are established using OLA-T with source power P_s=3, $\bar{P}_r$ 1.1 and RTT of 4. For upstream routing using OLACRA, the source node is located at a radius 13 with P_s = 1. A decoding threshold of 1 is chosen for the downlink and the uplink transmissions. $\bar{P}_r$ of 2.2 was used for the upstream levels. T_C was taken to be 500 time units.

Figure 10 (a) compares the FES under OLACRA under the *Deterministic* channel model and *Diversity Channel* model, for different values of RTT, while Figure 10 (b) shows the PDR, also versus RTT. We observe that for m = 3 (third order diversity) FES was 0.72 at RTT = 3 dB, whereas the FES for the deterministic case for the same value of RTT was 0.77. Similarly the probability of message delivery at the Sink is only 0.77 or the m=3 case at RTT of 3 dB, whereas the probability of success for the deterministic case is higher at 0.82 for the same RTT. But when the diversity order was 4 (m=4), the performance characteristics of the fading channel got closer to the deterministic case. For m=4 the probability was about 0.94 for an RTT of 4.7 dB, when the deterministic case had a probability of 0.97. It should also be noted that the FES performance of the m=4 case was not very different from the m=3 case, meaning that the higher probability of message reception obtained by having an additional RAKE finger was not at the cost of energy.

Figure 11 captures the variation of the probability that a message is not decoded by



(a)



(b)

Figure 10: (a) FES and (b) PDR versus RTT for Diversity Channel Model.

the Sink versus Node density ρ for different values of m (diversity order). The curve labeled 'initial bottleneck' shows the probability that there were no nodes in the first level in UL[1]. At m=1, which corresponds to the 'no diversity case', we observe that the probability of failure was 1 for $\rho < 1.15$. Even at a much higher density, $\rho = 2$, the probability of failure dropped only to 0.54. That it dropped with increasing density was consistent with the claim in [7] regarding non-orthogonal transmissions. However when m=2, the probability of failure tended to zero at a node density of 2.2. When m=3,

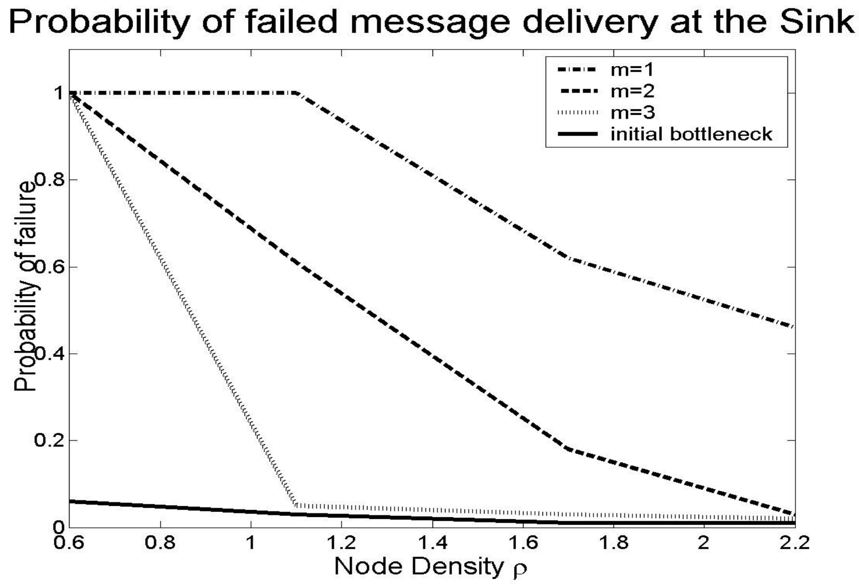


Figure 11: PDR versus Node Density.

probability of failure dropped to 0.01 at a node density of 1.1. It should be observed that the *m*=3 and 'initial bottleneck' lines were very close for $\rho \geq 1.1$, implying that at *m*=3, the probability of failure was dominated by the probability that there were no nodes in the first level ('initial bottleneck') since the probability of outage due to fading tends to zero.

Figure 12 shows the power delay profile of a node located in UL^3 at a radius of 7. *m* was chosen to be 3. The three vertical lines correspond to the power received at each of the orthogonal dimensions (RAKE fingers in this case). It was observed that the total received power at each of the RAKE fingers converged to about 2, thereby 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.

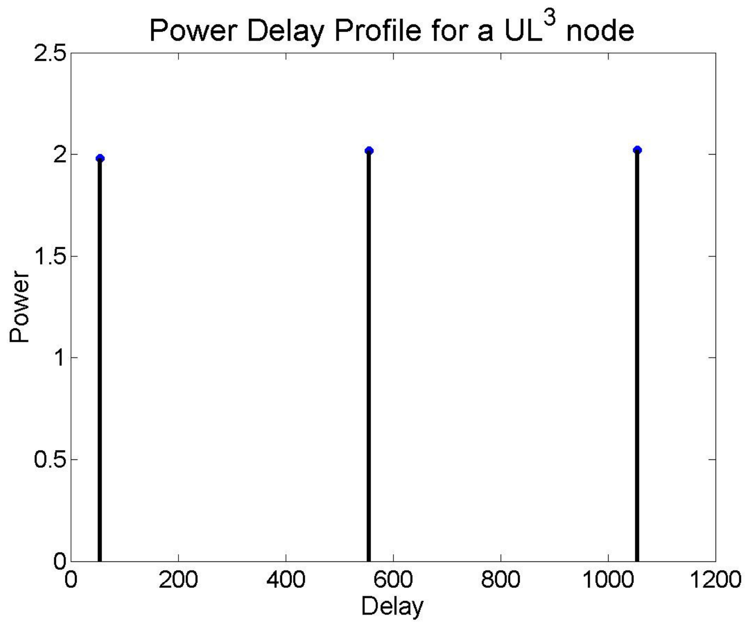


Figure 12: Power Delay Profile for OLACRA.

5.2 RESULTS FOR UNNORMALIZED VARIABLES (PRACTICAL SCENARIOS)

The results given so far and our system model has been in terms of normalized units. We would now like to consider some examples of un-normalized values for these variables to give an idea of what power levels and node densities can achieve the performance shown in the above results. This is given in Table 1. A similar table was presented in [14]. However in that work un-normalized parameters corresponding to a parameter called Decoding Ratio was considered. This was because the efficiency and performance of Basic OLA was shown in [4] to depend on the ratio $\frac{\tau_d}{\bar{P}_r}$ defined in [12] as

TABLE 1
Examples of Un-normalized variables

Example	Un-normalized Parameters				Normalized Parameters	
	d_o in m	P_t (dBm)	Node Density	RX sensitivity (dBm)	$\bar{P}_r$	τ_d
1	1	-53.01	2.2 nodes/ m^2	-90.00	1.1	1.0
2	1	-50.0	2.2 nodes/ m^2	-90.00	2.2	1.0
3	1	-59.58	10 nodes/ m^2	-90.00	1.1	1.0
4	1	-48.79	2.2 nodes/ m^2	-90.00	0.6	1.0
5	1	-39.17	2.2 nodes/ m^2	-90.00	5.5	1.0
6	1000	3.42	5 nodes/ km^2	-90.00	1.1	1.0
7	1000	-6.57	5 nodes/ km^2	-90.00	1.1	1.0

Decoding Ratio (*D*) using continuum analysis. *D* is related to the node degree, *K*, which is the average number of nodes in the decoding range of the transmitter, as $K = \Pi / D$. However the continuum assumptions do not hold at moderate and low densities. Since OLACRA has been evaluated at moderate densities considering discrete random node deployments, the performance of OLACRA depends not on the ratio D but on the values of $\bar{P}_r$ and τ_d separately. The normalization for power was given in (2). Since the distance d is normalized by a reference distance d_o, density will be normalized by d_o^2.

Therefore we have the normalized transmit power $\bar{P}_r$ as

$$\overline{P_r} = \frac{P_t \, in \, mW * G_T G_R}{\sigma_n^2} \left(\frac{\lambda}{4\pi d_0} \right)^2 * \frac{number \, of \; nodes * d_0^2}{Area \, in \, m^2} \qquad (5)$$

Table 1 shows different values of un-normalized power, density and receiver sensitivity for the normalized $\bar{P}_r$ and τ_d that we have considered in this thesis.

The validity of OLA-based accumulative cooperative transmission has been demonstrated extensively using analysis and simulation in [5, 13, 14]. Lately a Particle Computer-based experimental test-bed was set up by Krohn etal [30] that demonstrated the validity of OLA transmission and evaluated its benefits.

CHAPTER 6

CONCLUSION

OLACRA is a simple routing scheme that requires no centralized control and no knowledge of geographical location by the nodes. OLACRA is the only mechanism that achieves cooperative diversity in upstream routing in WSNs without requiring node addressing or localization.. OLACRA has been analyzed over deterministic channels where node transmissions are on non-faded orthogonal channels and also over diversity channels that are on faded channels with limited orthogonality. Intentional delay dithering is done to get diversity in diversity channels. Variants of OLACRA to enhance upstream connectivity are considered and the different schemes are compared. The protocols are tested using Monte Carlo simulations and energy efficiencies of over 80 percent relative to Basic OLA have been shown.

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