Reactive Routing For Multi-hop Dynamic Ad Hoc Networks Based On Opportunistic Large Arrays

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Abstract: A mobile ad hoc network is an infrastructureless multi-hop system of wireless autonomous mobile nodes. Reactive routing protocols like Ad hoc On Demand Distance Vector Routing (AODV) and Dynamic Source Routing (DSR) are appropriate for mobile environments, because they cope quickly with topological changes. Lately cooperative-transmission-based routing protocols have been proposed to further save energy and enhance reliability. However they require an existing conventional route and individual addressing of the cooperating nodes, which involves a lot of overhead. In this paper, we propose a new Opportunistic Large Array (OLA)-based extension to AODV, which incorporates cooperative diversity into both route discovery and data transmission without requiring any pre-existing route or any individual addressing of relay nodes. An OLA is a form of cooperative diversity in which a 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. Our proposed scheme inherits from OLA lower transmit energy and low computational overhead. However, this paper highlights a newly discovered feature of OLAs, which is robustness against mobility. We show through extensive simulation that this new technique yields significantly longer route lifetimes compared to the traditional AODV scheme, assuming node mobility according to the Random Waypoint Mobility Model. We also compare the end-to-end delays of the traditional and proposed schemes. To the best knowledge of the authors, this work is the only unicast, distributed, cooperative ad hoc routing scheme that does not require a pre-existing route.

1. Introduction

A Mobile Ad hoc Network (MANET) is a self-configuring network of mobile wireless nodes that forms an arbitrary topology without using existing infrastructure. Because of node mobility, the topology changes rapidly and hence these networks require *on-demand* routing protocols, which compute routes *on the fly*. Reactive routing protocols like Ad hoc On Demand Distance Vector Routing (AODV) [1] and Dynamic Source Routing (DSR) [2] have been shown to be appropriate for mobile environments, because they cope quickly with topological changes.

In this paper we propose a new reactive Opportunistic Large Array (OLA)-based distributed routing protocol, which can be interpreted as an extension to the multi-hop Ad Hoc On Demand Distance Vector Routing (AODV) algorithm. An OLA [3] is a form of cooperative transmission (CT) [4, 5] in which a 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. An OLA transmission has the same model as a multi-path signal with delay and Doppler spreads, and therefore can be successfully decoded by receivers designed to tolerate the spreads.

The objective of CT-based unicast routing is to determine a series of node clusters between the Source and Destination Nodes, such that the clusters are composed of cooperating nodes, and each cluster can reliably transmit to the next cluster. Most of the existing cooperative transmission-based ad hoc routing protocols [6, 7, 8, 9], assume that a conventional multi-hop route already exists. The cooperating nodes are recruited from along or near the route. Optimizations can be done to minimize energy [6, 7, 8, 9] or maximize the probability of reception [8, 9]. These approaches will not avoid the high level of complexity, overhead, and delay required to do multi-hop routing in highly dense networks.

In contrast, the proposed routing protocol avoids these scalability problems, because no nodes are individually addressed (aside from the Source and Destination Nodes) and the complexity of the proposed scheme is independent of node density, given the density is high enough to support OLA transmission [3]. Also, there is no centralized control and no coordination

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between pairs of individual relay nodes. In other words, the proposed scheme requires no explicit medium access control (MAC) function for a single flow; collisions from multiple simultaneously transmitting nodes are exploited to attain an SNR advantage through diversity combining [3]. Another distinction is that in our scheme, CT is incorporated in both the route set-up and data transmission phases, whereas to the best of our knowledge, in all existing schemes, cooperation is done only in the data transmission phase.

CT-based routes that do not require that the cooperators are part of a multi-hop route are several nodes wide and are more like a strip or "river" of nodes through a network. Without a pre-existing multi-hop route, other means are required to define the cooperating nodes. One previous work proposes using location information (e.g. GPS coordinates) to define the boundaries [10]. However, some MANET applications might not have location information. Also, to reduce the computational load, designers may wish to avoid using the coordinates for route computation, even if the coordinates are available. Another previous work is the OLA Concentric Routing Algorithm (OLACRA), which decides the cooperating nodes for upstream transmission in Wireless Sensor Networks (WSNs) (i.e. networks with a fixed Sink) by exploiting the concentric ring nature of OLA broadcasts [11, 12, 13]. OLACRA with Step-Size Control (OLACRA-SC) [14], a version of OLACRA in which the broadcast step (or ring) sizes are intentionally limited, was shown in [14] to be very energy-efficient.

The present paper makes three main contributions. The first is an extension of OLACRA-SC that enables OLA-based unicast routing in ad hoc multi-hop networks, and thereby significantly enlarges the scope of application of the OLACRA concept. Because the new routing protocol resembles AODV, we call it OLA-based AODV (OLA-AODV). The second contribution is to demonstrate through simulation a newly realized advantage of OLA-based routing, which is robustness to mobility. In this regard, we show the benefits of our routing algorithm in comparison with the traditional AODV. Thirdly, we analyze the end-to-end delay in our algorithm and compare it with the delay of the multi-hop AODV scheme. To the best knowledge of the authors, this is the only work that compares the end-to-end delays of multi-hop and OLA-based schemes.

2. System Model

The nodes are assumed to be half-duplex and distributed uniformly and randomly over a continuous area with average density ρ. We assume a node can decode and forward (DF) a message without error if its received Signal to Noise Ratio (SNR) is greater than or equal to a modulation-dependent threshold [3]. Assumption of unit noise variance transforms the SNR threshold to a received power criterion, which is denoted by the decoding threshold, τ_d.

We consider the *Deterministic Channel* model [3] where the power received at a node is the sum of the powers received from each of the node transmissions, and path-loss is the only channel impairment. This model implies that node transmissions occur on orthogonal non-faded channels. In [15] we have shown that the performance of the Diversity Channel, where transmissions occur on limited orthogonal faded channels, approaches the Deterministic Channel performance at moderate orders of diversity.

In the deterministic channel model [3], it is assumed that if a set of *n* relay nodes (say L_n) transmits simultaneously, the node *J* with coordinates (x_o, y_o) receives with power

$$P_{rec}^{J} = P_t G_t G_r \left(\frac{\lambda}{4\pi}\right)^2 \sum_{(x,y)\in L_n} l(x-x_o, y-y_o)$$

where *l(x,y)* is the path-loss function given by $l(x,y) = \left(x^2+y^2\right)^{-1}$, P_t is the un-normalized transmission power in mW, G_t and G_r are the transmit and receive antenna gains, and λ is the wavelength in meters.

In an earlier work [16], a device called the transmission threshold, τ_b, was found useful in limiting node participation. Even though the idea of using a transmission threshold to limit node participation was mentioned in [3], it was analyzed and developed for the first time in [11] and refined in [16]. A node tests its received SNR against τ_b, and if the SNR exceeds τ_b, then the node does not participate. This test limits the participation to the "significant" boundary nodes, which are those nodes that can just barely decode. The quantity $10\log_{10}\frac{\tau_b}{\tau_d}$, referred to as the Relative Transmission Threshold (RTT), defines the 'window' in dB to allow for relaying. τ_b can be used in the downlink OLA broadcast (OLA-T) [16] and upstream OLA unicast (OLACRA) to further save transmit energy [14].

3. Description of the OLA-AODV Protocol

Like the existing reactive routing protocols, such as AODV and DSR, our algorithm involves mainly three phases: (1) Route Request (RREQ) broadcast by the Source Node (2) Route Reply (RREP) unicast by Destination Node and (3) Unicast data transmission (DATA). As mentioned earlier, the RREQ and RREP phases are done using OLACRA-SC. For the convenience of the reader, the scheme has been described below. OLACRA-SC brings cooperative diversity to both route discovery and data transmission without requiring any centralized control and requires noPl individual addressing of relay nodes. Please note that OLACRA-SC has been modified slightly, as will be explained below, to suit our algorithm.

3.1 RREQ (Forward Path Set-up)

The Source Node initiates a broadcast route discovery process by sending a RREQ message when it needs to communicate with another node for which it has no routing information. The RREQ message contains the following fields

< *source address, broadcast id, destination address, downlink level number, SRC-bit, Uplink/Downlink bit* >

Like conventional AODV, the pair <*source address, broadcast_id*> uniquely identifies a RREQ, and the *broadcast_id* is incremented whenever a Source Node issues a new RREQ. The RREQ propagates through the network using the OLA-based cooperative transmission as explained below.

"Downstream Level 1" or DL^1 nodes are those that can DF the source-transmitted RREQ message. For the sake of reliability, no transmission threshold is used to form the first OLA. Only the nodes in DL^1 that do not satisfy the RREQ[†], and which have not relayed a RREQ with the same *broadcast id* and *source address,* form the first downlink OLA, O_{D1}. Each O_{D1} node relays the RREQ after incrementing the *downlink level number*. This change in *downlink level number* enables nodes that can decode the RREQ and which have not relayed this message before, to know that they are members of a new decoding level, DL^2.

The transmission threshold is used to form all remaining RREQ OLAs. A DL^2 node with received SNR less than τ_b forms the second OLA, O_{D2}, and relays after incrementing the *downlink level number*. This continues until the RREQ is broadcast over the network and reaches the Destination Node. During this broadcast process, each node is indexed with a particular *downlink level*. The levels form concentric rings. Downstream OLA boundaries formed in the Forward Path Set-Up phase are shown by the dotted circles in Figure 1(a).

The *SRC-bit* is used to distinguish the Source Node transmission from OLA transmissions, so relay nodes can know if they need to use a transmission threshold or not. Additionally, a *Uplink/Downlink bit* it appended to the message to indicate the direction of flow.

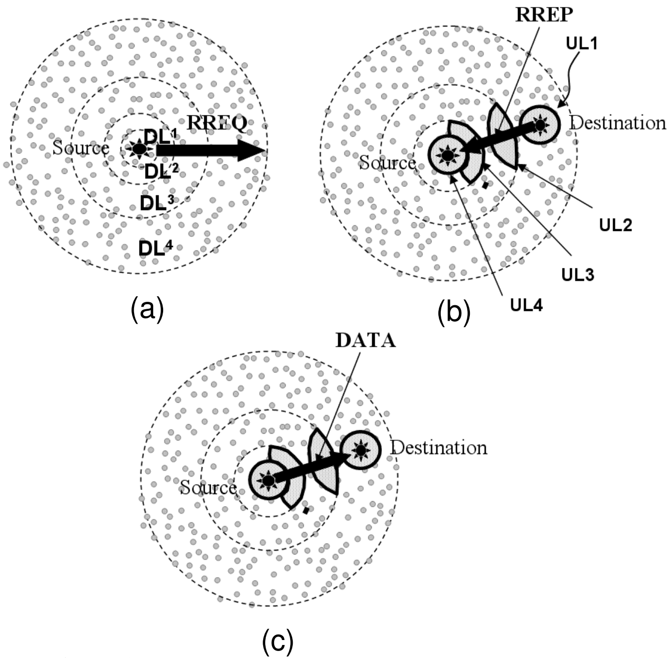


Figure 1. (a) RREQ phase (b) RREP phase (c) DATA

Our previous OLACRA-SC work [14] was for WSNs with a single Sink, so the broadcast message didn't require the address fields. Furthermore, we were considering only a single, fixed source and a single message in that work, and hence a waveform/preamble distinction was all that was required to differentiate levels.

Without power scheduling or use of the transmission threshold, the distance between level boundaries of consecutive downstream OLAs, also called the "step-size", is known to grow with the downstream OLA index [3, 16]. In order to increase the reliability in our RREP phase, we need to have equal downlink step-sizes. This is done by having a level-dependent transmission threshold, $\tau_{b,n}$, where n is the downlink level and optimizing it to get fixed downlink step-sizes [14].

Like the traditional AODV, every relay node keeps track of the information in the RREQ message in order to implement the reverse path setup, as well as the forward path setup that will accompany the transmission of the eventual RREP.

3.2 RREP (Reverse Path Set-up)

The second phase of the routing algorithm is the Reverse Path Set-up, which is initiated by the Destination Node when it receives the RREQ and has sufficient resources to carry out the transmission. Let us assume that the Destination Node was in the n^{th} downlink level, DL^n. The RREP gets back to the Source Node using the second phase of OLACRA-SC [14], which is

[†] A node satisfies the RREQ if it is the Destination Node.

reviewed below. The Destination Node in DL^n transmits the RREP message. A RREP has the same fields as the RREQ.

The RREP phase has "upstream" decoding levels, similar to the downstream decoding levels, but there are more conditions on an upstream decoding level than just being able to decode the RREP. The first upstream decoding level, or UL^1, contains all nodes in DL^n that DF the RREP that was transmitted by the Destination Node. For the sake of reliability, no transmission threshold is used to define the first upstream OLA, O_{U1}, so UL^1 and O_{U1} are the same. However, a transmission threshold is used for the rest of the upstream OLAs. The second upstream decoding level, UL^2, comprises all the nodes in DL^{n-1} that can DF the signal from O_{U1}, and the second upstream OLA, O_{U2}, comprises all the nodes in UL^2 that satisfy the transmission threshold. Now, to complete the sequences of upstream decoding levels and OLAs, we say that for $m > 1$, the m^{th} upstream decoding level, or UL^m, are all the nodes in DL^{n-m+1} that can DF the signal from $O_{U(m-1)}$, and O_{Um} comprises the nodes in UL^m that satisfy the transmission threshold. Figure 1(b) illustrates the sequence of upstream decoding levels; the upstream OLAs are not shown in this figure.

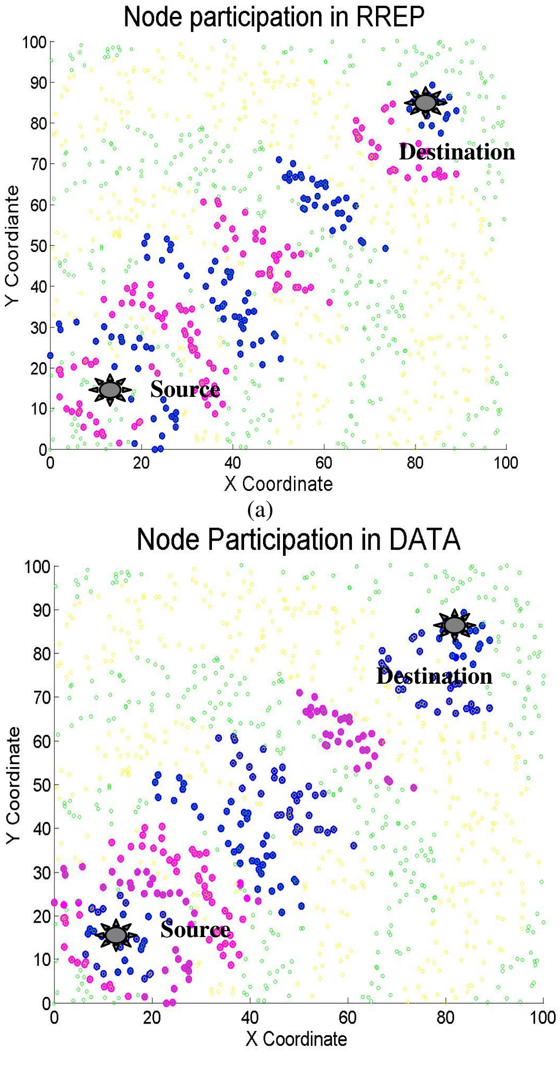
As in the RREQ Phase, the *SRC-bit* in the RREP Phase tells a node if it should apply the transmission threshold, τ_b.

3.3 Data Transmission

The union of the uplink decoding levels defines the *cooperative route*. As soon as the Source Node hears the RREP it starts DATA transmission through this cooperative route. Please note that cooperative route is defined by a set of nodes and not by an actual boundary. All the nodes in this cooperative route that can decode the DATA will relay it if they have not relayed it before.

In mobile networks, the cooperative route becomes wider and sparser with time because of the random motion of the nodes. A transmission threshold makes this route even sparser as it further limits node participation. OLAs must have a certain minimum density-power product for a given data rate to sustain propagation [10], and the density-power product requirement increases somewhat when a transmit threshold is used [16]. Therefore, to provide more robustness against mobility, no transmission threshold is used for the DATA phase.

The plots in Figure 2 show the OLAs in the RREP and DATA phases in OLA-AODV from one simulation outcome when the Source Node is at (15,15) and the Destination Node is at (85,85). To indicate the level membership, downlink level nodes (formed in RREQ) are shown using small dots with contrasting shades (green and yellow). The uplink level nodes (formed in RREP phase) in (a) and DATA nodes in (b) are shown using larger dots and contrasting colors (blue and magenta). We can observe that, as predicted by our protocol, we are able to form a cooperative route without requiring any centralized control. Additionally since the DATA phase doesn't observe distinctions between the RREP OLAs, we can see that the transmission in DATA phase takes a fewer number of hops compared to RREP. This plot is only for illustration purposes; more OLA-AODV simulations are analyzed in detail in Section 4.


Node participation in RREP

(a)

Node Participation in DATA

(b)

Figure 2. Node participation in (a) RREP and (b)DATA when source is at (15,15) and destination at (85,85)

Our proposed scheme shares many features with the traditional AODV. Like AODV, our scheme is also an *on-demand* algorithm, which doesn't require the

Source Node to transmit the whole route along with the DATA (i.e not a source routing scheme). A transmitting OLA in our scheme is analogous to a relay node in AODV, in that they both only remember only their immediate neighbors for the particular Source-Destination pair. Like in AODV, the immediate neighbors are established using the *backward* and *forward* pointers that are formed in the RREQ and RREP phase as described earlier. Our proposed scheme also inherits the lower overhead of the AODV scheme, but is more reliable than the latter because of the benefits of cooperative transmission.

4. Simulation Results

Monte Carlo simulation was done to demonstrate the validity of and explore the properties of the new OLA-AODV protocol. The Deterministic Channel model is considered. 1000 nodes are placed in a square field of dimension 100 m X 100 m. The Source Node is located at coordinates (50, 50) and the Destination Node is located at (10, 90). A receiver sensitivity of –90 dBm is assumed. G_t and G_r are taken to be 1 and the frequency of transmission is 2.4 GHz. The transmit power P_t of the Source and relay nodes is –30 dBm for AODV and –40 dBm for the OLA-AODV extension. The RTT values for the RREQ phase have been chosen as in [14] to give a fixed step-size of *0.8rd1* in the downlink, where *rd1* is the radius of the first downlink level. For the RREP phase a fixed RTT of 1.76 dB is used, whereas no RTT restriction is imposed on the DATA transmission phase.

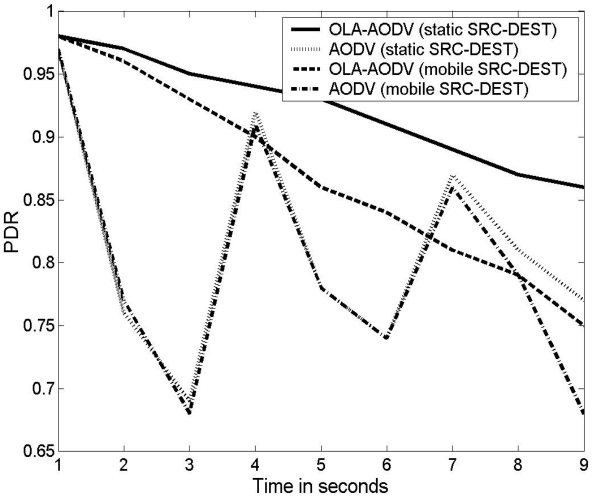


Figure 3. PDR versus Time.

For modeling mobility we use the Random Way Point Mobility Model [17]. Nodes randomly choose their velocity from an interval (0-5 m/s). The pause time, $T_{pause,}$ is taken to be zero. We consider two cases of mobility, (1) where all the nodes including Source and Destination Nodes are mobile (mobile SRC-DEST) and (2) where only the relay nodes are mobile (static SRC-DEST).

Figure 3 compares the performance of AODV and OLA-AODV in a mobile scenario. In order to find the Packet Delivery Ratio (PDR) in a multi-hop network we define a new function called 'connectivity function' which is taken to be zero when there is no route between the Source and Destination Nodes and is one when there is a route between the Source and Destination Nodes. We obtain the ensemble average over 100 trials of the connectivity function at every time instant to obtain the PDR as a function of time. We note that this way of finding PDR is slightly different from the conventional definition of PDR, where a time average is found. In our case, PDR is found as an ensemble average instead of a time average so that the dynamics can be revealed.

Table 1: Relative Latency (RL) for different node transmit powers

P_t (AODV) (dBm)	P_t (OLA-AODV) Static SRC-DEST (dBm)	RL
-30	-40	0.806
-20	-30	0.917

The PDR curves for both OLA-AODV cases gradually degrade with time, whereas the PDR curve for AODV routing schemes has a saw-tooth shape with diminishing peaks. The peaks of the saw-tooth correspond to route re-initializations and the troughs correspond to the time with least connectivity. Even with a lower transmit power (which means higher network lifetime) it is observed that both cases of OLA-AODV require fewer network initializations and is much more robust to mobility of nodes compared to AODV. Even after 8 seconds, the PDR for OLA-AODV (static SRC-DEST) is still over 0.85, whereas in AODV approximately three route discoveries have been carried out. But the performance of OLA-AODV is worse when the Source and Destination Nodes are also mobile, whereas mobility of Source and Destination Nodes doesn't have much impact on AODV.

In Table 1 we show the variation of Relative Latency (RL), which is defined as the ratio of the data transmission time for OLA-AODV (static SRC-DEST) to the data transmission time for AODV, for different power levels. We can see that even though the OLA-based extension uses a lower transmit power it requires less time to reach the Destination Node. Please note that in this figure only the transmission times for the unicast DATA have been considered. Since OLA-based schemes fair better in terms of latency in general [3], the RREQ and RREP phases also will be faster in OLA-AODV. However the RREQ and RREP have not been considered for obtaining results in this Table. Additionally only the DATA transmission is done at the powers listed in the table. The RREQ and RREP phases are done at –30dBm for AODV and –40dBm for OLA-AODV in both cases. We also observe that as the nodes start transmitting at higher relay powers, the end-to-end delay benefit of the OLA-based scheme decreases in comparison with the multi-hop AODV.

5. Conclusions

In this paper we proposed a new Opportunistic Large Array (OLA)-based extension to AODV, which incorporates cooperative diversity into both route discovery and data transmission without requiring any centralized control or individual addressing of relay nodes. Even with a lower transmit power it was observed that OLA-AODV requires fewer network initializations and is much more robust to mobility of nodes in comparison with the traditional AODV. In addition to this, we compared the end-to-end delays and showed that the OLA-based scheme outperforms the conventional AODV.

6. References

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