Reactive Robust Routing with Opportunistic Large Arrays

Lakshmi Thanayankizil and Mary Ann Ingram
School of Electrical and Computer Engineering, Georgia Institute of Technology
Atlanta, Georgia 30332-0250
{lakshmi,mai}@ece.gatech.edu

Abstract: An Opportunistic Large Array (OLA)-based reactive routing protocol, which we call OLA Routing On-Demand (OLAROAD), is investigated for mobile ad hoc networks for varying node densities. An OLA is a simple form of cooperative transmission (CT) in which a group of simple 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. OLAROAD incorporates CT into both route discovery and data transmission. It avoids the overhead involved in finding a conventional multi-hop route and individual addressing of relay nodes, which are problems of the other CT-based routing schemes. Through extensive simulations using the Random Way Point Mobility model, we show that the Packet Delivery Ratio (PDR) and latency of OLAROAD doesn't change with density whereas a traditional multi-hop scheme like AODV incurs much more overhead and delay as the density increases. We also compare the end-to-end delays where we take into account the delay due to route breakages and also the delay in data transmission.

1. Introduction

A Mobile Ad hoc Network (MANET) is a self-configuring network of mobile wireless nodes, in an arbitrary topology with no existing infrastructure. Because of node mobility, the topology changes rapidly and hence these networks require *on-demand* or reactive 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.

Cooperative Transmission (CT)-based ad hoc routing schemes have been proposed to increase reliability and save energy in ad hoc networks [3-7]. The objective of CT-based unicast routing is to determine a series of node clusters between the Source and cluster.* Most of the existing CT-based ad hoc routing protocols assume that a conventional multi-hop route already exists or the clusters have already been defined [3, 4, 5]. The cooperating nodes are recruited from along or near the route. Optimizations can minimize energy [3, 4] or maximize the probability of reception [4, 5]. However, approaches that require a pre-existing route will not avoid the high levels of complexity, overhead, and delay required to do multi-hop routing in dense mobile networks.

Lately a new Opportunistic Large Array (OLA)-based reactive routing protocol, called OLA Routing On-Demand (OLAROAD) in this paper, was proposed by the authors in [6]. An OLA [7] is a form of cooperative transmission (CT) [8] in which a group of simple 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. That an OLA, or "virtual array", occupies an area rather than a single point is one reason why OLA-based routing is tolerant of limited node motion. 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 total radiated energy of an OLA can be lower than that of a non-cooperating transmitter because of array and diversity gain.

OLAROAD avoids the problems of the existing cooperative routing protocols, because no nodes are individually addressed (aside from the Source and Destination Nodes) and pre-existing routes or clusters are not required. Also, there is no centralized control and no coordination between pairs of individual relay nodes. In other words, the scheme requires no explicit medium access control (MAC) function for a single flow; collisions from multiple simultaneously transmitting nodes are exploited to attain an Signal to Noise Ratio (SNR) advantage through diversity combining [7].

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The present paper compares AODV to OLAROAD for a mobile network. We show that as density increases, with node degree (average number of nodes in the decoding range of the transmitter) held constant, the AODV routes require a larger number of route refreshes. This is because as the density increases, the number of hops in the route also increases, and hence the probability that the route breaks due to mobility also increases. In contrast, the OLA-based cooperative route is invariant to changes in density and the route stays "fresh" longer in a mobile network because an OLA is defined over an area instead of at a point. Additionally we compare the end-to-end delays of the two protocols. We show that the end-to-end delay in our scheme is lower because of two reasons: less delay caused by route refreshes, and fewer number of hops in the cooperative route compared to the multi-hop route.

2. System Model

The nodes in the network are assumed to be half-duplex and distributed randomly over a continuous area with average density ρ. We assume a node can decode a message without error if its received SNR is greater than or equal to a modulation-dependent threshold [9]. 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. OLA transmissions on Rayleigh faded channels was analyzed in [7, 10]. The performance of the *Diversity Channel*, where transmissions occur on Rayleigh faded channels, was shown to approach the Deterministic Channel performance at moderate orders of diversity in [10].

In the Deterministic Channel model, 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 transmit power in mW, G_t and G_r are the transmit and receive antenna gains, and λ is the wavelength.

In an earlier work [9], a device called the transmission threshold, τ_b, was found useful in limiting node participation. The idea of using the transmission threshold was first mentioned in [3], and was analyzed and developed in [9]. 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 has been proposed for OLA broadcast (OLA-T) [9] and upstream OLA transmission in WSNs (OLACRA) to further save transmit energy [10, 11].

3. Description of the OLAROAD 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). OLAROAD was introduced in [6], under the name OLA-AODV, but is described briefly below for the convenience of the reader.

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, DATA, 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 decode 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[1], 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

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

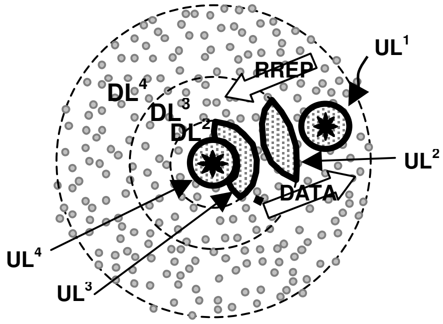

Figure 1: RREQ, RREP and DATA phases in OLAROAD scheme.

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 as shown by the dotted circles in Figure 1.

The *DATA* bit distinguishes the DATA and RREQ transmissions. The *Uplink/Downlink bit* is appended to the message to indicate the direction of flow.

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 Phase II 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 is in the n^{th} downlink level, DL^n. 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 is another condition on an upstream decoding level beside just being able to decode the RREP: the nodes must also be in a certain downlink level. The first upstream decoding level, or UL^1, contains all nodes in DL^n that decode the RREP. 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 decode the signal from O_{U1}, and the second upstream OLA, O_{U2}, comprises all the nodes in UL^2 that satisfy the transmission threshold. In general, we may say that for $m > 1$, the m^{th} upstream decoding level, or UL^m, has all the nodes in DL^{n-m+1} that can decode the signal from $O_{U(m-1)}$, and O_{Um} comprises the nodes in UL^m that satisfy the transmission threshold. The thick solid curves in Figure 1 enclose the upstream decoding levels, and the arrow labeled "RREP" shows the direction of the RREP message.

3.3 DATA Transmission

The union of the uplink decoding levels defines the *cooperative route*. As soon as the Source Node decodes the RREP it starts DATA transmission through this cooperative route. In other words, the DATA flows through the same decoding levels illustrated in Figure 1 for the RREP, but in the direction indicated by the arrow labeled "DATA". 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 are eligible to 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. This is illustrated by the simulation result in Figure 2, which shows the nodes that form the cooperative route at t=0s (when the route is just formed) as filled circles, and at t =7 s (after some time has elapsed) as open circles. A transmission threshold makes this route even sparser as it further limits node participation. Therefore, to provide more robustness against mobility, no transmission threshold is used for the DATA phase.

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 their immediate neighbors for the particular Source-Destination pair. As 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 shares 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 is done to explore the properties of OLAROAD protocol. A square field of dimension 100 m X 100 m is considered. The Source

Node is located at coordinates (50 m, 50 m) and the Destination Node is located at (10 m, 90 m). The receiver sensitivity is –90 dBm. G_t and G_r are taken to be 1 and the frequency of transmission is 2.4 GHz.

When we compare OLAROAD and AODV, the node density will be the same, but the relay power will be 10 dB lower for OLAROAD than for AODV, such that AODV's node degree is 31.4 while OLAROAD's node degree will be 3.14. We do this in an effort to make the per-hop total transmit powers of the two protocols *roughly* equal. We note that if we reduced the node degree for AODV to be more comparable to that of OLAROAD (by reducing AODV transmit power), AODV's performance would be significantly degraded because many more hops would be needed in the route.

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.

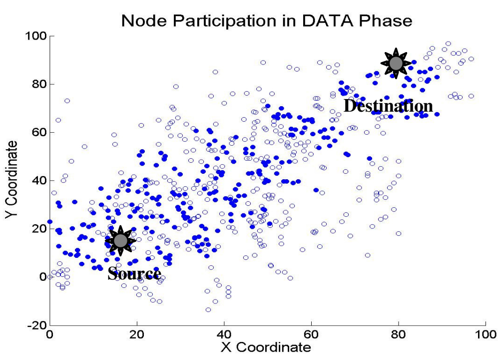

Figure 2: Node Participation in DATA phase (filled circles show nodes at t=0s and open circles show nodes at t=7s). Source at (15, 15), Destination at (85,85). meters.

For modeling mobility we use the Random Way Point Mobility Model [2]. Nodes randomly choose their speed from an interval (0-5 m/s). The pause time, T_{pause} , is taken to be zero.

In order to find the Packet Delivery Ratio (PDR) in a multi-hop network, we define a new function called the '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, which is a time average. In our case, PDR is found as an ensemble average instead of a time average so that the dynamics can be revealed.

Two densities and sets of transmit powers are considered in our simulation. For ρ= 0.1 nodes/m^2, 1000 nodes are distributed randomly in the square field. The transmit power P_t of the Source and Relay nodes is –30 dBm for AODV and –40 dBm for OLAROAD, and these powers are used for all the three phases of the protocols. For ρ=1 nodes/m^2, 10,000 nodes are considered and the transmit power is -40dBm for AODV and -50dBm for OLAROAD, and these powers are used for all the three phases of the protocols.

Figure 3 demonstrates how PDR varies with time and node density. The PDR curves for the AODV cases have a saw-tooth variation. The peaks of the saw-tooth correspond the times immediately after a route discovery and the troughs correspond to the times with the least connectivity. As time and density increase, the route refresh times in AODV become more random and vary more with trials, which is the reason for diminishing differences between peaks and troughs.

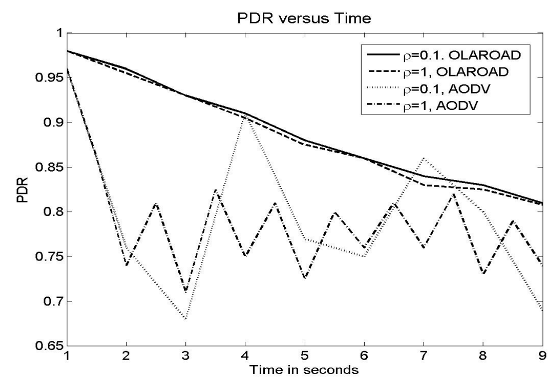

Figure 3: PDR versus Time for AODV and OLAROAD Schemes.

We see that the PDR of OLAROAD is independent of the node density, whereas AODV requires more route refreshes (and hence additional overhead and delay) as the density increases. This is because at higher densities nodes transmit at lower power (to keep the node degree constant) and hence the AODV route from Source to Destination has larger number of shorter-length hops. If any one of these hops fails, the route fails, so the failure of the route increases with the number of hops. In contrast, the number of hops in OLAROAD is determined by the node degree and stays the same in both densities considered.

Table 1 shows the variation of Relative Refresh Rate (RRR) with the node density, ρ. RRR is defined as the ratio of the average refresh rate of AODV to that of the OLAROAD scheme. The average refresh rate is defined as the total number of route refreshes performed over the simulated period of 15 seconds. The densities and transmit powers are chosen as shown in the table. The node density is varied while keeping the node degree the same. We see that as the density is increased the

RRR increases, meaning that the refresh rate in AODV is higher at higher densities.

In Table 2 we show the variation of Aggregate Relative Latency (ARL), which is defined as the ratio of the end-to-end delay for OLAROAD scheme to the end-to-end delay for AODV, for different power levels. The DATA transmission is at the power levels listed in Table 2. The RREQ and RREP phases are done at –30dBm for AODV and –40dBm for OLAROAD in both cases.

Table 1: Relative Refresh Rate (RRL) for different ρ .

Node Density Nodes/ m^2	P_t (AODV) dBm	P_t (OLAROAD) dBm	*RRR*
0.05	-27	-37	1.62
0.1	-30	-40	2.8
1	-40	-50	5.3
2	-43	-53	5.7

Please note that here we take into account the data transmission time after the cooperative route is formed and also the time for route refreshes and route discoveries after the route breaks. We can see that even though OLAROAD uses a lower transmit power per node it requires less time to reach the Destination Node. For obtaining results in this table, we run the simulation for 15 seconds and calculate the end-to-end delay for each packet is calculated and a time average is calculated. The ratio of the time average of the end-to-end delay for both of the schemes gives ARL. We also observe that as the nodes start transmitting at higher relay powers, the end-to-end delay benefit of OLAROAD decreases in comparison with AODV.

Table 2: Aggregate Relative Latency (ARL) for different P_t for ρ=0.1.

P_t (AODV) (dBm)	P_t (OLAROAD) (dBm)	ARL
-30	-40	0.712
-20	-30	0.822

5. Conclusions

This paper considers the routing overhead and performance penalties from route refreshing for routing protocols in mobile ad hoc networks. AODV routes were shown in simulation to be more fragile than the OLA-based routes of OLAROAD, and the difference in route refresh rates grows as density increases for constant node degree. This implies a lower route refresh rate and consequently a lower latency and a higher packet delivery ratio for OLAROAD compared to AODV.

6. References

[1] C.E. Perkins, E.M. Belding-Royer, "Ad hoc On-Demand Distance Vector Routing." Proc. of the 2nd IEEE Workshop on Mobile Computing Systems and Applications, New Orleans, February 1999, pp. 90-100.

[2] J. Broch, D. A. Maltz, D. B. Johnson, Y.-C. Hu, and J. Jetcheva, “A performance comparison of multi-hop wireless ad hoc network routing protocols,” in *Mobile Computing and Networking* , 1998, pp. 85–97.

[3] S. Savazzi and U. Spagnolini, “Energy aware power allocation strategies for multi-hop cooperative transmission schemes,” IEEE Journal on Selected Areas in Communications, 25, 2, pp. 318-327, February 2007.

[4] X. Fang, T. Hui, Z. Ping and Y. Ning, “Cooperative routing strategies in ad hoc networks” Vehicular Technology Conference, 2005. VTC 2005-Spring. 2005.

[5] B. Gui, L. Dai, and L.J. Cimini Jr., "Routing Strategies in Multihop Cooperative Networks," in IEEE WCNC, March 2007.

[6] L. V. Thanayankizil and M.A. Ingram, “Reactive routing for multi-hop dynamic ad hoc networks based on opportunistic large arrays,” Wireless Mesh and Sensor Networks Workshop, Global Communications Conference (GLOBECOM), December 2008.

[7] B. S. Mergen, A. Scaglione ``On the power efficiency of cooperative broadcast in dense wireless networks”, IEEE JSAC, Volume 25, Issue 2, February 2007 Page(s):497 – 507.

[8] J. N. Laneman, D. Tse, and G. W. Wornell, “Cooperative Diversity in Wireless Networks: Efficient Protocols and Outage Behaviour,”IEEE Trans. Inf. Theory, vol. 50, no. 12, pp. 3063–3080, Dec. 2004.

[9] A. Kailas, L. Thanayankizil and M. A. Ingram, “A Simple Cooperative Transmission Protocol for Energy-Efficient Broadcasting Over Multi-Hop Wireless Networks," Journal of Communications and Networks (Special Issue on Wireless Cooperative Transmission and Its Applications), vol. 10, no. 2, pp. 1-8, Jun 2008.

[10] L. V. Thanayankizil, A. Kailas, and M. A. Ingram, "Opportunistic large Array Concentric Routing Algorithm (OLACRA) for Upstream Routing in Wireless Sensor Networks" *submitted* to IEEE Transactions on Mobile Computing.

[11] L. V. Thanayankizil, A. Kailas, and M.A. Ingram, "Energy-Efficient Strategies for Cooperative Communications in Wireless Sensor Networks," International Conference on Sensor Technologies and Applications (SENSORCOMM 2007), October 2007.