Performance Analysis of Zone Routing Protocols in Mobile Ad Hoc Networks

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***Abstract*—In Mobile Ad Hoc Networks (MANETs), routing is a challenging task due to node mobility, traffic and network size. It is very important to analyze the scalability characteristics of the routing protocols with respect to these parameters. Zone Routing Protocol (ZRP) is considered to be one of the most scalable routing protocols due to its multi-scoping and hybridization features. We propose a general, parameterized model for analyzing control overhead of ZRP. A generic probabilistic model for data traffic is also proposed which can be replaced by different traffic models. Our analytical model is validated by comparisons with simulations performed under different network scenarios. In our simulation results, we have observed that the optimal zone radius lies at a point where proactive and reactive overhead components of ZRP are approximately equal as observed in [1]. Further, as the mobility increases the optimal zone radius value decreases, and as the traffic increases the value of optimal zone radius increases. If a node operates away from the optimal zone radius setting then it has to bear additional routing overhead. We show that the additional overhead is around 35% higher under a wide range of mobility scenarios.**

I. Introduction

Since the inception of wireless technologies, the application domain of Mobile Ad Hoc Networks (MANETs) is growing. All nodes in MANET are mobile in nature, so a MANET has dynamic topology structure. Moreover, without prior notice each node is free to join or leave a MANET whenever it wants. MANET is also self-organizing and self-configuring since it does not rely on fixed infrastructure and works in shared wireless media. Lastly, each node in MANET is equipped with limited resources. With these characteristics of MANET, performing routing in MANET is a challenging task.

There are many routing protocols available in literature. Excellent survey of these can be found in [2]. They are mainly classified in two categories called - proactive routing and reactive routing. In proactive routing, the routes to all destinations are determined at the start-up and maintained by using a periodic route update process. So, these schemes cannot scale well as the network size increases. In reactive routing, each node tries to reduce routing overhead by *only* sending routing packets when it needs to communicate with other nodes. So, these schemes cannot scale well as number of traffic sessions increase. Zone Routing Protocol (ZRP[3]) combines both proactive and reactive routing strategies to get the advantages of both.

ZRP has the network topology as overlapping zones centered at each node. Within a zone, proactive IntrAzone Routing Protocol (IARP) is used to maintain local zone topology information. For nodes outside the zone, reactive IntErzone Routing Protocol (IERP) is used for sending data. Like the traditional reactive routing protocols, IERP also performs route discovery and route maintainance activities. To reduce the routing overhead while performing reactive route requests, Boardercast Resolution Protocol (BRP) is used which broadcasts the route queries through the boarders of the zones.

A. Related Work

Since ZRP uses both proactive and reactive approach, the key parameter by which it can establish a balance between both strategies is zone radius. [4] has proposed zone radius estimation techniques which minimizes the total ZRP overhead. Other protocols named IZRP[1], TZRP[5], FZRP[6] are proposed in literature as the extensions to the basic ZRP version. IZRP (Independent Zone Routing) protocol has proposed mechanisms for calculating the optimal zone radius of the node. These mechanisms are known as *min searching* and *adaptive traffic estimation*. It allows each node to have its own independent zone size. TZRP (Two-Zone Routing) protocol has proposed a zone-based architecture to decouple the (basic hybrid) protocol's ability to adapt to traffic pattern from the ability to adapt to mobility. FZRP (Fish-eye Zone Routing) protocol has proposed an architecture where the proactive part of ZRP is designed with Fish-eye routing. A detailed attempt for performance analysis of ZRP overhead against numerous different parameters via simulation in OPNET can be found in [7]. In literature, [8] and [9] have attempted to model the routing overhead for different routing protocols. [8] has performed routing overhead analysis for only AODV, DSR and OLSR. [9] only considered the asymptotic analysis of the routing overhead.

B. Our Work

Our work aims to model and analyze the routing overhead incurred by ZRP since it is considered to be one of the most scalable routing protocol for MANETs. We have tried to take into account different network parameters in our analytical model and to establish the relationship between zone radius and network parameters. Our model gives a formula to calculate the optimal zone radius, given values for other network parameters. To our knowledge, no other work in literature has attempted to derive such relationships.

C. Paper Outline

The rest of the paper is structured as follows: In Section II, we present the analytical model for ZRP routing overhead. In Section III, we present the simulations carried out to validate the analytical model for ZRP routing overhead. Finally, in section IV, we present our conclusions.

II. Analytical Model for ZRP Overhead

A. Assumption and Network Model

To simplify our analysis, we have made the following assumptions.

1) The nodes are distributed uniformly across the area of the network.
2) The zone-radius of every node in the network is same.
3) The overhead induced by route maintainance is not considered to simplify the analysis.

The parameters used to model the network are summarized in table-I. R is used to estimate the area of the network, so it can also be treated as average path length to any arbitrary destination in the network. N and R together model the density of the nodes in the network. λ_s denotes the number of traffic sessions generated per second by every node. Lastly, λ_s^R denotes the number of traffic sessions for nodes in outside the zone generated per second by every node. So, λ_s^R models the reactive traffic.

TABLE I
Network Model

Parameter	Description
N	Number of nodes in network
ρ	Zone radius (hops)
R	Network Radius (hops)
d	Average inter-node distance (meters)
t_{LSU}	Inter Link-State-Update time (seconds)
λ_s	Traffic sessions generated per second by every node
λ_s^R	Reactive traffic sessions generated per second by every node

B. Proactive Control Traffic Overhead

In our analysis, we have considered pure Link-State(LS) based routing approach for proactive routing, where each node sends periodic updates to its zone. This update contains the link status information of node with its neighbors. We have derived the expression for total number of such update packets as follows.

1) Number of nodes in r-hop neighborhood in network of N nodes (n): Using the assumption of uniform distribution of the nodes, we have estimated the number of nodes in r-hop neighborhood by using the ratio of r-hop neighborhood area to the total network area.

$$n \approx \frac{r\text{-hop Area}}{\text{Total Area}} * N \approx \frac{\pi * (r*d)^2}{\pi * (R*d)^2} * N \approx \left(\frac{r}{R}\right)^2 N \quad (1)$$

2) Upper bound on Proactive Overhead: The number of update messages sent for one LSU is directly proportional to the number of nodes in the zone. Moreover, the LSU is sent using $'TTL = \rho - 1'$, that is, only internal nodes are going to rebroadcast it. In other words for each LSU, all the nodes in the zone except the peripheral nodes have to (re)broadcast it to their neighbors. Within a zone with radius ρ, the number of broadcast messages are equal to number of nodes within $(\rho - 1)$-hop neighborhood. By using the result in eq-(1) the upper bound on proactive overhead(P_{Ov}) can be given as:

$$P_{Ov} = O\left(\frac{N^2}{t_{LSU}}\left(\frac{\rho - 1}{R}\right)^2\right) \quad (2)$$

3) Broadcast Message Reduction: The number of broadcast messages for a single LSU can be reduced by exploiting already available topology information. Like, dominating set idea used in Optimized Link State Routing (OLSR)[10] or rooted spanning tree in Topology Broadcast based on Reverse-Path Forwarding (TBRPF)[11]. In OLSR, the number of broadcast messages reduces to number of MPRs in network. IN TBRPF, the number of broadcast messages reduces to number of non-leaf nodes in network. Lets denote this optimization by O_p. It represents the reduction in number of broadcast messages sent.

4) Proactive Overhead: Thus, the proactive overhead can be given as:

$$P_{Ov} = \frac{O_p N^2}{t_{LSU}}\left(\frac{\rho - 1}{R}\right)^2 \quad (3)$$

$\ldots$ where $0 < O_p \leq 1$

C. Reactive Control Traffic Overhead

The reactive overhead is estimated by taking product of two terms: 1) Number of queries generated by all nodes i.e. Reactive Traffic and 2) Number of messages generated per such query.

1) Reactive Traffic: For modeling reactive traffic (λ_s^R), we have defined the traffic distribution with respect to hop distance of the destinations. Lets denote the CDF of this traffic distribution by $F_t(r)$, which is defined as

$$F_t(r) = Pr(\text{traffic for destinations which lie at hop distance} \leq r) \quad (4)$$

Now, we have defined the reactive traffic as

$$\lambda_s^R = \lambda_s(1 - F_t(\rho)) \quad (5)$$

Traffic is assumed to be uniformly distributed with respect to all the nodes. So, $F_t(r)$ can be formulated using the ratio of r-hop neighborhood area to the total network area.

$$F_t(r) = \frac{r\text{-hop Area}}{\text{Total Area}} = \frac{\pi * (r*d)^2}{\pi * (R*d)^2} = \left(\frac{r}{R}\right)^2 \quad (6)$$

Hence, the reactive traffic (λ_s^R) under the assumption of uniform distribution is given by,

$$\lambda_s^R = \lambda_s\left(1 - \left(\frac{\rho}{R}\right)^2\right) \quad (7)$$

2) Messages per Query(m): In ZRP, the node propagates the query-message to the *minimal* set of neighbors through which all *uncovered* peripheral nodes can be reached. This is called *bordercasting* of the query. As compared to flooding the bordercast mechanism reduces the number of broadcast messages per query. We observed two types of message reduction phenomena, which are:

1) *Internal Pruning:* Since the query-message is rebroadcasted to only a subset of neighbors, there exists some internal (neighbor) nodes who do NOT rebroadcast the query-message. In our work, we have not modelled this type of message reduction. This reduction can be modelled by calculating the cardinality of minimum connected dominating set (MCDS).
2) *Coverage Pruning:* Once the query-message reaches to the point where the node does not have any uncovered peripheral nodes it stops bordercasting the query-message. In our work, we have modelled this type of message reduction.

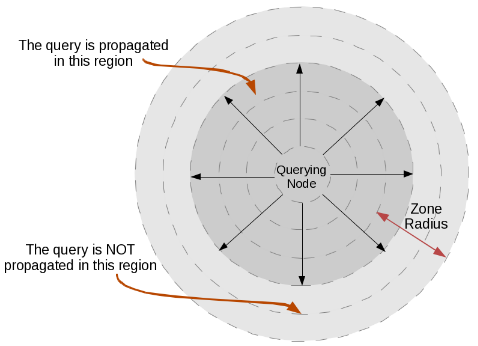


Fig. 1. Query Propagation in ZRP (Coverage Pruning)

For example, consider the case as shown in figure-1. For simplifying the analysis, we assume that the node is located at the center of the network. Here, the query-message is broadcasted only by the nodes in the dark-shaded region and NOT by the nodes in the light-shaded region. Here, we can see that once the query-message reaches at the boundary of the dark-shaded region, there are no more uncovered peripheral nodes. Moreover, we can observe that - as the zone radius increases, the dark-shaded region shrinks and the number of query-messages being broadcasted reduces.

Thus, the number of messages per query can be estimated using the ratio of the dark shaded region to the total region. So, we can define the messages per query (m) as

$$m = N * \frac{\pi * ((R - (\rho - 1)) * d)^2}{\pi * (R * d)^2} = \left(1 - \frac{\rho - 1}{R}\right)^2 \quad (8)$$

3) Reactive Overhead: Thus, using eq-5,7,8, we can define reactive overhead (R_{Ov}) for uniformly distributed traffic case as

$$R_{Ov} = \lambda_s N^2 \left(1 - \left(\frac{\rho}{R}\right)^2\right) \left(1 - \frac{\rho - 1}{R}\right)^2 \quad (9)$$

D. ZRP Overhead

The ZRP overhead (ZRP_{Ov}) can be given by summing proactive and reactive overhead from eq-(3) and eq-(9).

$$ZRP_{Ov} = \frac{O_p N^2}{t_{LSU}} \left(\frac{\rho - 1}{R}\right)^2 + \lambda_s N^2 \left(1 - \left(\frac{\rho}{R}\right)^2\right) \left(1 - \frac{\rho - 1}{R}\right)^2 \quad (10)$$

III. Simulation Results

This section presents the simulations carried out to validate the analytical model for ZRP routing overhead.

A. Simulation Environment

The NS2 simulation environment is used to simulate the ZRP protocol. All the simulations are performed under the following specifications. The network consists of 80 mobile nodes spread in an area of 1800mx1800m. Nodes move according to Random-Way-Point mobility model over the entire simulation time. Because of the movement of the nodes, the distribution of nodes is not purely uniform over time in contrast to analytical model. For each experiment, two instances of *uniformly distributed* traffic scenarios are employed and simulation is performed for each traffic scenario. In each traffic scenario, the number of data packets per session is uniformly distributed in $[1, 10]$. The inter-arrival time between sessions are exponentially distributed with parameter IST. The source of a particular session generates data packets at the constant rate of 4 packets per second, where the size of each packet is 64 bytes. The performance metrics are measured over a range of routing zone radii(ρ) configurations, from purely reactive routing ($\rho = 1\ hop$) to approximately purely proactive routing ($\rho = 5\ hops$). We have evaluated ZRP routing overhead for each scenario. The overall ZRP overhead is viewed as the sum of proactive (IARP), reactive (IERP) and neighbor discovery (NDP) overhead.

B. Experiment Setup

For validating ZRP overhead expression, it is tested against four different scenarios by varying mobility and traffic characteristics. The details of these scenarios are listed in the table-II.

TABLE II
Scenarios to validate ZRP overhead expression

Scenario	Mobility	Traffic
I	Low($V_{max} = 5m/s$)	High($IST = 8sec$)
II	Low($V_{max} = 5m/s$)	Low($IST = 20sec$)
III	High($V_{max} = 20m/s$)	High($IST = 8sec$)
IV	High($V_{max} = 20m/s$)	Low($IST = 20sec$)

The needed parameter values to evaluate the ZRP overhead expression are mapped from the simulation parameters and are summarized in table-III. N is mapped by the number of nodes in network, which is 80. O_p is taken as 1 since no optimization is employed in proactive routing. ρ varies between 1 to 5. R is estimated by analyzing the geometrical characteristics of the nodes. We have estimated R by taking time average of hop-distances between node-pairs. We have estimated λ_s by taking the time average of traffic sessions per node. We have estimated t_{LSU} by taking the time average of broadcasted LSUs per node.

TABLE III
MAPPED PARAMETER VALUES TO EVALUATE ZRP OVERHEAD EXPRESSION

Scenario	N	O_p	ρ	R	λ	t_{LSU}
I	80	1	1,..,5	4.176	0.11	6.58
II	80	1	1,..,5	4.176	0.04	7.40
III	80	1	1,..,5	4.426	0.11	5.45
IV	80	1	1,..,5	4.426	0.04	5.43

C. ZRP Overhead Comparisons

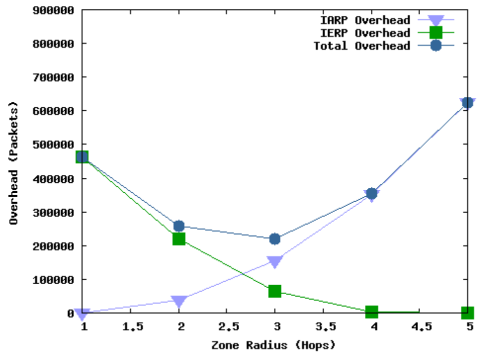
For all four scenarios, the comparison of analytically evaluated ZRP overhead and simulated ZRP overhead is shown in figure-2, 3, 4, 5. Due to the difference of the node distribution between analytically evaluated case and simulated case, following may be observed:

1) In all scenarios, the proactive overhead increases at a higher rate in analytically evaluated case than the simulated case.
2) In all scenarios, the reactive overhead is less in analytically evaluated case than the simulated case.
3) Because of above two differences in patterns of proactive and reactive overhead, the optimal zone radius setting is shifted right by 1 in simulations as compared to analytical results.

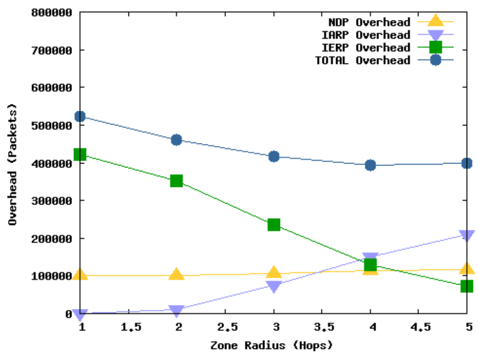
In all scenarios, the optimal zone radius setting lies at a point where the difference of proactive and reactive overhead is the smallest. In other words, zone radius optimality lies where the proactive and reactive overhead components are balanced. This result is observed in [1] and in complete agreement with our simulations. The optimal zone radius setting is different under different network conditions. We observe that as the mobility increases the optimal zone radius value decreases. For example, consider the scenarios II(low mobility) and IV(high mobility). Here, the optimal radius decreases from 3 to 2. We also observe that as the traffic increases the value of optimal zone radius increases. For example, consider the scenarios IV(low traffic) and III(high traffic). Here, the optimal radius increases from 2 to 4. If the nodes operate away from the optimal zone radius setting, it has to bear additional overhead. Table-IV shows the percentage additional overhead incurred due to the deviation from optimality.

TABLE IV
ADDITIONAL OVERHEAD DUE TO NON-OPTIMAL ZONE RADIUS SETTING (IN %)

	Zone Radius				
Scenario	**1**	**2**	**3**	**4**	**5**
I	32.76	17.49	5.95	0.00	1.67
II	35.61	4.96	0.00	5.01	14.30
III	23.03	5.79	0.64	0.00	2.61
IV	18.52	0.00	1.54	7.16	20.60

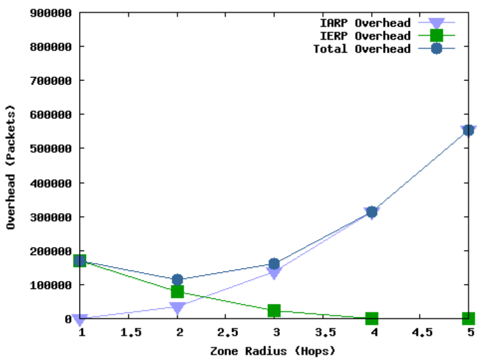


(a) Theoretically Evaluated

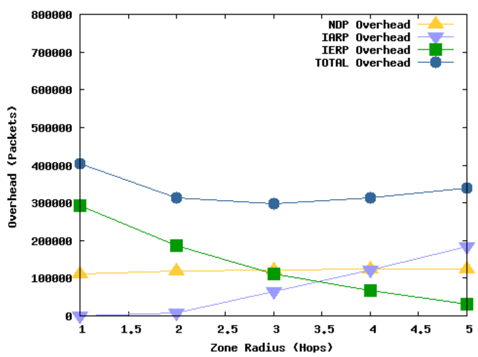


(b) Simulation

Fig. 2. Scenario-I (IST=8sec, V_{max}=5m/s)

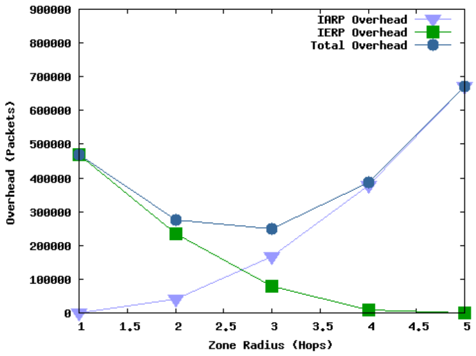


(a) Theoretically Evaluated

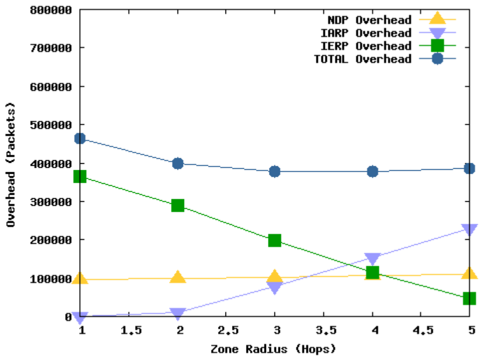


(b) Simulation

Fig. 3. Scenario-II (IST=20sec, V_{max}=5m/s)

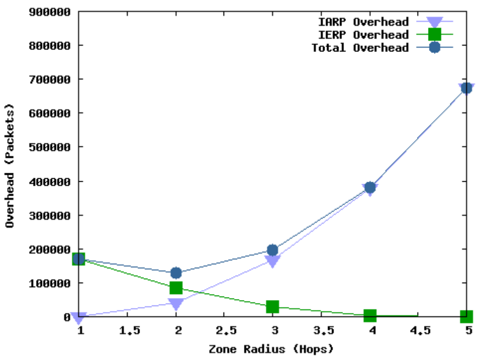


(a) Theoretically Evaluated

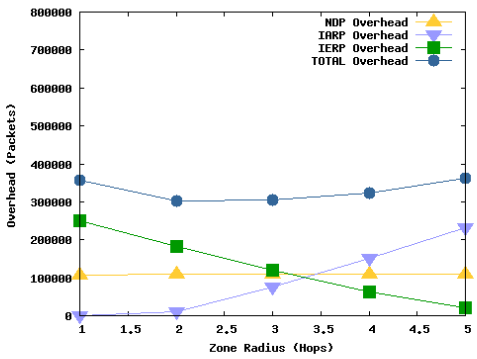


(b) Simulation

Fig. 4. Scenario-III (IST=8sec, V_{max}=20m/s)



(a) Theoretically Evaluated



(b) Simulation

Fig. 5. Scenario-IV (IST=20sec, V_{max}=20m/s)

IV. Conclusion

We have proposed an analytical model that allows us to determine the routing overhead incurred by the scalable routing framework ZRP. The proposed model is parameterized such that it can accommodate various traffic models for MANETs. We have validated the analytical model with simulations in similar environment.

The optimal zone radius setting is different under different network conditions. We observe that as the mobility increases the optimal zone radius value decreases. And as the traffic increases the value of optimal zone radius increases. In our simulation results we have observed that the optimal zone radius lies where the proactive and reactive overhead components of ZRP are approximately equal. If the nodes operate away from the optimal zone radius setting, it has to bear additional overhead. This deviation is quite high in case of low mobility(upto 35%) than in high mobility(upto 23%).

The optimal zone radius setting varies according to network conditions. ZRP framework must behave adaptively against these conditions to give efficient and scalable performance. In order to make ZRP adaptive, the mechanisms must be devised for detecting the non-optimality of zone radius setting. In addition to that, the cost-benefit analysis must be done to understand the tradeoff involved between the optimality detection cost and additional overhead cost incurred due to non-optimality.

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