Fuzzy-controlled processing of packets for mobile networks

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Abstract: Ad hoc networks are collections of mobile nodes communicating with each other through wireless media without any fixed infrastructure. The nodes have limited battery power; hence energy efficiency is required to optimize network performance. In this paper, we have designed a fuzzy controller named *Power Aware Router* (PAR) that is embedded in each node of the network. Whenever a route-request packet arrives at a node n_i, the node immediately consults its PAR to decide whether to broadcast the route-request to its downlink neighbors or drop it. The parameters considered by PAR are broadly classified into two categories - *node dependent parameters* and *session dependent parameters*. Remaining energy of n_i, congestion around it, relative velocity w.r.t. its predecessor in the communication path and present number of its downlink neighbors are *node dependent parameters* taken care of by the PAR of n_i. *Session dependent parameters* come into existence if the route-request packet has been generated as a result of some link breakage in between a communication session. In that situation, PAR of n_i takes into account the number of link breakages that already occurred in the respective session and the number of data packets yet to be transmitted. In the simulation section, we have compared some state-of-the-art and well-known routing protocols in ad hoc networks, for eg. DSR (dynamic source routing), AODV (ad hoc on-demand distanve vector), ABR (associativity based routing) and FORP (flow-oriented routing protocol with their PAR-embedded versions i.e. PAR-DSR, PAR-AODV, PAR-ABR and PAR-FORP. Very encouraging results are reported. PAR-embedded intelligent protocols produce huge improvements compared to their original versions. Performance matrices considered in this article are, energy consumption, routing overhead, delivery ratio and latency, each versus total number of nodes in the network and total number of connections or links.
Keywords: Ad hoc network, fuzzy controller, power awareness, routing.

1. INTRODUCTION

A mobile ad hoc network is an infrastructure-less, self-organizing and rapidly deployable network where a node communicates with another directly or indirectly through some intermediate nodes. Thus, all nodes in an ad hoc network basically function as mobile routers participating in the underlying routing protocol for selecting and maintaining the routes [1-7]. Routing is one of the key issues in ad hoc networks due to their highly dynamic and distributed nature. Since mobile nodes are powered with limited battery capacity, energy efficiency in routing [1, 3, 4, 5, 9] is a very important design criteria for these kinds of networks. Power failure of a mobile node not only affects the node itself but also its ability to forward packets on behalf of others and thus, overall network life time.

Several energy efficient routing protocols are available in literature on ad hoc networks [7-13]. They can be broadly categorized based on when the energy optimization is performed. A mobile node consumes its battery power not only when it actively sends or receives packets but also when it stays idle listening to the wireless medium for possible communication requests from other nodes. By convention, during this idle period also, a node is bound to broadcast HELLO message at regular intervals in order to detect its current set of downlink neighbors. All nodes residing within its radio-range reply with an acknowledgement as soon as they receive the HELLO message. Thus, energy efficient routing protocols minimize either the active communication energy (i.e. the energy required to transmit and receive data packets) or the energy in inactive period or both, as much as possible. For protocols that belong to the former category, the active communication energy can be reduced by adjusting each nodes radio-power during transmission/forwarding of a message to one of its downlink neighbors to be just enough to reach the receiver and not more than that. This transmission power control approach can be extended to determination of an optimal routing path [17] that minimizes the total transmission energy required to deliver packets from source to the destination.

For protocols that minimize energy consumption during inactive periods, each mode can save the inactivity energy by switching its mode of operation into sleep/power-down mode when there is no data to transmit and receive. This leads to considerable energy savings, especially when the network environment is characterized by low duty cycle of communication activities. Another important approach to optimizing active communication is load distribution approach [18]. While the primary focus of the above two approaches is to minimize energy consumption of individual nodes, the main goal of load distribution method is to balance the energy usage among the nodes while avoiding overloaded nodes during selection of a routing path. Usage of directional antenna also inculcates the flavor of power-awareness in ad hoc routing protocols by delivering packets to the desired receivers only. By exploring the directionality of beams, overlaps between beams of nodes are reduced to a great extent which substantially increases the signal accuracy.

In the present article, we have applied the following techniques of energy savings in nodes:

i) Minimizing power consumption of a node during transmission/forwarding of a message.
ii) Directional antennas.
iii) Adaptive HELLO protocol.
iv) Selective broadcasting of route-request packets.

Please note that, in this paper, we have designed a fuzzy controller named *Power Aware Router* (PAR) that is embedded in each node of the network. Whenever a route-request packet arrives at a node n_i, the node immediately consults its PAR to decide whether to broadcast the route-request to its downlink neighbors or drop it. Some input parameters of PAR of a node n_i depend upon certain characteristics of n_i; they are remaining energy of n_i, congestion around it, relative velocity w.r.t. its predecessor in the respective communication path and present number of its downlink neighbors. Other inputs depend upon some characteristics of the communication session. These Session dependent parameters come into existence if the route-request packet has been generated as a result of some link breakage in between a communication session. In that situation, PAR of n_i takes into account the number of link breakages that already occurred in the respective session and the number of data packets yet to be transmitted. PAR requires that a route-request packet must include the information that whether it is a fresh one or has been generated as a result of some link breakage, the number of packets already transmitted to the destination before link breakage (if a link was broken) and the number of packets yet to be transmitted.

The remainder of this paper is organized as follows. Section 2 presents the state-of-the-art routing protocols on ad hoc networks. Section 3 describes the above-mentioned power saving techniques in detail. Section 4 demonstrates and explains the simulation results while section 5 concludes the paper.

2. POPULAR ROUTING PROTOCOLS FOR AD HOC NETWORKS

The routing protocols proposed so far in the literature on ad hoc networks, are generally categorized as table-driven and demand-driven based on the timing of route updation. With table-driven routing protocols, each node attempts to maintain consistent, up-to-date routing information to every other node in the network. This is done in response to changes in the network by having each node update its routing table and propagate the updates to its neighboring nodes. Thus, it is proactive in the sense that when a packet needs to be forwarded the route is already known and can be immediately used. The routing table is constructed using either link state or distance vector algorithms containing a list of all the destinations, the next hop node and the number of hops to each destination. Many routing protocols, for eg. destination sequenced distance vector (DSDV), wireless routing protocol (WRP), global state routing (GSR), source tree adaptive routing (STAR) and cluster-based gateway switch routing (CGSR) etc. belong to this category and they differ in the number of routing tables manipulated and the methods used to exchange and maintain routing tables [17].

On the other hand, with demand driven routing, routes are discovered only when a node requires communicating with any other node. Route discovery and route maintenance are two main procedures here. The source node initiates route discovery process by transmitting route-request packets to its downlink neighbors. These downlink neighbors again broadcast that route-request packet within their radio-circle and so on. The procedure continues until and unless the destination node is reached or number of hops traversed by the route-request packets crosses maximum allowable hop count of the network. Once the route-request packet reaches the destination node, it responds by unicasting a route-reply packet back to the source node informing about the optimal communication path selected by the destination. This particular path will be used by the source during subsequent transmission of data packets to the destination till any of its links, say from node n_i to node n_j, breaks. In order to handle the link breakage situation, n_i informs the source about it. In response, the source immediately re-initiates route-discovery process to complete communication with the destination. Dynamic source routing (DSR), ad hoc on-demand distance-vector (AODV), light-weight mobile routing (LMR), flow-oriented routing protocol (FORP) and associativity-based routing (ABR) are mention-worthy reactive routing protocols as far as ad hoc networks are concerned. In DSR and AODV, the performance metric is hop count of the path. On the other hand in FORP, optimal path is selected based on link expiration time (LET) and route expiration time (RET). Associativity based routing (ABR) is a beacon-based communication scheme where downlink neighbors are used to update associativity tables of nodes. With these tables the nodes are able to classify whether a downlink neighbor is stable or unstable. Its uniqueness lies in the use of associativity ticks to form routes based on the stability of its routers.

3. ADOPTED ENERGY EFFICIENCY TECHNIQUES

The energy efficiency techniques applied in this paper are mentioned in the introduction section. Among them, the first two are quite self-explanatory. The adaptive HELLO protocol and selective broadcasting of route-request using PAR are described here in details.

i) Adaptive HELLO Protocol - a node emits a HELLO beacon for every $\varnothing$ meters of distance it moves. Thus, nodes moving at higher speeds emit HELLO beacons at higher rates, similarly, nodes moving at lower speeds emit HELLO beacons at lower rates. To control the high rate of beaconing at higher speeds, nodes use a minimum beacon interval (MNB). Due to adaptive nature of the protocol, a node that is pausing will not generate HELLO beacons for the duration of the pause. However, if downlink neighbors of a node n_i do not receive HELLO beacons from n_i for along time, they may timeout n_i from their uplink neighbor tables. To avoid this problem, nodes use a maximum beacon interval (MXB). A node is bound to broadcast HELLO message at least once in every MXB time units. Each HELLO beacon broadcasted by n_i within its radio-range consists of the current timestamp along with the following information about itself:

- unique identification number of the node
- speed
- direction of movement
- geographical position in terms of latitude and longitude
- radio-range
- maximum (initial) battery power
- battery charge consumed so far
- size of the message queue
- number of filled locations in the queue at that time
- number of downlink neighbors
- average of bandwidth of all the channels (both uplink and downlink) connected to it

The nodes which receive this HELLO message reply by sending an acknowledgement. Attributes of an acknowledgement message are absolutely same as the HELLO message transmitted by the same node. The performance of the adaptive beaconing depends on the parameter $\varnothing$. If it is small, then the neighbor table will be very accurate at the cost of the increased message overhead. On the other hand, if $\varnothing$ is large, then the overhead will be very low at the cost of stale neighborhood information. Depending on the value of $\varnothing$, one can tradeoff overhead for accuracy. The advantage is that nodes beacon infrequently, yet sufficient to cope with the mobility. Also, nodes adapt to mobility. Nodes that are pausing generate HELLO packets infrequently (once in every MXB time units). By suppressing HELLO beacons during a pause, nodes save many beacon messages as well as possible acknowledgements to those. Please note that, attributes of an acknowledgement message are same as those of HELLO messages.

ii) Selective broadcasting of route-request packets – If a route-request packet arrives at a node n_i, it consults its PAR to decide whether to forward the packet or drop. Decision of PAR is based on the following parameters:

- Remaining energy quotient – Let, maximum battery power and battery power consumed up to current time t of a node n_i, be denoted as E_i and $e_i(t)$, respectively. Then, remaining energy quotient $\propto_i(t)$ of n_i is formulated in (1).

  $$\propto_i(t) = 1 - e_i(t) / E_i \tag{1}$$

  As per the above formulation, for any node n_i, $\propto_i(t)$ lies between 0 and 1. Values of it close to 1 indicate the fact that, from the perspective of battery power, it is capable enough to forward the route request packet it has just received.

- Predecessor affinity – Assume that n_j is a predecessor of n_i in a communication path, velocity of n_i at time t is denoted as $\upsilon_i(t)$ whereas velocity of n_i with respect to its uplink neighbor n_j at time t is $v_{i,j}(t)$. So, $v_{i,j}(t) = \upsilon_i(t) - \upsilon_j(t)$. Let $u_{i,j}(t)$ be the time duration for which n_i has been within radio-circle of n_j after it entered into the radio-circle of n_i last time, up to time t. Coordinate positions of both n_i and n_j are statistically estimated for the timestamps t+1, t+2, t+3 up to $t+m(t)\sigma'_{i,j}$ where m(t) is the remaining number of packets to be sent by the sender and $\sigma'_{i,j}$ is the transmission delay along the average-length route in the network. Assume that R_{min} and R_{max} denote the minimum and maximum radio-ranges in the network respectively, H is the highest allowable hop count and v_s is the signal speed. Then, $\sigma'_{i,j} = H(R_{min} + R_{max})/2v_s$. Let $\sigma_{i,j}$ be the timestamp within the above-mentioned interval up to which n_i is expected to remain downlink neighbor of n_j. Hence the formulation of affinity $\beta_i(t)$ of n_i w.r.t. its predecessor n_j at time t is expressed in (2).

  $$\beta_i(t) = (1+ v_{i,j}(t))^{-1} (1-1/(1+ u_{i,j}(t))) ((\sigma_{i,j} +1) / (m(t)\sigma'_{i,j} +1)) \tag{2}$$

  Inclusion of $(1-1/(1+ u_{i,j}(t)))$ in the above formulation of predecessor affinity is based on the fact that if a node n_i has been within downlink neighborhood of n_j for a long time, then it is expected that n_i will continue to reside within radio-circle of n_j in future. The part $((\sigma_{i,j} +1) / (m(t)\sigma'_{i,j} +1))$ is solely a prediction of the future of neighborhood relation between n_i and n_j depending upon their relative velocities exchanged as part of HELLO and acknowledgement messages. Predecessor affinity gets strength with decrease in relative velocities of the involved nodes n_i and n_j. $(1+ v_{i,j}(t))^{-1}$ specifies impact of present relative velocity $v_{i,j}(t)$ over $\beta_i(t)$. Lesser the velocity of n_i w.r.t. n_j, higher the affinity between them. From (2) it may be noted that, $\beta_i(t)$ also lies between 0 and 1. Values close to1 indicate high predecessor affinity.

  This parameter is extremely important from the perspective of PAR. If n_i itself has little chance of continuing participation in the communication path i.e. it has got a fickle bond with predecessor n_j, then from practical point of view, n_i should have little interest in broadcasting the route-request packet that it received from n_j.

- Remaining packet load – Assuming that a total of $\rho_{s,d}$ packets were to be transmitted from source n_s to destination n_d among which only $\rho'_{s,d}(t)$ packets have been delivered, remaining packet load $\gamma_i(t)$ on any intermediate node n_i at time t is given by,

  $$\gamma_i(t) = \rho'_{s,d}(t) / \rho_{s,d} \tag{3}$$

  Since $\rho'_{s,d}(t) / \rho_{s,d}$, $0 \le \gamma_i(t) \le 1$. Higher the remaining packet load, higher is the responsibility of n_i to forward the route-request packet it has received, provided it has sufficient battery power and its wireless link with its predecessor is strong enough in terms of relative velocity.

- Congestion around – Bandwidth $B_i(t)$ of a node n_i is defined to be the average of bandwidth of all the channels (both uplink and downlink) connected to n_i at time t. $N_i(t)$ and Ui(t) denote the set of downlink and uplink neighbors of n_i at time t, respectively. Let, maximum size of message queue of any node n_j is M_j and filled portion of the queue at time t is denoted as $\theta_j(t)$. Congestion $g_i(t)$ around a node n_i at time t is formulated in (4).

$$g_i(t) = \{\prod_{n_j \in \{N_i(t) \cup U_i(t)\}} q_i(t)\}^{1/(|N_i(t)|+|U_i(t)|)} \quad (4)$$

$$q_i(t) = ((\theta_j(t)+1) / (M_j+2))^{B_i(t) / B_j(t)} \quad (5)$$

Conceptually, $g_i(t)$ indicates the combined effect of signal collision and message forwarding load at node n_i at time t. Present message forwarding load is denoted as $((\theta_j(t)+1)/(M_j+2))$. Please note that a 2 is added to its denominator to enforce fractional value for this parameter. Otherwise its bandwidth will loose its effects. $g_i(t)$ must not be zero if any one of its uplink/downlink neighbor has empty message queue at time t. Adding 1 to $\theta_j(t)$ in formulation of $q_i(t)$ serves the purpose. Influence of signal collision on the transmissions generated by n_i at time t decreases with the nodes (n_i's) own bandwidth, and increases with the same of it's the then uplink as well as downlink neighbors. As per the formulation of congestion in (4), $0<g_i(t)<1$. High values of it indicate high congestion around n_i which may discourage it to forward the route request.

- Downlink cardinality quotient – For a node n_i, downlink neighbor cardinality quotient $\psi_i(t)$ of n_i at time t, is mathematically expressed in (6).

$$\psi_i(t) = 1 - 1/(|N_i(t)| + 1) \quad (6)$$

From the formulation in (6), $0 \le \psi_i(t) < 1$. Values of downlink cardinality close to 1 indicate the fact that if n_i broadcasts a route-request packet, it will reach a huge number of nodes in a shot.

- Link breakage overhead – Let $r_{s,d}$ denote the total number of link breakages that occurred in one particular communication session from source n_s to destination n_d. Then link breakage overhead $l'_{s,d}(t)$ at time t is given by,

$$l'_{s,d}(t) = 1 - 1/(r_{s,d}(t) + 1) \quad (7)$$

If a communication route from source n_s to destination n_d suffers from huge number of link breakages, then route-requests generated by n_s for n_d will have little weightage to routers in the path. Link breakage overhead for any router, source and destination nodes lies between 0 and 1.

PAR divides crisp ranges of the above parameters into sub-ranges and fuzzy variables are assigned to them as per table I. P is the output of PAR.

TABLE I

CRISP RANGE DIVISION OF PARAMETERS OF PAR

Crisp ranges for $\propto$	Crisp ranges for β	Crisp ranges for γ, g, ψ, l′ and P	Fuzzy variable
0 – 0.40	0 – 0.50	0 – 0.30	a
0.40 - 0.65	0.50 – 0.70	0.30 – 0.60	b
0.65 – 0.85	0.70 - 0.90	0.60 – 0.80	c
0.85 – 1.00	0.90 – 1.00	0.80 – 1.00	d

According to the study of discharge curve of batteries heavily used in ad hoc networks [18], on an average, at least 40% of initial battery charge is required to remain in operable condition (indicated as fuzzy variable a in table I); 40% - 65% is satisfactory (fuzzy variable b) whereas the range from 65% - 85% (fuzzy variable c) of full battery capacity ensures pretty good longevity of the corresponding router. Higher values of remaining energy coefficient (α) are more than sufficient. Velocity affinity (β) specifies apparent regularity in time-variant hop of the current router with its predecessor. If a router n_i has little probability of continuing its participation in a route from source n_s to destination n_d, then it gives little weightage to route-requests generated by n_s after a link breakage. Like remaining energy quotient, good predecessor affinity is also indispensable for a path. It is evident from table I that we are stricter in case of predecessor affinity than remaining energy quotient, as far as range division is concerned. The reason is that, unlike remaining energy quotient, several statistical approximations are involved in the formulation of predecessor affinity. In order to reduce the effects of errors that may be introduced as a result of the above mentioned statistical approximations, range division of predecessor affinity is more restricted (the ranges 0-0.50, 0.50-0.70, 0.70-0.90, 0.90-1.00 are denoted as fuzzy variables a, b, c and d respectively) than the same of remaining energy quotient. As far as the other parameters (remaining packet load γ, congestion around g, downlink cardinality quotient ψ and link breakage overhead l') are concerned, they are less significant than remaining energy quotient and predecessor affinity. Their ranges are uniformly divided; 0-0.30, 0.30-0.60, 0.60-0.80 and 0.80-1.00 are denoted as fuzzy variables a, b, c and d respectively.

Table II combines the effects of remaining energy quotient and predecessor affinity to produce a temporary output t1. Since both of them are equally indispensable for sustainability of a hop, PAR assigns equal importance to them in the fuzzy rule base of table II. t1 is combined with remaining packet load in table III. Among these two, t1 dominates because it is combination of two input parameters both of which are more important then remaining packet load. Table III produces another temporary output t2. Fuzzy composition of t2 and congestion g is shown in table IV which generates t3 as output. Table V integrates the effects of t3 and downlink cardinality quotient producing next phase temporary output t4. t4 and link breakage overhead are combined in table VI to produce output P of PAR.

TABLE II
FUZZY COMBINATION OF $\propto$ AND β PRODUCING t1

$\propto \rightarrow$ $\beta \downarrow$	a	b	c	d
a	a	a	a	a
b	a	b	b	b
c	a	b	c	c
d	a	b	c	d

TABLE III
FUZZY COMBINATION OF t1 AND γ PRODUCING t2

t1 $\rightarrow$ $\gamma \downarrow$	a	b	c	d
a	b	b	c	d
b	a	b	c	d
c	a	a	b	c
d	a	a	b	c

TABLE IV
FUZZY COMBINATION OF t2 AND G PRODUCING t3

t2 $\rightarrow$ g $\downarrow$	a	b	c	d
a	b	b	c	d
b	a	b	c	d
c	a	b	c	d
d	a	a	b	c

TABLE V
FUZZY COMBINATION OF t3 AND ψ PRODUCING t4

t3 $\rightarrow$ $\psi\downarrow$	a	b	c	d
a	b	b	c	d
b	a	b	c	d
c	a	b	c	d
d	a	a	b	c

TABLE V
FUZZY COMBINATION OF t4 AND l' PRODUCING P

t4 $\rightarrow$ $l'\downarrow$	a	b	c	d

a	a	b	c	d
b	a	b	c	d
c	a	b	c	d
d	a	a	b	c

4. SIMULATION RESULTS

Simulation of the mobile network has been carried out using ns-2 [21] simulator on 800 MHz Pentium IV processor, 40 GB hard disk capacity and Red Hat Linux version 6.2 operating system with specification of parameters shown in table VI. Graphical comparisons of performance between state-of-the-art routing protocols DSR, AODV, FORP, ABR and their PAR-embedded versions appear in figures from 1 to 16. Emphatic improvements are produced by PAR-embedded versions of the above-mentioned protocols. Number of nodes has been taken as 150, 500, 1000, 2000, 3500 and 6000 in six different independent simulation studies. For each such simulation run, speed of a node is chosen randomly between various ranges; the ranges are 0-25m/s (denoted as rn1), 10-30m/s (denoted as rn2), 25-55 m/s (denoted as rn3), 0-75m/s (denoted as rn4), 75-150m/s (denoted as rn5) and 20-150m/s (denoted as rn6). Total 36 simulation runs have been performed. Performance metrics used for comparison are as follows:

Definition 1: Percentage of packet delivery ratio (PPDR)

Let, $D^{\sim}_{ij}$ denotes the number of packets successfully delivered during communication sessions from n_i to n_j; $M^{\sim}_{ij}$ indicates the number of packets generated by n_i for n_j (n_i and n_j are any two arbitrary nodes in the network); Z indicates the set of all nodes in the network. Percentage of packet delivery ratio (PPDR) of the network is expressed as,

$$PPDR = (1/|Z|) \sum_{n_i, n_j \in Z} (D^{\sim}_{ij} / M^{\sim}_{ij}) \times 100 \quad (8)$$

Definition 2: Routing Overhead (RO)

Let, $S^{\sim}_{ij}$ denotes the total number of messages (including route discovery packets) transmitted during communication sessions from n_i to n_j; Z indicates the set of all nodes in the network. Then, routing overhead of the network can be expressed as (9).

$$RO = (1/|Z|) \sum_{n_i, n_j \in Z} S^{\sim}_{ij} \quad (9)$$

Definition 3: Per Node Delay in Seconds (PNDS)

Let, t^s_{ij} and t^f_{ij} denote the timestamps (in seconds) of initiation and completion, respectively, of a communication session from n_i to n_j. Per node transmission delay (in seconds) of the network can be expressed as (10).

$$PNDS_{ij} = (1/|Z|) \sum_{n_i, n_j \in Z} (t^f_{ij} - t^s_{ij}) \quad (10)$$

Definition 1: Percentage of energy consumption (PEC)

Let, $E^{\sim}_i$ and E_i denote the energy consumed by n_i throughout the simulation period and maximum battery power of the same node. Z indicates the set of all nodes in the network. Then, percentage of energy consumption (PEC) of the network is expressed as,

$$PEC = (1/|Z|) \sum_{n_i \in Z} (E^{\sim}_i / E_i) \times 100 \quad (11)$$

TABLE VI
SIMULATION PARAMETERS

Parameter	**Value**
Network Area	900×900 m^2 in first twelve runs, 2000×1000 m^2 in next twelve runs, 900×3000 m^2 in last twelve runs
Node velocity ranges	rn1, rn2, rn3, rn4, rn5 and rn6 (values of these ranges are described earlier)
Transmission Range	10 – 100 m in first twelve runs, 50 – 400 m in next twelve runs, 10 – 700 m in last twelve runs
MNB	20 seconds for first twelve simulation runs, 30 seconds for next twelve and 45 seconds for last twelve simulation runs
MXB	60 seconds for first twelve simulation runs, 100 seconds for next twelve and 150 seconds for last twelve runs
$\varnothing$	5 m
Number of nodes	150 - 6000
MAC layer	IEEE 802.11g
Traffic type	Constant bit rate (128 kbps/second)
MAX_RETRY	4
Packet Size	64 bytes in first twelve runs, 128 bytes in next twelve runs, 256 bytes in last twelve runs
Bandwidth	1- 4 Mbps in first twelve runs, 2 – 7 Mbps in next twelve runs, 1-10 Mbps in last twelve runs
Mobility model	Random waypoint mobility model in first twelve runs, Random walk mobility model in subsequent twelve runs and Gaussian model in last twelve runs
Simulation Time	3000 s for each run

- In terms of ***packet delivery ratio,*** improvements of PAR-embedded versions of DSR, AODV, FORP and ABR, compared to their ordinary versions, are graphically shown in figures 1 to 4. PPDR has been plotted w.r.t. total number of nodes in the network and number of connections or links in the network for various velocity ranges rn1, rn2, rn3, rn4, rn5 and rn6 (values of these ranges are described earlier). In most cases, PAR-embedded protocols eliminate unnecessary rebroadcasting of route-request packets. This reduces packet loads on the network which, in turn, produces lesser signal collision and congestion. As a result, packet delivery ratio increases. However, for all the protocols it may be observed that packet delivery ratio increases as the number of nodes and number of connections or links in the network increase up to a certain extent. After that the packet delivery ratio starts decreasing with increase in number of nodes or links. The reason is that, when number of nodes is as low as 150, discovering a route to the destination may not always be possible due to the deficiency of intermediate nodes or routers. The problem gradually vanishes as the number of nodes or links increase up to a certain extent. After that, the network gets overloaded with nodes. As a result, huge signal congestion and collision take place reducing the packet delivery ratio. Losses of packets are sometimes mistakenly believed to be due to link breakages. In order to repair those links, route requests are again broadcasted. This, in turn, produces even more packet load, more collision and packet loss. On the contrary, PAR-embedded protocols facilitate the nodes to drop route-requests when they are highly congested or staying on the verge of battery exhaustion. Hence, under highly congested scenario also, PAR-embedded protocols can generate substantial improvement compared to their ordinary versions.

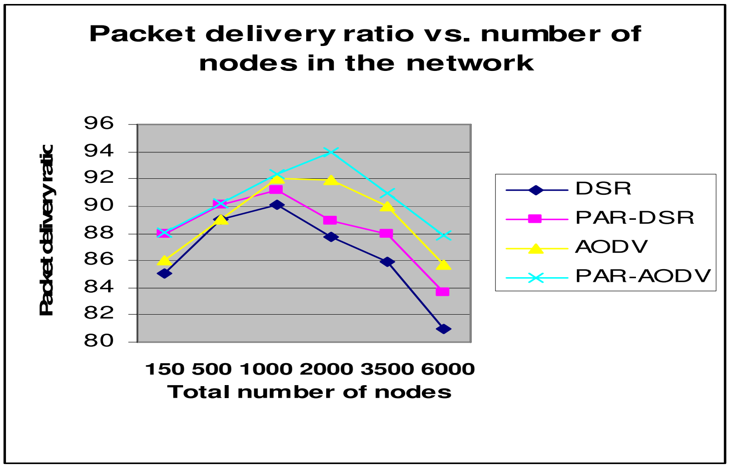

Fig1: Packet delivery ratio vs. total number of nodes in the network for DSR, PAR-DSR, AODV and PAR-AODV

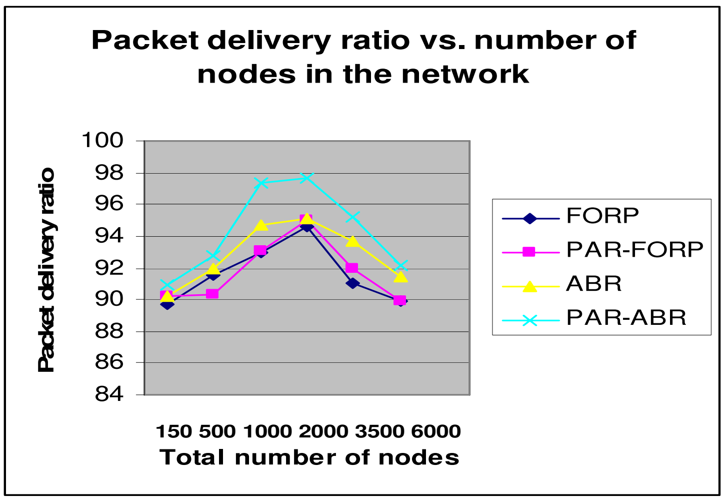

Fig2: Packet delivery ratio vs. total number of nodes in the network for FORP, PAR-FORP, ABR and PAR-ABR

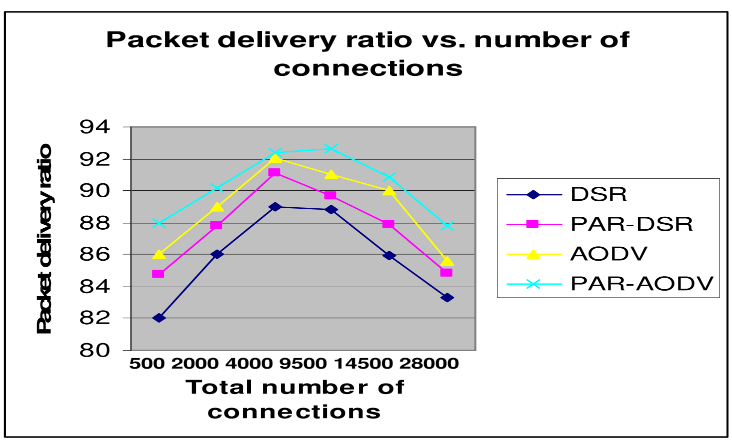

Fig3: Packet delivery ratio vs. total number of connections for DSR, PAR-DSR, AODV and PAR-AODV

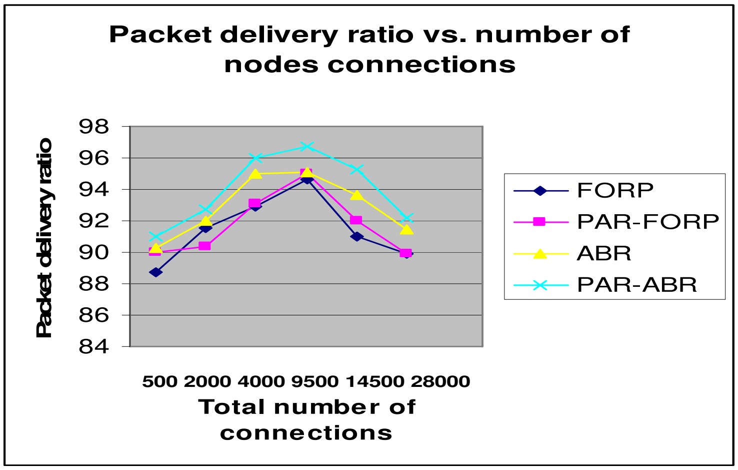

Fig 4: Packet delivery ratio vs. total number of connections for FORP, PAR-FORP, ABR and PAR-ABR

- In terms of ***routing overhead,*** improvements of PAR-embedded versions of DSR, AODV, FORP and ABR, compared to their ordinary versions, are graphically shown in figures 5 to 8. PAR-embedded protocols instruct network elements or nodes to selectively broadcast route-requests. As described earlier, the selection is based on certain node-dependent and session-dependent parameters. This produces significant improvement in terms of message cost even when the number of nodes in the network is as high as 6000.

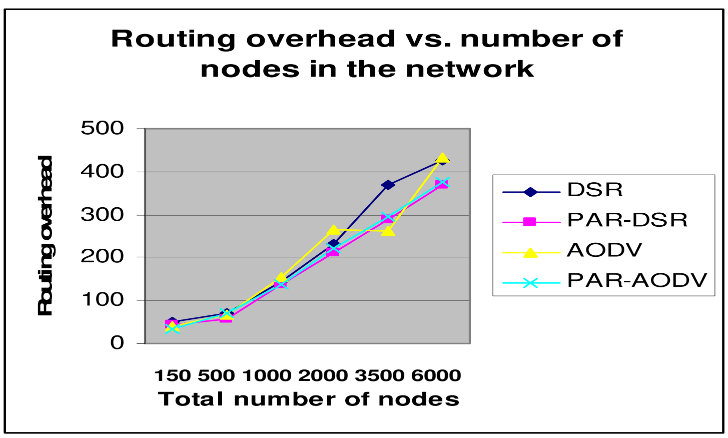

Fig5: Routing overhead vs. total number of nodes for DSR, PAR-DSR, AODV and PAR-AODV

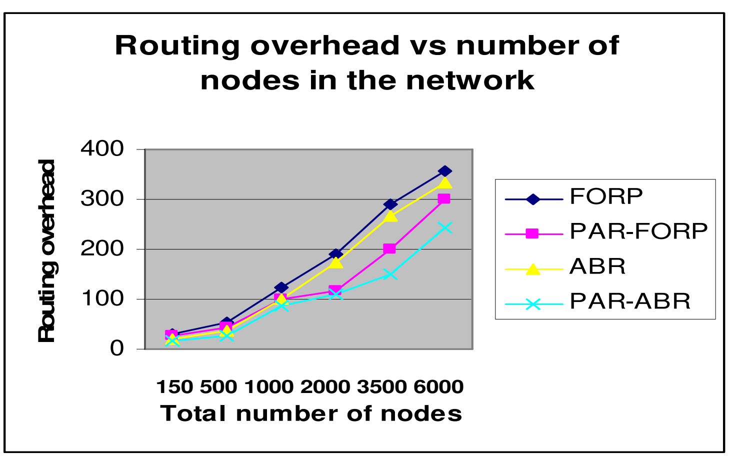

Fig6: Routing overhead vs. total number of connections for FORP, PAR-FORP, ABR and PAR-ABR

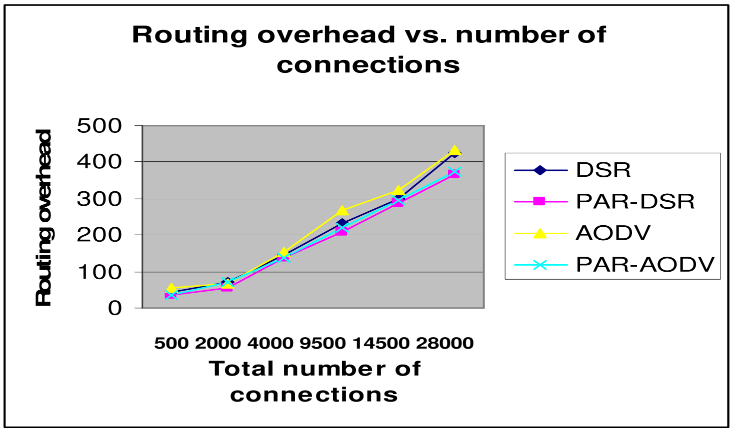

Fig7: Routing overhead vs. total number of connections for DSR, PAR-DSR, AODV and PAR-AODV

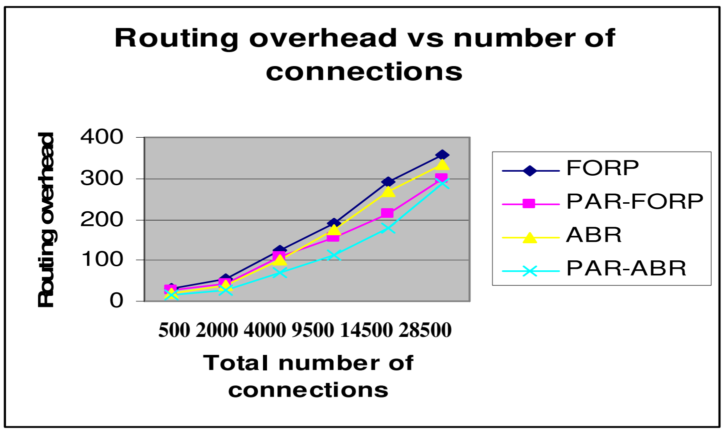

Fig8: Routing overhead vs. total number of connections for FORP, PAR-FORP, ABR and PAR-ABR

- In terms of ***transmission delay,*** improvements of PAR-embedded versions of DSR, AODV, FORP and ABR, compared to their ordinary versions, are graphically shown in figures 9 to 12. PAR-embedded protocols generate less signal collision and packet loss. Hence, transmission delay in the network significantly decreases. The improvement is even more noticeable when number of nodes in the network is as high as 6000.

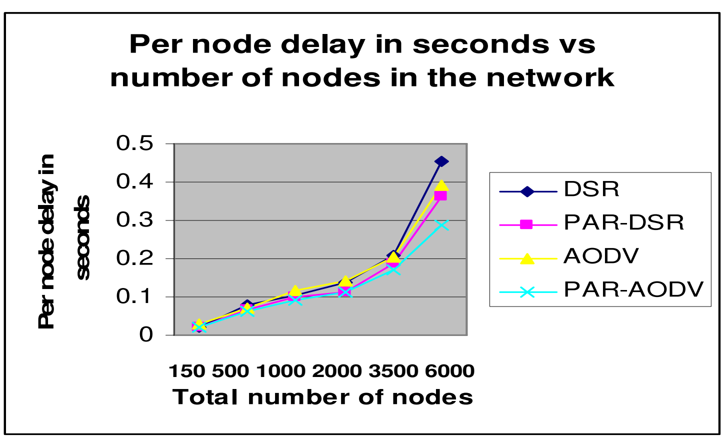

Fig9: Per node delay in seconds vs. total number of nodes for DSR, PAR-DSR, AODV and PAR-AODV

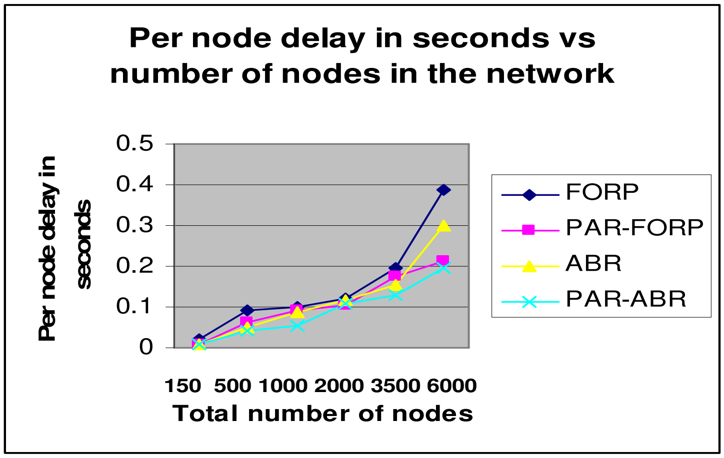

Fig10: Per node delay in seconds vs. total number of nodes for FORP, PAR-FORP, ABR and PAR-ABR

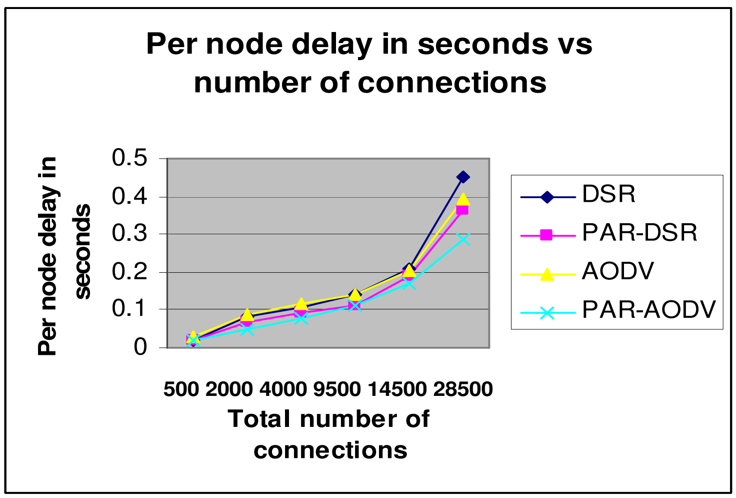

Fig11: Per node delay in seconds vs. total number of connections for DSR, PAR-DSR, AODV and PAR-AODV

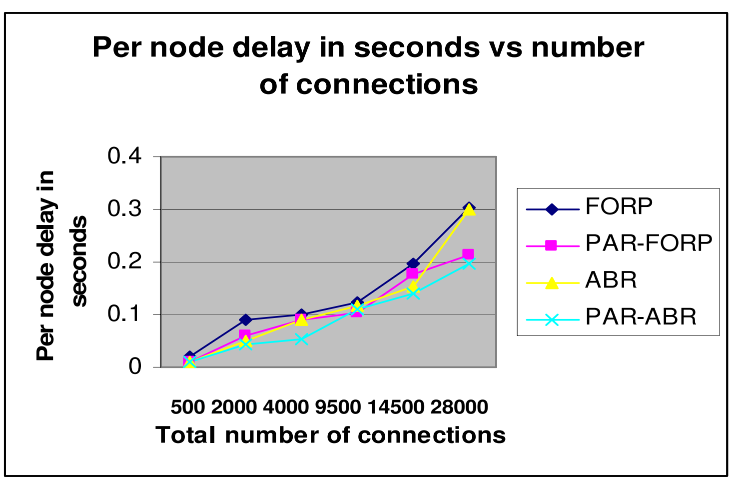

Fig12: Per node delay in seconds vs. total number of connections for FORP, PAR-FORP, ABR and PAR-ABR

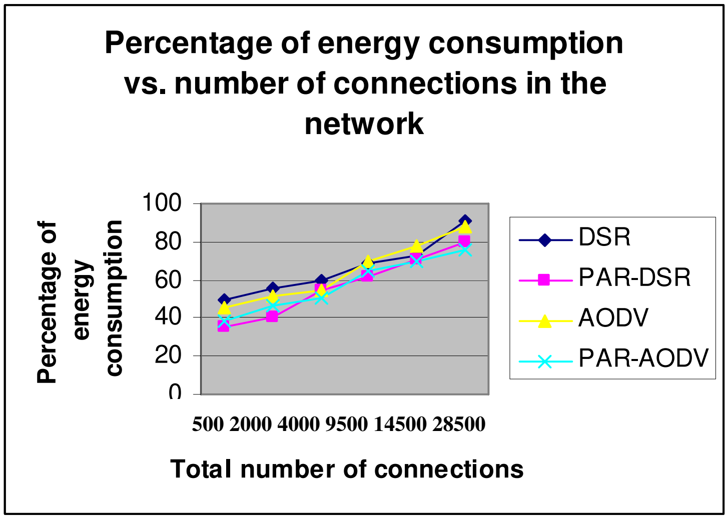

Fig13: Percentage of energy consumption vs. total number of connections for DSR, PAR-DSR, AODV and PAR-AODV

- In terms of ***percentage of energy consumption,*** improvements of PAR-embedded versions of DSR, AODV, FORP and ABR, compared to their ordinary versions, are graphically shown in figures 13 to 16. PAR-embedded protocols instruct nodes to drop route-requests if they do not have sufficient battery power. Moreover, it reduces packet load on the network; routers have lesser number of route-requests to forward. Applications of adaptive HELLO protocol as well as directional antenna inculcate energy efficiency in PAR-embedded protocols. Hence, energy consumption of nodes in the network significantly decreases.

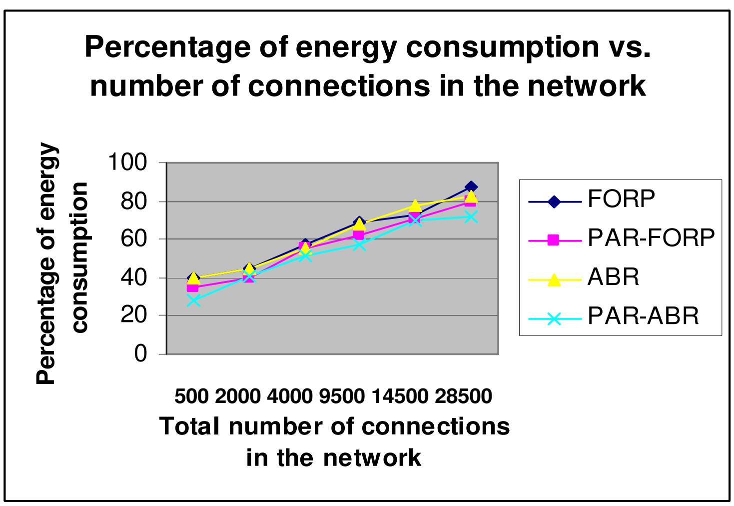

Fig14: Percentage of energy consumption vs. total number of connections for FORP, PAR-FORP, ABR and PAR-ABR

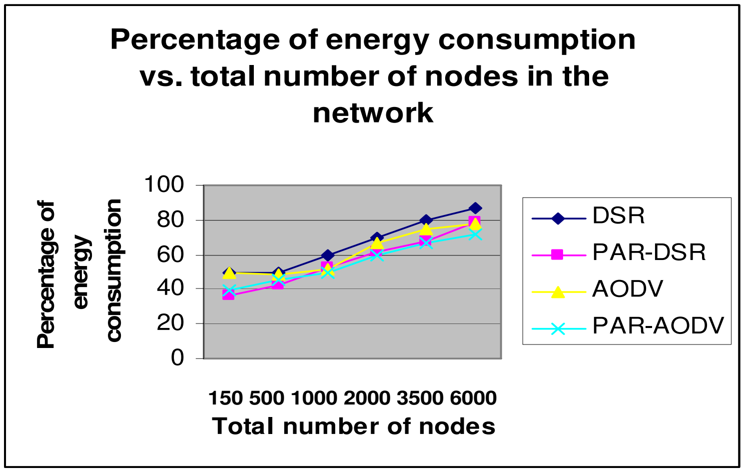

Fig 15. Percentage of energy consumption vs. total number of nodes in the network for DSR, PAR-DSR, AODV and PAR-AODV

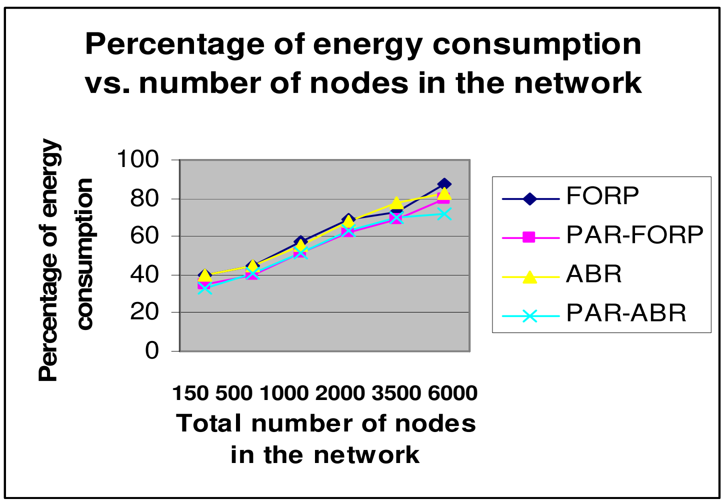

Fig16: Percentage of energy consumption vs. total number of nodes for FORP, PAR-FORP, ABR and PAR-ABR

5. CONCLUSION

PAR-embedded protocols inculcate intelligence in nodes of the ad hoc network so that instead of blindly forwarding all route-requests, they judge importance of those packets as well as their own capability in terms of remaining battery life and relative velocity w.r.t. its predecessor node in the communication path. Through extensive simulation studies it has been established that PAR-embedded protocols produce substantial performance enhancement compared to their ordinary versions.

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