Fuzzy Controlled Energy Efficient Routing Protocol (FE^2RP) for Mobile Ad Hoc Networks

Anuradha Banerjee
Department of Computer Applications
Kalyani Govt. Engg. College
West Bengal, India

Paramartha Dutta
Department of Computer Sciences
Visva-Bharati University
West Bengal, India

Subhankar Ghosh
Department of Computer Science
Regent Education and Research Foundation
West Bengal, India

ABSTRACT

A mobile ad hoc network is an infrastructure less network where the nodes are free to move randomly in any direction. The nodes have limited battery power. Hence we require energy efficient routing techniques that reduce cost of communication i.e. energy consumption in nodes, automatically increasing the network throughput. Fuzzy Controlled Energy Efficient Routing Protocol (FE^2RP) determines status of each node in the routes depending upon their remaining energy, communication load, average neighbour affinity and geographical position w.r.t territory of the network. The status is evaluated as either ready or not-ready. Generally during route discovery phase, route-request packets arrive at the destination through multiple paths. One of the routes with least number of ready nodes, is elected as the optimal path for communication.

Keywords:

Battery power, throughput, neighbour affinity, route-request, optimal path.

1. INTRODUCTION

An ad hoc network is a group of wireless mobile devices through by battery, which communicate with each other multi-hop wireless links without any fixed infrastructure or centralized administration. In order to increase node life and maintain network connectivity, we need energy efficient routing protocols. Several such protocols are there in the literature [2, 9, 15, 5, 6, 4, 3, 18, 7, 10, 16, 19, 1, 20, 17, 13, 11, 12, 14, 8]. Among them, Conditional Min - Max Battery Cost Routing (CMMBCR) [2], Location - Based Power Conservation scheme (LBPC) [9], Signal Strength based energy efficient routing (S^2E^2R) [15], Energy Conserving Prioritized Pheromone Aided Routing Algorithm (EC-PPRA) [5], QoS Enabled Power Aware Routing (QEPAR) [6] and Energy- Efficient Ad Hoc on -Demand Routing (EEAODR) [4] are state of the art. A threshold value is defined in the content of CMMBCR, which is between 1 and 500. If minimum battery capacity among nodes in a route is more than the threshold, then CMMBCR [2] elects the route with minimum total transmission power; otherwise it the route possessing maximum value for minimum battery capacity of nodes. LBPC [9] utilizes location information of first hop neighbours of a node to adjust transmission range of the sender. EC-PPRA [5] uses the Pheromone mechanism to make routing decision while turning off the network interface of not-ready nodes. In S^2E^2R [15], when a node receives a route request packet, it calculates the routing level back off time as being inversely proportional to the received power of the route request packet. An efficient cost function is proposed in [3], which prevents message traffics from being sent through the nodes with low energy and more buffered packets.

The protocol EEAODR [4] tries to balance energy load among nodes so that a minimum power level is maintained and network longevity is increased. The protocol QEPAR [6] provides QoS in terms of power and bandwidth. It increases the network throughput by finding out the optimal path from source to destination. It is based on a table driven approach in which each node maintains a Neighbouring Node Table (NNT) containing the information about the nodes falling in its vicinity. Each node in the network broadcasts a Beacon request message to retrieve the information regarding available bandwidth and battery power of those nodes. Among the various paths through which the route - request arrive at the destination, any one with the highest path weight is elected as optimal and chosen for communication between the pair of source and destination nodes. Message packets are not forwarded to the nodes that fall short of bandwidth and battery power. However, none of these protocols focus on the stability of a node w.r.t its downlink neighbours (shortly termed as neighbours) in terms of relative velocity, proximity and radio-range, size of message queue and its portion filled with message forwarding requests etc. parameters collectively. These parameter are extremely important from the point of view of energy efficiency in ad hoc network.

Our proposed protocol FE^2RP determines whether a node in a communication route is ready or not, based on its remaining energy, number of uplink neighbours, pending forwarding load, average affinity as well as proximity with downlink neighbours, and geographical position of the node in terms of latitude and longitude. In order to determine status of a node, a fuzzy controller named Status-Decider (SD) is embedded in each node. Generally in today's dense ad hoc network, route-request packets arrive at the destination node from source through multiple paths. One of the routes containing least number of ready nodes is elected for communication.

2. DETAILS OF FE^2RP AND RULE BASE

2.1 Goal

The goal of FE^2RP is to compute the overall energy efficiency of various routes through which the route-request packets transmitted by the source reaches the destination and then select the best route among all these options. In subsection B we have identified the various factors that affect the energy efficiency of a route in ad hoc networks. These factors are based on heuristics routing characteristics in ad hoc networks. In FE^2RP, the observations are expressed in the form of if-then rules which are the basic unit of fuzzy function approximation. Advantages of fuzzy logic are that it is flexible, conceptually easy to understand and based on natural language. Moreover, it is tolerant of imprecise data and can model non-linear functions of arbitrary complexity. All these are very relevant from the point of view of dynamic characteristic of ad hoc networks.

2.2 Overview of Status Decider

Design of a status decider is based on the following heuristics:
(i) Lesser is the remaining energy of a node, lesser will be its ability to take part in communication sessions in near future.

(ii) If a node has a heavily loaded message queue, then its rate of energy depletion will be high in near future driving it towards a sooner exhaustion.

(iii) If the number of uplink neighbours of a node is high, then the chances of arrival of new message forwarding request, is also high.

(iv) If the downlink neighbours of n_i are close to n_i, then the energy required to transmit/forward packets to those downlink neighbours will be much less compared to what would have been required if downlink neighbours of n_i stay far from n_i.

(v) If a node n_j has been continuously residing within radio-range of another node n_i for a long time, then it is expected that n_j will stay within radio-range of n_i in near future.

(vi) It is always better to include the nodes with low relative velocity w.r.t its downlink neighbours, in communication routes, because that will reduce the chance of link breakage. Hence the cost of repairing broken links is also saved.

(vii) If a node is closer to center of the network than its periphery, then chances are high that a lot of traffic will pass through that node, increasing its energy consumption. It is better to exchange these nodes in communication routes.

2.3 Input Parameters of SD

(i) **Remaining Energy Index** - The remaining energy index $e_i^{'}(t)$ of node n_i at time t is given by,

$$e_i^{'}(t) = 1 - \frac{e_i(t)}{E_i} \tag{1}$$

where $e_i(t)$ and E_i denote the consumed energy of n_i till time t and full battery capacity of n_i. Please note from (1) that, $0 \leq e_i^{'}(t) \leq 1$. Values of $e_i^{'}(t)$ close to unity indicate that n_i is well-equipped in battery charge and ready to take part in communication. Equation (1) is applicable even with remaining energy model as long as the distance related battery capacity can be isolated empirically.

(ii) **Pending Forwarding Load** - Let total size of message queue of node n_i be denoted as M_i and number of pending requests at time t be $m_i(t)$. Then pending forwarding load $L_i(t)$ of n_i at time t is given by,

$$L_i(t) = \sqrt{(\frac{m_i(t)}{M_i})(\frac{A_i(t)}{M_i})} \tag{2}$$

$A_i(t)$ is the average size of message queue of n_i till time t. It reflects the rate of call arrival at node n_i. Since $0 \leq m_i(t) \leq M_i$,$L_i(t)$ lies between 0 and 1. Please note that $L_i(t)$ increases as M_i becomes close to MaxQ. Lesser is the pending forwarding load of a node, lesser will be its rate of energy depletion in near future. Equation (2) is applicable through pending forwarding load for their maximum and minimum lengths to its rate of energy consumption.

(iii) **Uplink Neighbours Load** - If R_{max} is the highest possible radio-range in the network, then all uplink neighbours of a node are at most R_{max} distance away from it. Let the total area of the network be AR and its number of nodes is N. Then density φ of the network is,

$$\varphi = \frac{N}{AR} \tag{3}$$

Equation (3) is related by uplink neighbouring load to their highest radio-range. As per uniform node distribution, the expected number of uplink neighbours of any node is $\varphi \Pi R_{max}^2$. If the actual set of uplink neighbours of node n_i at time t be denoted as $U_i(t)$, then its uplink neighbour load $Ul_i(t)$ at time t be formulated as,

$$Ul_i(t) = \begin{cases} \frac{|U_i(t)|}{\varphi \Pi R_{max}^2} & if \frac{|U_i(t)|}{\varphi \Pi R_{max}^2} < 1 \\ 1 & \text{otherwise} \end{cases} \tag{4}$$

As per the above formulation, $Ul_i(t)$ lies between 0 and 1. Lesser is the value of $Ul_i(t)$, lesser will be its expected rate of arrival of packet forwarding requests. Equation (4) is associated by means of rate of arrival of packet sending requests at time t.

(iv) **Average Downlink Neighbour Affinity** - Let us, assume that a link from n_i to one of its downlink neighbours n_j, is part of an established communication path. If the link breaks in between a communication session, then n_i tries to find an alternative path to n_j or any successor of it, till the destination node. For this, n_i broadcasts a rout-request specifying n_j and its successors, as destination. This alternative path will definitely go through some downlink neighbour n_k of n_i, where $n_k \neq n_j$. If the strength of the wireless bond between n_i and n_k is not good, then n_i will again have to find an alternative path. Discovering an alternative path will require n_i to broadcast route-request again. This will increase the cost of communication thereby reducing the network throughput. So, it is always better to include those nodes in a communication path that maintains strong wireless bond with most of its downlink neighbours.

In order to formulate average downlink neighbour affinity, we need the following definitions.
(Minimum Communication Delay in a Multi-Hop Path):
Definition 1: Since the minimum length of a multi-hop path in an ad hoc network is 2, minimum delay Γ_{min} for multi-hop communication is given by,

$$\Gamma_{min} = \frac{2R_{min}}{\sigma} \tag{5}$$

where σ is velocity of the wireless signal and R_{min} is minimum acceptable radio-range in the network. Equation (5) is connected through the minimum communication delay with their radio range in a multi-hop path.

Definition 2: Maximum Communication Delay in a Multi-Hop Path $\Longrightarrow$ Assuming H to be the maximum allowable hop count in the network, maximum number of routes in a communication path is (H - 1). If τ denotes the upper limit of waiting time of a packet in message queue of any node, then maximum delay Γ_{max} for multi-hop communication is given by,

$$\Gamma_{max} = \frac{HR_{max}}{3 + (H-1)\tau} \tag{6}$$

Equation (6) is applicable with the maximum communication delay with their radio range in a multi-hop path. In the most case of delay or maximum delay situation, a packet has to traverse the maximum available number of hops i.e. H with length of each hop being equal to the maximum possible radio-range i.e. R_{max}. Hence the total distance traversed by the wireless signal in its worst case journey from source to destination is HR_{max}. The signal velocity is σ i.e. a packet can traverse σ unit distance in unit time. Hence, the time required to travel the distance HR_{max}, is (HR_{max}/σ). This is the upper limit of travelling time for a packet. Also the waiting time in routers is involved in this case. Maximum age of a packet in message queue of a router is assumed to be τ and (H - 1) is the highest possible number of routers in a path. So, the upper limit of waiting time of a message throughout its journey from source to destination is (H - 1)τ. The maximum delay Γ_{max} for multi-hop communication is actually the sum total of the upper limits of the above-mentioned travelling time and waiting time for a packet.

The downlink neighbours affinity $\beta_{ij}(t)$ between the nodes n_j and its predecessor n_i at time t is defined in equation (7), where n_j has been continuously residing within neighbourhood of n_i from time-stamp (t - $\bar{w}_{ij}(t)$) to current time t.

$$\beta_{ij}(t) = \begin{cases} 0 & if\ \bar{w}_{ij}(t) \leq \Gamma_{min} \\ 1 & if\ \bar{w}_{ij}(t) \geq \Gamma_{max} \\ T & \end{cases} \tag{7}$$

where T = $[f1_{ij}(t)\ f2_{ij}(t)\ f3_{ij}(t)]^{\frac{R_{max}-R_{min}+1}{3(R_i-R_{min}+1)}}$

$$f1_{ij}(t) = \frac{\bar{w}_{ij}(t) - \Gamma_{min}}{\Gamma_{max} - \Gamma_{min}} \tag{8}$$

$$f2_{ij}(t) = 1 - \frac{1}{\mid v_i(t) - v_j(t) \mid + 1} \tag{9}$$

$$f3_{ij}(t) = 1 - \frac{d_{ij}(t)}{R_i} \tag{10}$$

$v_i(t)$ specifies velocity of node n_i at time t. An other symbols carry their usual meaning. The situation $\bar{w}_{ij}(t) \leq \Gamma_{min}$ indicates that either n_j is completely new as a downlink neighbour of n_i or n_j did not steadily reside within radio-range of n_i even for a time interval as small as Γ_{min}. Hence the affinity is negligible, denoted as 0. On the other hand, if $\bar{w}_{ij}(t) \geq \Gamma_{max}$, then it indicates that n_j has been continuously residing within radio-range of n_j for a long time duration, more than that may be required at the most, for a message to traverse from any source to any destination in the network. Hence the affinity between the corresponding nodes is very strong, indicated as 1.

Otherwise the ratio $(\frac{\bar{w}_{ij}(t)-\Gamma_{min}}{\Gamma_{max}-\Gamma_{min}})$ is used to predict future of the neighbourhood relation between n_i and n_j, based on their history of intersection so far. If $\bar{w}_{ij}(t)$ is close to Γ_{min}, then $f'_{ij}(t)$ takes a small fractional value. Similarly, if $\bar{w}_{ij}(t)$ approaches Γ_{max}, then value of $f'_{ij}(t)$ proceeds towards 1.

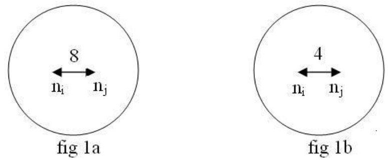

Fig. 1. Communication between two links with affinity

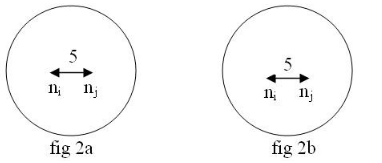

Fig. 2. Communication between two links with affinity

Magnitude of the relative velocity of n_i w.r.t n_j at time t, is given by, $\mid v_i(t) - v_j(t) \mid$. Its effect on $\beta_{ij}(t)$ is modelled as, $\{1 - \dfrac{1}{\mid v_i(t) - v_j(t) \mid +1}\}$, which always takes a positive fractional value even when $v_i(t) = v_j(t)$. As the magnitude of the relative velocity between n_i and n_j decreases, affinity between the two nodes increase. As far as $f3_{ij}(t)$ is concerned, $d_{ij}(t)$ denotes the distance between n_i and n_j at time t. Since $d_{ij}(t) \leq$R$_i$, $(1 - \frac{d_{ij}(t)}{R_i})$ ranges between 0 and 1. As $d_{ij}(t)$ decreases, survivability of the link between n_i and n_j increases. The situation can be illustrated through fig1.

Let R_i = 12 and the current time is t; $d_{ij}(t)$ = 8 units in fig 1a and $d_{ij}(t)$ = 4 units in fig 1b. Also assume that $\mid v_i(t) - v_j(t) \mid$=2 in both scenarios in figures 1a and 1b. If the velocities of n_i and n_j do not change, then the link from n_i to n_j will survive for (12 - 8)/2 = 2 units time corresponding to the situation in fig 1a and (12 - 4)/2 = 4 units time in for the scenario in fig 1b. Hence, high proximity increases stability of the link from n_i to n_j.

Please note from equation (7) that the ratio $(\frac{R_{max}-R_{min}+1}{R_i-R_{min}+1})$ is exponentiated over $f1_{ij}(t)\ f2_{ij}(t)\ f3_{ij}(t)$. 1 is added in both numerator and denominator to avoid indeterminacy situation when R_{max} = R_{min} = R_i. As R_i approaches R_{max}, the ratio $(\frac{R_{max}-R_{min}+1}{R_i-R_{min}+1})$ becomes close to 1. For other values of R_i (definitely $R_{min} \leq$R$_i$ $\leq$R$_{max}$), value of that ratio is greater than 1. Hence, increase in radio-range of a node increases its affinity with its downlink neighbours. This is quite practical since increase in radio-range of a node increases its capacity of embracing its downlink neighbours. The situation can be depicted in figures 2a and 2b.

In fig 2a, R_i = 14 units and in fig 2b R_i = 7 units. In both cases distance i.e. between n_i and n_j at current time t is 5 units. Assume that, $\mid v_i(t) - v_j(t) \mid$= 3 units in fig 2a and $\mid v_i(t) - v_j(t) \mid$= 2 units in fig 2b. If the relative velocity of n_i w.r.t n_j does not change, then the link between n_i and n_j will survive for (14 - 5)/3 = 3 time unit in the situation in fig 2a and (7 - 5)/2 = 1 time unit corresponding to the situation in fig 2b.

Hence, if radio-range of a node is large, it can embrace a downlink neighbour for some time in spite of high relative velocity.

Table 1. Range division of parameters

Crisp Range Division of $e^{'}$	N	Fuzzy Variables
0 - 0.40	0 - 0.25	a1
0.40 - 0.60	0.25 - 0.50	a2
0.60 - 0.80	0.50 - 0.75	a3
0.80 - 1.00	0.75 - 1.00	a4

Table 2. Fuzzy Composition of $e^{'}$ and $\beta^{'}$ Producing temp1

$e^{'}\rightarrow$,$\beta\downarrow$	a1	a2	a3	a4
a1	a1	a1	a1	a1
a2	a1	a2	a2	a2
a3	a1	a2	a3	a3
a4	a1	a2	a3	a4

If the set of downlink neighbours of node n_i at time t be denoted as $N_i(t)$, then its average downlink neighbour affinity $\beta_i^{'}(t)$ is given by,

$$\beta_i^{'}(t) = \frac{1}{|N_i(t)|} \sum_{n_j \in N_i(t)} \beta_{ij}(t) \qquad (11)$$

(v) Network Heart Quotient - Let (x_c_r, y_c_r) be co-ordinate of center of the smallest circle circumscribing the network and R^2 be its radius. Also assume that-geographical position of node n_i at time t is $(x_i(t), y_i(t))$. Then, network heart quotient $N\_H_i(t)$ of n_i at time t is given by,

$$N\_H_i(t) = \frac{\sqrt{(x\_c_r - x_i(t))^2 + (y\_c_r - y_i(t))^2}}{R^2} \qquad (12)$$

It is evident from equation (12) that 0 $\leq$N$_H_i(t) \leq 1$. Values close to 1 indicate that n_i is very close to periphery of the network at time t and hence the message forwarding load in n_i at time t is much smaller than it would have been if its distance to center of the network would have been much smaller compared to R^2.

2.4 Rule Bases of SD

Table I shows crisp range division of SD along with its corresponding fuzzy variables. Subscripts is omitted for simplicity of presentation and t is assumed to be the current time.

[In table N = Crisp range division of L, Ul, $\beta^{'}$, N_H, ready-index]

According to the study of power discharge curve of batteries heavily used in ad hoc networks, at least 40% (represented as fuzzy variable a1) of total battery power is required to remain in operable condition; 40% - 60% (represented by fuzzy variable a2) is satisfactory, 60% - 80% (denoted as a3) is good while the next higher range (80% - 100%, denoted by fuzzy variable a4) is considered more than sufficient. Ranges of all other parameters of SD are uniformly divided i.e. 0% - 25% denoted as a1, 25% - 50% given by a2, 50% - 75% represented by a3 and 75% - 100% as a4 ready-index(t) indicates how much ready n_i is at time t. It is output i of SD and follows uniform range distribution between 0 and 1. Table II combines the parameters $e^{'}$ and $\beta^{'}$ producing temporary variable temp1. Since both of them are equally important from the perspective of survival of a link, both $e^{'}$ and $\beta^{'}$ are assigned equal weight in table II.

Fuzzy composition of temp1 and Ul producing temp2 is stored in table III. Table IV combines temp2 and L generating another intermediate output temp3. Ready-index of a node is obtained from table V where temp3 is combined with N-H. From table III to table V, one input comes from earlier rule base where as the other input is a new parameter. In all these tables, the output of previous rule base dominates, because the output of previous rule

Table 3. Fuzzy Composition of temp1 and Ul Producing temp2

temp1$\rightarrow, Ul\downarrow$	a1	a2	a3	a4
a1	a1	a2	a3	a4
a2	a1	a2	a3	a3
a3	a1	a1	a2	a3
a4	a1	a1	a2	a3

Table 4. Fuzzy Composition of temp2 and L Producing temp3

temp2$\rightarrow, L\downarrow$	a1	a2	a3	a4
a1	a1	a2	a3	a4
a2	a1	a2	a3	a4
a3	a1	a2	a2	a3
a4	a1	a1	a2	a3

Table 5. Fuzzy Composition of temp3 and N-H Producing ready-index

temp3$\rightarrow, N - H\downarrow$	a1	a2	a3	a4
a1	a1	a2	a3	a4
a2	a1	a2	a3	a4
a3	a1	a2	a3	a4
a4	a1	a2	a2	a3

base always contains a fuzzy combination of parameters $e^{'}$ and $\beta^{'}$, both of which are more important than any other parameters of SD.

3. DESCRIPTION OF THE PROTOCOL FE^2RP

Each node maintains two caches - (i) cache C_1 of the best routes to the recently communicated destinations and (ii) cache C_2 of recently arrived route-request messages. Also the status decider fuzzy controller (SD) is embedded in each node. Whenever a source node n_s needs to communicate with some destination n_d, n_s first checks its cache C_1 to find out whether any valid route already exists for n_d in the cache. Validity of a route is determined by its age in the cache C_1. There exists an upper limit on the age of routes in C_1. If age of a route in C_1 is greater than the pre-defined upper limit, then the route is termed invalid, otherwise it is valid. If no valid route exists for n_d in C_1 of n_s, then n_s broadcasts a route-request (RREQ) to its neighbours. When an intermediate node (destination on router) receives the RREQ, it ensures that the received RREQ is not a duplicate, in order to prevent looping in paths. If newly arrived RREQ is not present in C_2 of the intermediate node, then it is evident that the RREQ is not duplicate. Now before forwarding the RREQ, the intermediate node computes its own ready-index using its SD. If the remaining energy index is possible for the intermediate node is positive then it takes part in a communication session. Ready-index of the router is appended to the RREQ along with its id and geographical position. After that the router checks its C_1 for finding out if it has a valid route for n_d. In case of availability of such a path, the router forwards the RREQ along that path. Otherwise, it broadcasts the RREQ to all of its neighbours. When the destination gets the first RREQ, it waits for a pre-defined time period for arrival of the same RREQ through other paths. After the wait period is over, the destination computes efficiency of each path as follows:

$$eff(R) = \frac{M}{N} \times (1 - \frac{N}{H}) \times \frac{L}{N} \qquad (13)$$

where M = $\sum_Q$pivot-ready-index(n_i) and Q = $n_i \in R$,$n_i \neq n_s$ and $n_i \neq n_d$
N = number of nodes (R)
L = non-ready-count(R)
Here number of nodes(R) indicates the total number of nodes in R and H is the maximum allowable hop count in the network. If ready-index of n_i is a2, then pivot-ready-index (n_i) is the average of lower limit and upper limit corresponding to the fuzzy variable a2 in table I. So, pivot-ready-index (n_i) is (0.25 + 0.5/2) i.e. 0.375. Similarly if ready-index of n_i is a4, then pivot-ready-index (n_i) is 0.875. A node is termed as ready provided its ready-index is either a1 or a2; otherwise it is not-ready. Non-ready-count(R) is the number of not-ready routes in R. The formulation in equation (13) is based on the concept that efficiency of a route increases with increase in average pivot-ready-index of a node, number of not-ready nodes and decrease in number of nodes.

One of the routes with maximum efficiency is elected for communication and it is sent to the source with route-reply (RREP) message. A node receives the RREQ packet for the first time and it sets up a reverse path to the source. The algorithm of FE^2RP is presented below with due explanation.

Assumption: source n_s wants to initiate communication with destination n_d at time t.

STEPS OF SOURCE
if $n_d \in N_s(t)$ then
send-msg-direct (s, d, t, m);
/* in this situation destination n_d is a direct downlink neighbour of source n_s. The function send-msg-direct sends the message in directly in one hop from source n_s to destination n_d at time t */
else
begin
j = search (s,C_1,d);

/* The above function search (s,C_1,d) tries to find out a valid route for n_d in C_1 of n_s at time t. The function returns -1 if no such route is found or age of the route is greater than the predefined upper limit of age of any route in cache C_1 of any node. Otherwise the search function returns the identification number of the node next to n_s in the valid route found in C_1 of n_s */

if j $\neq$ -1 then
send-msg (s, d, t, m, j);
/* in send-msg function, n_s sends the message to n_d at time t where n_j is the node next to n_s in the valid route found in C_1 of n_s */
else
broadcast-RREQ (s, d, t);
/* In the broadcast-RREQ function, source n_s broadcast EEEQ to all of its downlink neighbours at time t for discovering a route to destination n_d */
end

STEPS OF A ROUTER n_j

k = chk-duplicate (s, d, t, C_2, j);

/* In the chk-duplicate function n_j checks whether the RREQ transmitted by n_s for discovering a route to n_d at time t, already exists in C_2 of n_j or not; if exists, then 1 is returned , otherwise 0 is returned */
if k = 0 then
/* RREQ is not a duplicate */
begin
p1 = remaining-energy-index(j);
if p1 $\neq$ a1 then
begin
/* n_j is not exhausted; so it can take part in communication */
p2 = ready-index(j);
/* using SD of n_j, n_j determines its own ready-index using its SD and stores it in the variable p2 */
l = search (j, C_1, d);
if l $\neq$ -1 then
/* a valid route for n_d exists in C_1 of n_j */
send-RREQ (s, d, t, l, p2, x_j, y_j);
/* In the above send-RREQ function the RREQ generated by n_s for n_d at time t, is forwarded to n_l. The ready index p2 of n_j is appended to the RREQ along with x_j and y_j. x_j and y_j are current latitude and longitude of n_j, respectively */
else
broadcast-RREQ-router (s, d, t, j, p2, x_j, y_j);
/* In the above mentioned broadcast-RREQ-router function, n_j broadcasts the RREQ generated by n_s for n_d at time t, to all of its downlink neighbours. Before forwarding, n_j appends its ready index i.e p2 with the RREQ along with x_j and y_j which are its current latitude and longitude, respectively. */
end
end

STEPS OF DESTINATION
Receive the first broadcast-RREQ-router initiated at time t by node n_s.
R = extract-route (broadcast-RREQ-router);
/* The function extract-route extracts routes from RREQ */
eff (R)= compute-efficiency (R);
/* efficiency of R is computed as per equation (13) by compute-efficiency function */
maxeff = eff (R)
/* efficiency of the first route is so far maximum */
maxrt = R
/* maxrt is the route with maximum efficiency so far and its efficiency is maxeff */
set a timer with value TH
/* TH is the time duration for which n_d waits to receive the same RREQ through different paths */
repeat
receive next broadcast-RREQ-router;
R' = extract-route (broadcast-RREQ-router);
eff(R') = compute-efficiency(R');
if eff(R')> maxeff then
begin
maxeff = eff(R')
/* maxeff is the maximum efficiency so far among all the routes through which RREQ of n_s generated at time t for n_d, has arrived at n_d */
maxrt = R'
/* maxrt is the route having maximum efficiency so far */
end
until the timer expires
send-RREQ (d, s, t, R');

/* The above route-reply corresponds to the RREQ generated by n_s for node n_d at time t. The RREQ is sent from n_d to n_s and it recommends to n_s the path R' for communication */

4. COMPLEXITY OF FE^2RP

4.1 Space Complexity

The space complexity of FE^2RP is mainly due to the fuzzy rule base tables of SD and the two caches C_1 and C_2. As far as the labels of SD are concerned, the required space is computed as

Table 6. SIMULATION ENVIRONMENT

Items	Values
Number of nodes	40, 80, 200, 500, 1000, 2000
Total no of simulation time	30
Radio-Range	A''
Network area	B''
Node Speed	C''
Mobility Pattern 1	Random Waypoint, Random walk
Mobility Pattern 2	Gaussian
Simulation time in each run	500 seconds
MAC Protocol	IEEE 802.11G

follows: (i) For table I, 4 rows and 3 columns, i.e. 12 spaces. (ii) For each of the tables II, III, IV and V, there are 4 rows and 4 columns since the tables are stored in 4 x 4 matrix form. Hence the required space is 16 for each table and 64 for all of the tables II, III, IV and V.
So, the storage space required for SD is (12 + 64)= 76. Assuming that a maximum of M' entries can be stored in C_1 of any node and a maximum of P' entries can be stored in C_2 of any node, the space complexity for C_1 is M' and the same due to C_2 is P'. So, the overall space complexity of FE^2RP is O(M' + P').

4.2 Time Complexity

Time complexity of FE^2RP is mainly due to access to tables of SD and searching in C_1 and C_2. In order to determine the fuzzy variable corresponding to the crisp range division of parameters, exactly 1 table access is required in table I for each parameter. Total 6 parameters are there (5 input and 7 output parameters)in SD. Hence, total 6 table access are required for determination of fuzzy variable corresponding to the crisp range division of all parameters of SD. Then ready-index of all routers need to be computed as per the logic of FE^2RP. This requires exactly 4 table accesses per router, corresponding to each fuzzy rule base table. So, total (6 + 4)=10 table accesses are mandatory for determination of ready-index of each router. The highest number of routers that can be present in a communication path, is H-1. So, the time complexity of FE^2RP is 10(H-1) i.e. O(H). Please note that FE^2RP applies binary search technique in both C_1 and C_2. So, the search complexities are O($\log_2 M'$) and O($\log_2 P'$) in caches C_1 and C_2, respectively. Hence, the overall time complexity of FE^2RP is O(H + $\log_2 M'$ + $\log_2 P'$).

5. SIMULATION

5.1 Setup and Metrices

The simulation is carried out on an 800 MHZ Pentium IV processor 40 GB hard disk and Red Hat Linux version 6.2 Operating System. The simulator used is ns-2 which is a well known packet level simulator. Details about the simulation environment appears in table VI.
[In table VI, A'' = 10-30 m in 1st 10 runs, 5-45 m in next 10 runs and 40-100 m in last 10 runs; B'' = 1000 $\times$1000m^2 in first 10 runs, 2000 $\times$500m^2 in next 10 runs and 1000 $\times$4000m^2 in last 10 runs and C'' = 0-35 m/s in first 10 runs, 10-100 m/s in next 10 runs and 0-75 m/s in last 10 runs]
The simulation metrics are as follows:
(i) Message cost (total number of messages transmitted)
(ii) Energy consumption (cumulative consumed energy of all nodes)
(iii) percentage of packet delivery ratio (total number of data packets properly delivered to their respective destination to total number of data packets transmitted $\times$ 100)
(iv) Minimum remaining energy index $\times$ 100 (the minimum of remaining energy index of all nodes in the network $\times$ 100)
(v) Average remaining energy index $\times$ 100 (the average of remaining energy index of all nodes in the network $\times$ 100)
(vi) Average end-to-end delay (total required time for completion of a communication session divided by total number of communication sessions)
Our proposed protocol FE^2RP is compared with CMMBCR, LBPC, QEPAR, EEAODR and S^2E^2R. The results are presented in figures 3 through 8.

5.2 Results and Discussion

The results are averaged over 30 sets of simulation runs and plotted at 95% confidence interval. Results emphatically support the performance enhancement produced by FE^2RP compared to its above-mentioned state-of-the-art competitors. Unlike these competitor protocols, FE^2RP considers affinity of routers in a path, with respect to their corresponding downlink neighbours. The affinity is a rigorous measure of stability of links in the route. stable links break less frequently compared to the unstable ones. In order to repair a broken link from n_i to n_j, n_i has to broadcast new route-request packets in the network to discover a suitable alternative of the broken part of the route. The alternative route may break again leading to more link breakages and injection of more route-request packets in the network. The increase in message cost increases energy consumption in nodes and end-to-end delay. Since the phenomenon of link breakage occurs much less in FE^2RP, is less vulnerable in comparison to other protocols in terms of link breakage.

So FE^2RP also considers residual energy, pending communication load, number of uplink neighbours and position of a node w.r.t center of the network. All these rigorously inculcate the flavour of power awareness. Actually, FE^2RP encourages inclusion of those nodes in a communication path that have high remaining lifetime, low pending forwarding load, low relative velocity w.r.t downlink neighbours, high proximity with them along with continuity in neighbourhood relation for a considerably long time. This leads to a great reduction in message cost as well as energy consumption, as evident from figures 3 and 4.
Due to the power awareness of FE^2RP, the nodes having small remaining lifetime or whose message queues are already crowded, are not preferred by FE^2RP for establishing a new communication session through them. In this way, a balanced communication load in maintained in the network. This also helps to preserve network connectivity by avoiding partitions. Hence the minimum and average remaining node energy produced by our proposed protocol, is much higher than the same produced by its competitors. This is illustrated in figures 5 and 6.
Since message cost in FE^2RP is much lesser than others, packets in FE^2RP take lesser signal contention and collision, increasing the packet delivery ratio and decreasing end-to-end delay, as shown in figures 7 and 8. Also it may be noted from figure 7 that, as the number of nodes increases, initially the packet delivery ratio also increases. The reason is better connectivity between nodes due to sufficient number of downlink neighbours. But as the node density reaches saturation point, the packet delivery ratio starts decreasing for all the protocols.

6. CONCLUSION

FE^2RP is a fuzzy controlled power aware routing protocol that focuses on rigorous analysis of the components of power efficiency of a protocol in mobile ad hoc networks. Using the fuzzy controller named Status Decider (SD) in each node, each node pro-actively finds out whether it is too ready to take part in a new communication session or not FE^2RP encourages inclusion of not-ready nodes in a communication route and also prefers the

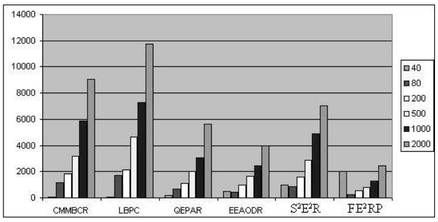

Fig. 3. Message cost vs number of nodes

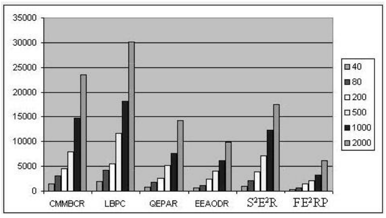

Fig. 4. Energy Consumption vs number of nodes

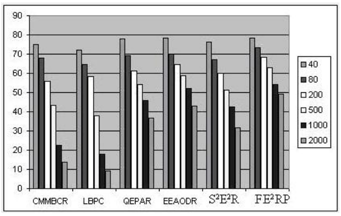

Fig. 5. Minimum remaining energy index x 100 vs number of nodes

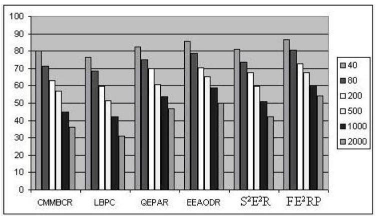

Fig. 6. Average remaining energy index x 100 vs number of nodes

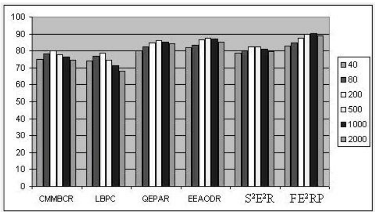

Fig. 7. Percentage of packet delivery ratio vs number of nodes

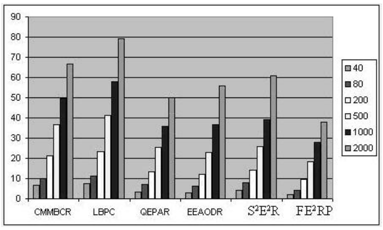

Fig. 8. Average end-to-end delay in milliseconds vs number of nodes

routes involving small number of nodes. This reduces the overall cost of messages and energy consumption maintaining a suitable balance of packet forwarding load in the network.

7. REFERENCES

[1] Anuradha Banerjee and Paramartha Dutta. Fuzzy-controlled power-aware routing protocol (fprp) for mobile ad hoc networks. In *International Journal of Computer Applications (0975 8887)*, volume 11, December 2010.

[2] C.K.Toh. Maximum battery life routing to support ubiquitous mobile computing in wireless ad hoc networks. In *IEEE Communications Magazine*, June 2001.

[3] M. Bandai et. al. Signal strength based energy efficient routing for ad hoc networks. In *IEICE Transactions on Communications*, volume E 91.B, pages 1006–1014, June 2010.

[4] Mehdi Lotfi et. al. A new energy efficient routing algorithm based on a new cost function in wireless ad hoc networks. *Journal of Computing*, 2, June 2010.

[5] P.K. Suri et. al. Qos enable power-aware routing protocol for manets. *International Journal of Engineering, Science and Technology*, 2:4880–4885, 2010.

[6] S.K. Dhurandher et. al. Eeaodr: An energy-efficient ad hoc on-demand routing protocol for mobile ad hoc networks. *International Journal of Communication Systems*, 22(7), July 2009.

[7] Z. J. Haas and M. R. Pearlman. The performance of query control schemes for the zone routing protocol. In *In Proceedings of SIGCOMM*, volume I, page 167177, Jan 1998.

[8] Luo Junhai, Xue Liu, and Ye Danxia. Research on multicast routing protocols for mobile ad-hoc networks. In *Elsevier,*, 2007.

[9] Kaabneh, Halasa K., and H A., Al-Bahadili. An effective location-based power conservation scheme for mobile ad hoc networks. *American Journal of applied Sciences*, B:1708–1713, 2008.

[10] J. Widmer M. Mauve. A survey on position-based routing in mobile ad hoc networks. In *IEEE Network Magazine*, volume 15, pages 30–39, Nov 2001.

[11] N. Meghanathan. Energy consumption analysis of the stable path and minimum hop path routing strategies for mobile ad hoc networks. In *International Journal of Computer Science and Network Security*, volume 7, pages 30–39, October 2007.

[12] A. Misra and S. Banerjee. Mrpc: Maximizing network lifetime for reliable routing in wireless environments. In *Proceedings of WCNC*, 2002.

[13] N. Nikaein and C. Bonnet. Alm adaptive location management model incorporating fuzzy logic for mobile ad hoc networks. In *in Proceeding of Med Hoc Net, Italy*, pages 1489–1499, 2002.

[14] K.Srinivasa Rao, R.Sudhistna Kumar, P. Venkatesh, R.V.Sivaram Naidu, and A.Ramesh. Development of energy efficient and reliable congestion control protocol for multicasting in mobile adhoc networks compare with aodv based on receivers. In *International Journal of Engineering Research and Applications (IJERA*, volume 2, pages 631–634, Mar-Apr 2012.

[15] Yuanchuang Hu Rongsheng Dong and Jianming Liu. Ecppra: An energy efficient routing protocol for ad hoc networks. *JOURNAL OF NETWORKS*, 5:748–755, June 2010.

[16] C. Raghavendra. PAMAS S. Singh. Power aware multi-access protocol with signalling for ad hoc networks. In *SIGCOMM Computer Communication Review*, volume 7, pages 5–26, Dec 1998.

[17] J. Wu and H. L. Li. On calculating connected dominating set for efficient routing in ad hoc wireless networks. In *Proc. 3rd Intl. Wksp. Discrete Algorithms and Methods for Mobile Comp. and Commun.*, page 714, 1999.

[18] G. Pei X. Hong, M. Gerla and C.-C. Chiang. A group mobility model for ad hoc wireless networks. In *In Proceedings of the ACM/IEEE MSWIM*, volume I, page 10, August 1999.

[19] D. Estrin Y. Xu, J. Heidemann. Geography-informed energy conservation for ad hoc routing. In *MobiCom2001*, volume 8, pages 12–18, July 2001.

[20] J. Y. Yu and P. H. J. Chong. 3hbac (3-hop between adjacent clusterheads): a novel non-overlapping clustering algorithm for mobile ad hoc networks. In *Proc. IEEE Pacrim03*, volume 1, page 31821, August 2003.