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Fuzzy-controlled Load-balanced Broadcasting (FLB) In Clustered Mobile Ad Hoc Networks

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Abstract

Problem statement: In mobile ad hoc networks owing to node mobility, broadcasting is expected to be more frequently used to find route to a particular destination, to page a host and to alarm all hosts. The simplest and commonly used mechanism for broadcasting is flooding, where every node retransmits every uniquely received message exactly once. Despite its simplicity, it can result in highly redundant retransmission, contention and collision in the network, a phenomenon referred to as broadcast storm problem. Several approaches have been proposed to mitigate this problem inherent with flooding. However, none of those schemes guarantees minimum redundancy with 100% delivery ratio. **Present Approach:** The present study proposes a fuzzy-controlled load-balanced broadcast scheme (FLB) in a multi-hop clustered ad hoc network that guarantees complete packet delivery at no redundancy. Each node n_j elects its most eligible uplink neighbor n_i within its cluster and that uplink neighbor n_i has to take the responsibility of transmitting all broadcast messages to n_j. Hence, the redundancy is zero. **Results:** Simulation results show that the proposed broadcast algorithm provides high packet delivery ratio at minimum overhead and minimum delay, w.r.t. other state-of-the-art broadcast algorithms.

Keywords: Ad hoc network, Broadcasting, Fuzzy, Load-balance, Redundancy.

1. Introduction

A mobile ad hoc network is a wireless network that is self-organized with many mobile nodes. No static infrastructure such as a wired backbone is available. All nodes are free to move around and the network topology may change frequently. Due to limited transmission range of wireless network interface, nodes are required to forward messages for those located outside the radio-coverage, thereby forming a multi-hop network. Possible applications include emergency rescue in disaster situations, communication between mobile robots, exchanging information in the battlefield etc. [1-5]. Each node can directly send information in single hop within a pre-specified circle around the node. That circle is called radio-circle and its radius is called radio-range. If a node n_j stays within the radio-circle of another node n_i at time t, then n_j will be called a downlink neighbor of n_i at time t and n_i will be called an uplink neighbor of n_j at that time. In this situation n_i can directly transmit information to n_j without the assistance of any intermediate node as router. Otherwise, the communication between the nodes n_i and n_j is multi-hop.

Broadcast is a common operation in ad hoc networks. By broadcast, a message is propagated to all nodes in the network. The problem of redundancy is highly involved in case of broadcasting. For example, if a node has multiple uplink neighbors, then it will receive the broadcast message from all those uplink neighbors resulting in redundancy.

Broadcast is useful in delivering messages to users with unknown location or group of users whom the source need not exactly know [5]. Broadcast plays an important role in routing, network management etc. Many on-demand or reactive routing protocols (dynamic source routing (DSR) [2], ad hoc on-demand distance vector routing (AODV) [3], on-demand multicast routing protocol (ODMRP) [4] etc.) rely on broadcast to discover a route between two nodes or to update group status and multicast routes. Broadcast is also a viable candidate for multicast in ad hoc networks with rapid changing topology. In the next section I discuss some state-of-the-art broadcast algorithms.

2. Related Work

A density based innovative flooding (DBF) algorithm is proposed in [6]. In this algorithm, each node forwards a message based on its neighbor density and neighbor density of its previous node from which the broadcasted message. In a cluster of loosely couples nodes with few intermediate nodes as neighbors, the probability of forwarding the broadcasted message will be high. On the other hand, if a node is having high density of neighbors, then there will be lots of chances of packet collision at that point. Density based flooding tries to avoid that situation by assigning low priority at that point.

The article in [7] proposes a tree based broadcast (TBB) method that maintains a spanning tree in the network. The algorithm is fully distributed, decentralized and resource-efficient. Broadcast operation is performed using a tree by forwarding the message not to all neighbors, but only those neighbors in the tree structure. Since the tree is acyclic, each message is received only once by each node, giving two advantages over the existing methods. Firstly it is needless to store the previous broadcasts in order to avoid endless multiplications of broadcast messages along a cycle of links. Only the originator of a broadcast message needs to store it and pay attention to whether its broadcast was successful or not if it is of great importance. Secondly, it is very economical considering how many times a broadcast message should be forwarded.

A reliable broadcast (RB) method is proposed in [8], which combines area based and neighbor-based technique of broadcast. Each node gains knowledge of neighbors and maintains neighbor list. The algorithm calculates the relative position of the nodes with respect to broadcast source node. The nodes that are farthest from the source rebroadcasts next. The algorithm tries to minimize the number of rebroadcasts by intermediate nodes and thus reduces message cost.

Reference [9] proposes a method for reduction of broadcast traffic (RBT) in mobile ad hoc networks. It focuses on the fact that communication links in ad hoc networks break frequently due to node mobility. As the nodes move, a node receiving a packet on the boundary of communication range of a transmitter node is allowed to drop the packet, as the receiver may soon move out of the radio range of the transmitter. To approximate the distance between receiver and transmitter, receiver signal strength information is used.

Probabilistic broadcast approaches [10], broadly called gossip, offer a simpler alternative to deterministic approaches. With gossiping, nodes forward packets with a pre-specified probability. The key idea is that when this probability is chosen correctly, the entire network receives the broadcast message with very high probability, even though only a non-deterministic subset of nodes has forwarded the message. Gossiping is a simple solution yet capable of achieving better reliability and load-balancing. However, choosing its correct value is difficult, since it is closely related to network topology information. In absence of topology information, estimating the value of gossip probability is risky. Moreover, the topology of ad hoc networks change from time to time due to link failure and node failure, and therefore a suitably chosen gossip probability may become sub-optimal later. The article in [6], proposes a smart gossip technique which assigns importance to each node in achieving dissemination. The importance of a node increases when other nodes heavily depends on it to disseminate the broadcasted message. The important of a node increases when other nodes heavily depend on it to disseminate a message. The important nodes transmit with a proportionally higher probability. Other nodes that are less crucial for achieving dissemination still transmit for the purpose of reliability but with a lower probability. Initially, when dependencies are not known, gossip probability of each node equals 1. Overtime as nodes learn about their dependencies, the gossip probabilities are refined.

In double covered broadcasting [11], when a sender broadcasts a packet, it selects a subset of 1-hop neighbors as its forward nodes to forward the broadcast based on a greedy approach. The selected forward nodes satisfy two requirements: (1) They cover all the nodes within 2 hops of the sender. (2) The sender’s 1-hop neighbors are either forward nodes or non-forward nodes but covered by at least two neighbors, once by the sender itself and once by one of the selected forward nodes. After receiving the broadcast packet, each forward node records the packet, computes its forward nodes and re-broadcasts the packet as a new sender. The retransmissions of the forward nodes are received by the sender as the acknowledgement of receiving the packet. The non-forward 1-hop neighbors of the sender do not acknowledge receipt of the broadcast. The sender waits for a predefined duration to overhear the rebroadcasting from its forward nodes. If the sender fails to detect all its forward nodes retransmitting during this duration, it assumes that a transmission failure has occurred for this broadcast because of the transmission error or because the missed forward nodes are out of its transmission range. The sender then re-sends the packet until all forward nodes are retransmitted or the maximum number of retries is reached. The proposed algorithm utilizes the method that the sender overhears the retransmission of the forward nodes to avoid the ACK implosion problem. Also, the algorithm guarantees that each node is covered by at least two transmissions so that it can avoid a single error due to the transmission collision. Moreover, the algorithm does not suffer the disadvantage of the receiver-initiated approach that needs a much longer delay to detect a missed packet.

3. Overview of FLB

Our proposed algorithm FLB works in a clustered environment. For clustering purpose, I have used a multi-hop clustering algorithm based on neighborhood benchmarks (MCNB [12]). This article assumes that all network links are bidirectional. The score $s_i(t)$ of a mobile node n_i, at time t, used to indicate qualification of the node to be a cluster-head, is defined as, $s_i(t)= |D_i(t)| / lf_i$ where $D_i(t)$ is the set of downlink neighbors of n_i at time t and lf_i is the number of link failures encountered by n_i in unit time, indicating link stability of its neighborhood. A node is attached to a cluster provided distance of the new node from head of the cluster is less than or equal to the hop count in the network.

Each cluster has a cluster-head and all cluster members (nodes in a cluster other than the cluster-head) are connected to it. The isolated nodes that are not member of any cluster, are treated as heads of single node cluster. In order to remove redundancy, a constraint is imposed that a node cannot be member of more than one cluster. If source of a broadcast operation is not a cluster-head, it sends the broadcast packet to head of its own cluster. All cluster-heads are connected to each other in single or multi-hop paths. When a cluster-head receives a broadcast packet from its upstream cluster-head, it chooses some gateways or forward nodes to forward the packet to all cluster-heads in its coverage set. The coverage set is updated by excluding the cluster-head sender and those cluster-heads in the senders coverage set that are piggybacked with the broadcast packet. The coverage set of this cluster-head together with its selected forward nodes are piggybacked with the broadcast packet for the forwarding purpose. On the other hand, a cluster-head will do nothing if it receives a duplicate packet. Similarly, cluster members also drop duplicate packets.

A cluster member belonging to the cluster C1, elects its most eligible uplink neighbor among all of its uplink neighbors in cluster C1, by means of recommendation of a fuzzy controller named “Broadcast Neighbor Decider (BND)” which is embedded in every node in the ad hoc network. The parameters of n_i considered by BND of node n_j (here n_i is an uplink neighbor of n_j and both n_i and n_j belong to the same cluster) are residual energy, existing communication load, predictive communication load of n_i and strength of the wireless bond between n_i and n_j. The most eligible uplink neighbor of n_j that belongs to the same cluster as n_j, is assigned the responsibility of transmitting broadcast message to n_i. Design of BND is based on the following heuristics:

i) If a node is already running short of battery power, it should not be assigned the additional responsibility of forwarding broadcast packets to any of its downlink neighbors.

ii) If message queue of a node is almost full and its rate of call arrival is high, then its communication load is huge. As a result, unnecessary delays will be introduced during broadcast operation if nodes like this are elected as most eligible uplink neighbor. The situation will worsen if a) the node has a huge number of uplink neighbors and b) it has already been chosen as most eligible uplink neighbor by a large fraction of its downlink neighbors.

iii) Node n_i will be considered extremely important from the perspective of partition avoidance provided the uplink neighbors of n_i find it difficult to disseminate information to the network without n_i and the downlink neighbors fail to receive information from the network through the nodes other than n_i. If the additional responsibility of most eligible uplink neighbor is assigned to such important nodes then their rate of energy depletion will increase resulting to fast exhaustion and network partition, which is not desirable. Hence, the nodes that play important role in maintaining network connectivity are not suitable candidates for being most eligible uplink neighbors of any node. On the other hand, if uplink neighbors of a node n_j has a huge number of downlink neighbors and downlink neighbors of n_j has a huge number of uplink neighbors, then n_j is a good candidate for being most eligible uplink neighbor of some node.

iv) In spite of mobility, the wireless bond between a node n_j and its most eligible uplink neighbor n_i should survive for a significantly long time. Otherwise, n_j will have to frequently elect its most eligible uplink neighbor, increasing complexity of FLB and delay in broadcasting packets.

The observations expressed above are 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 encouraged us to design the scheme of FLB using fuzzy logic.

4. Parameters of BND

1. The residual energy index $\alpha_i(t)$ of n_i at time t is given by,

$$\alpha_i(t) = (1-e_i(t)/E_i) \quad (1)$$

$e_i(t)$ and E_i specify the consumed energy of n_i till time t and maximum battery power of the same node. From the formulation in (1) it is evident that $\alpha_i(t)$ ranges between 0 and 1. The higher is the value of $\alpha_i(t)$ the more well-equipped is the node to take charge of most eligible uplink neighbor of some node.

2. The uplink neighbor affinity $\beta_{ij}(t)$ of the link from n_i to n_j at time t indicates strength of the wireless bond between those two nodes. If n_i has low velocity relative to n_j, then there is high chance that their link will survive for a significantly long time in future. Moreover, the possibility of survival of the link from n_i to n_j increases if n_i has a high radio-range. The situation can be illustrated from figures 1, 2a, 2b, 3a and 3b, based on the assumption that the nodes are moving with uniform velocities.

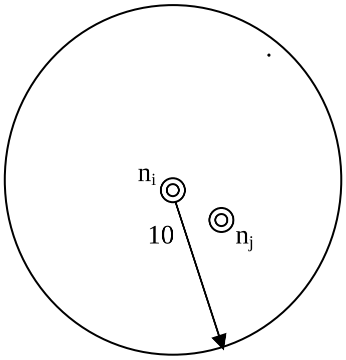

Fig 1

Fig 1: Let the current distance between n_i and n_j be 4 m and radio-range of n_i be 10 m. If the relative velocity of n_i w.r.t. n_j is 2 m/s, then the link between them will survive for (10-4)/2 si.e. 3 s. On the other hand if the velocity of n_i w.r.. n_j be 3 m/s, then the said link will survive for (10-4)/3 s i.e. 2s. Hence low relative velocity of nodes is good for survival of the link between them.

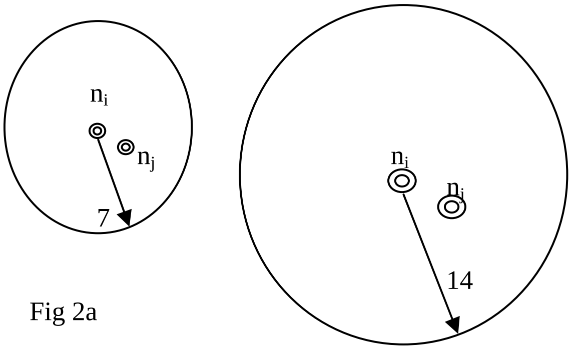

Fig 2a

Fig 2b

Fig 2a and 2b: Let the current distance between n_i and n_j be 5 m and radio-range of n_i be 7 m. If the relative velocity of n_i w.r.t. n_j is 2 m/s, then the link between them will survive for (7-5)/2 s i.e. 1 s. On the other hand if radio-range of n_i is 14 m/s and relative velocity of n_i w.r.t. n_j increases to 3 m/s then the said link will survive for (14-5)/3 s i.e. 3s. Hence high radio-range of a node is good for survival of the link between the node and any of its downlink neighbors.

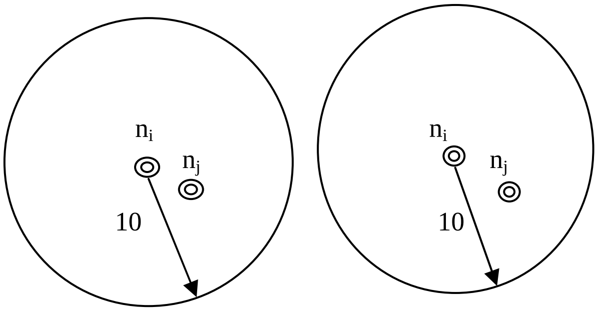

Fig 3a Fig 3b

Fig 3a and 3b: Let the current distance between n_i and n_j be 4 m in fig 3a and 6 m in fig 3b. In both the figures, radio-range of n_i is 10 m. If the relative velocity of n_i w.r.t. n_j is 2 m/s, then the link between them will survive for (10-4)/2 s i.e. 3 s in fig 3a. On the other hand in fig 3b the said link will survive for (10-6)/2 s i.e. 2s. Hence low distance of a node from its downlink neighbor is good for survival of the link between them.

$$\beta_{ij}(t) = (1 - c_{ij}(t)\, r_i)\,(1 - d_{ij}(t)/(R_i+1)) \qquad (2)$$

Where $c_{ij}(t) = (1-1/(|v_i(t) - v_j(t)| +1))$
and $r_i = (R_{max}-R_i+1)/(R_{max}-R_{min}+1)$

For any node n_i, $v_i(t)$ specifies its velocity at time t and R_i specifies its radio-range. Assuming that R_{min} and R_{max} denote the minimum and maximum possible radio-ranges of the network, for any node n_i, R_i lies between R_{min} and R_{max}. $d_{ij}(t)$ indicates distance of n_j from its uplink neighbor n_i at time t. Magnitude of the relative velocity of n_i w.r.t. n_j or the same of n_j w.r.t. n_i, is given by $|v_i(t) - v_j(t)|$.

It may be noted from (2) that $\beta_{ij}(t)$ increases with decrease in $c_{ij}(t)$, r_i and $d_{ij}(t)$. Also $c_{ij}(t)$ decreases with decrease in $|v_i(t) - v_j(t)|$. This rightly models the situation that affinity between a node and its downlink neighbor increases with decrease in their relative velocity. As far as r_i is concerned, it decreases as R_i approaches the upper limit R_{max} of radio-ranges in the network. Hence, $\beta_{ij}(t)$ increases with increase in R_i. In the mathematical expression of r_i, 1 is added in both numerator and denominator. The reason is that otherwise r_i would have been 0 in the situation R_i=R_{max} and that would nullify the effect of relative velocity of n_i w.r.t. n_j on $\beta_{ij}(t)$, which is not desirable. For any node n_j and its uplink neighbor n_i, distance $d_{ij}(t)$ between them at time t must be less than or equal to R_i. It is evident from (2) that affinity $\beta_{ij}(t)$ reduces as $d_{ij}(t)$ becomes close to R_i and obtains maximum value if $d_{ij}(t)$ is equal to 0. Please note that 1 is added with R_i in (2) to retail the effects of $c_{ij}(t)$ and r_i on $\beta_{ij}(t)$ when $d_{ij}(t)$ is equal to R_i.

Since $c_{ij}(t)$ and r_i are fractions and $d_{ij}(t)$ is less than or equal to R_i, so $\beta_{ij}(t)$ ranges between 0 and 1. Values close to 1 emphasize worthiness of n_i as most eligible uplink neighbor of n_j.

3. Communication Load $\gamma_i(t)$ of node n_i at time t depends upon the following things:
i) The pending message forwarding load present in message queue of n_i at time t.
ii) The uplink neighbor load of n_i at time t
iii) The number of downlink neighbors that have already chosen n_i as most eligible uplink neighbor
Let AR and N denote the total geographical area of the network and total number of nodes in the network. Then density ψ of nodes in the network is given by,

$$\psi = N/AR \quad (3)$$

Also assume that $U_i(t)$ and $D_i(t)$ denote the set of uplink and downlink neighbors within the same cluster of n_i, respectively, of node n_i at time t. Since R_{max} is the maximum possible radio-range of the network, the maximum distance of n_i from any of its uplink neighbors is R_{max}. If density of nodes is uniform, then the maximum number of uplink neighbors of any node n_i is $\psi\pi R^2_{max}$. Assume that among $|D_i(t)|$ number of downlink neighbors, $\rho_i(t)$ number of nodes have selected n_i as most eligible uplink neighbor till time t.
The Communication Load $\gamma_i(t)$ is mathematically expressed as,

$$\gamma_i(t) = 1 - [(m_i(t) / M_i)\, f_i(t)\, (\rho_i(t) / |D_i(t)|)]^{1/3} \quad (4)$$

Where $f_i(t) = \mathrm{MIN}\{(|U_i(t)| / \psi\pi R^2_{max}),1\}$

$m_i(t)$ and M_i specify the number of filled locations in message queue of n_i at time t and total number of locations in message queue of the same node. It is quite evident that $\gamma_i(t)$ increases with increase in $m_i(t)$, $|U_i(t)|$ and $\rho_i(t)$ while $m_i(t)$ ranges between 0 and M_i and $\rho_i(t)$ ranges between 0 and $|D_i(t)|$. As far as $|U_i(t)|$ is concerned, it ranges from 0 to N. But it is good for n_i if upper limit of $|U_i(t)|$ is restricted within $\psi\pi R^2_{max}$ which is the maximum under uniform node distribution. If the number of uplink neighbors of n_i increase abruptly, chances of call arrival at n_i in future also increase. MIN is a function that returns the minimum value among its arguments. Please note that if $|U_i(t)|$ is greater than or equal to $\psi\pi R^2_{max}$, then $\mathrm{MIN}\{(|U_i(t)|/ \psi\pi R^2_{max}),1\}$ evaluates to 1. Otherwise, $\mathrm{MIN}\{(|U_i(t)| / \psi\pi R^2_{max}),1\}$ is a positive fraction. Please note that $|U_i(t)|$ cannot be 0 in a clustered environment, because in a cluster, all members are connected to the cluster. So, there has to be at least 1 uplink neighbor for each cluster member. It is evident from (4) that $\gamma_i(t)$ ranges between 0 and 1. The higher is the value of $\gamma_i(t)$ the more well-equipped is the node to take charge of most eligible uplink neighbor of some node.

4. Connectivity Contribution $\delta_i(t)$ of n_i at time t is formulated as,

$$\delta_i(t) = \delta_{i1}(t) \times \delta_{i2}(t) \quad (5)$$

$$\delta_{i1}(t) = \mathrm{MIN}\left\{ \left\{ \prod_{n_j \in U_i(t)} (|D_j(t)| / \psi\pi R^2_j) \right\}^{1/|U_i(t)|}, 1 \right\} \quad (6)$$

$$\delta_{i2}(t) = \mathrm{MIN}\left\{ \left\{ \prod_{n_j \in D_i(t)} (|U_j(t)| / \psi\pi R^2_{max}) \right\}^{1/|D_i(t)|}, 1 \right\} \quad (7)$$

$\delta_i(t)$ increases with increase in $\delta_{i1}(t)$ and $\delta_{i2}(t)$. $\delta_{i1}(t)$ acquires a high value if the uplink neighbors of n_i at time t are equipped with sufficient number of downlink neighbors at that time and similarly, $\delta_{i2}(t)$ obtains a high value if the downlink neighbors of n_i at time t are equipped with sufficient number of uplink neighbors at that time. For a node n_j with radio-range R_j, $\psi\pi R^2_j$ is considered sufficient number for downlink neighbors which is equal to the highest number of downlink neighbors for the radio-circle of radius R_j under uniform node distribution. Similarly, $\psi\pi R^2_{max}$ is considered sufficient number for uplink neighbors which is equal to the highest number of uplink neighbors for any node under uniform node distribution. Please note that for any node $n_j \in U_i(t)$, $D_j(t)$ cannot be empty since it contains at least n_i; similarly, for any node $n_j \in D_i(t)$, $U_j(t)$ cannot be empty since it contains at least n_i. Values of $\delta_i(t)$ close to 1 increase capacity of n_i as most eligible uplink neighbor of its downlink neighbors.

5. Design of Rule Bases of BND

The parameters of BND are divided into crisp ranges and the corresponding fuzzy variables are shown in table 1. Subscripts are omitted for the purpose of simplicity.

Table 1
Crisp Ranges of Parameters and Fuzzy Variables

Crisp ranges of α	Crisp ranges of β, γ, δ	Fuzzy variable
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

According to the study of discharge curve of batteries heavily used in ad hoc networks, at least 40% (fuzzy variable a1 represents the range 0-0.40) of total charge is required to remain in operable condition; 40%-60% (fuzzy variable a2) of the same is satisfactory, 60%-80% (fuzzy variable a3) is good and the next higher range (i.e. 80%-100% or fuzzy variable a4) is more then sufficient from the perspective of remaining energy. All other parameters follow uniform range distribution between 0 and 1 i.e. (0-0.25 as a1, 0.25-0.50 as a2, 0.50-0.75 as a3 and 0.75-1.00 as a4).Table 2 combines the effects of α and β producing temporary output t1. Both are given equal importance since they are equally indispensable for survival of the link from a node to its downlink neighbor. The other parameters contribute to delay-efficiency of the link. The fuzzy composition of t1 and γ appears in table 3. In this table, t1 is assigned more importance than γ because t1 is a composition of two parameters both of which are more important than γ. The temporary output t2 generated by table 3 is combined with δ in table 4 producing final output el of BND.

Table 2
Fuzzy Combination of α and β producing output t1

$\alpha\rightarrow$ $\beta\downarrow$	a1	a2	a3	a4
a1	a1	a1	a1	a1
a2	a1	a2	a2	a2
a3	a1	a2	a3	a3
a4	a1	a2	a3	a4

Table 3
Fuzzy Combination of t1 and γ producing output t2

t1$\rightarrow$ $\gamma\downarrow$	a1	a2	a3	a4
a1	a1	a2	a3	a3
a2	a1	a2	a3	a3
a3	a1	a2	a3	a4
a4	a2	a3	a3	a4

Table 4

Fuzzy Combination of t2 and δ producing output el

t2$\rightarrow$ $\delta\downarrow$	a1	a2	a3	a4
a1	a1	a2	a3	a3
a2	a1	a2	a3	a3
a3	a1	a2	a3	a4
a4	a1	a2	a3	a4

If more than one uplink neighbors of a node n_i acquire highest value for el, then any one of those candidates is selected as most eligible uplink neighbor of n_i.

6. Message Description

FLB requires each node to broadcast HELLO message within its radio-range at regular intervals. If a node n_j exists within the radio-range of another node n_i, then n_i is termed as an uplink neighbor of n_j. The attributes of HELLO message generated by n_i at time t consists of the following information:

- source node identification number n_i
- current timestamp t
- current geographical location $(x_i(t),y_i(t))$ in terms of latitude and longitude
- radio-range R_i
- current velocity $v_i(t)$
- the number of downlink neighbors that have already selected n_i as most eligible uplink neighbor
- total number of uplink neighbors in the same cluster
- consumed battery power $e_i(t)$ at time t
- Total battery power E_i
- Starting time t_i of operation of n_i, in the network

Each node n_j residing within the radio-range of n_i, replies with an acknowledgement (ACK) message. Its attributes are as follows:

- source node identification number n_j
- destination node identification number n_i
- current timestamp t'
- current geographical location $(x_j(t),y_j(t))$ in terms of latitude and longitude
- current velocity $v_j(t)$

Format of a broadcast message initiated by n_i and forwarded by n_j is as follows:

- forwarding node identification number n_j
- current timestamp t'
- source identification number n_i
- message initiation timestamp t_{b_s}
- current velocity $v_j(t)$

If the link of a node n_i with its most eligible uplink neighbor n_j breaks at time t_b, then n_i elects its next most eligible uplink neighbor n_k and sends to n_k a special status message with the following attributes:

- source node identification number n_i
- destination node identification number n_k
- current timestamp t'
- timestamp t_b of the break

- source identification number and timestamp of initiation of last 3 broadcast message received within timestamp t_b (it is expected that nodes at approximately same distance (in terms of number of hops) from cluster-head receive broadcast messages at approximately same time).

Receiving the status message if n_k finds that some broadcast message was not received by n_i, n_k transmits those to n_i. Chance of some redundancy exists here if the nodes at approximately same distance (in terms of number of hops) from cluster-head do not receive broadcast messages at approximately same time.

7. Algorithm Complexity

- ***HELLO Message Overhead***

In FLB, HELLO messages are transmitted by every node at regular intervals to gather local topology information and elect the most eligible uplink neighbor. Assuming N to be the total number of nodes in the network and Δ to be the average node degree, the HELLO overhead H_OVHD(t) at time t is formulated as,

$$H\_OVHD(t) = N \times \Delta \times (t - t_{start}) / \tau' \quad (8)$$

Where τ' is the uniform interval between HELLO messages of each node and t_{start} is the starting time of operation of the network.

- ***Redundancy in FLB***

In FLB, a node n_i cannot receive broadcast message from more than one uplink neighbor. Hence, ideally, the redundancy is 0.

- ***100% delivery ratio in FLB***

FLB is based on a clustered architecture and it assumes that all cluster-members are connected to their respective cluster-heads. So, most eligible uplink neighbor n_k of any node n_i must be connected to the cluster-head through some route. n_i will receive the broadcast message as soon as n_k receives it from the cluster-head. So, ideally, the delivery ratio of FLB is 100%.

- ***Complexity of Selecting The Most Eligible Uplink Neighbor***

Assume that the average number of uplink and downlink neighbors of a node be Δ' and Δ, respectively. The complexities of computing values of input parameters of BND for one uplink neighbor, is O(1). For combining the input parameters, tables 1, 2, 3 and 4 need to be consulted. Table 1 is required for crisp range division and determination of fuzzy variables for those ranges. BND had got 4 input parameters. So, 4 accesses to table 1 is required. Then, during combination of those parameters, exactly one access to each of the tables 2, 3 and 4 is needed. In order to determine el of an uplink neighbor, 7 (i.e. O(1)) table accesses are required. Hence, for Δ' uplink neighbors, the cost of determining el is $O(\Delta')$. Among all those el's the best one is to be computed. In the best case, el of the uplink neighbor considered first is a4. So, the best case cost is 1. On the other hand, the corresponding worst case cost is $(\Delta'-1)$ (i.e. $O(\Delta')$) , where el of first $(\Delta'-1)$ uplink neighbors is not a4. So, the overall complexity of selecting the most eligible uplink neighbor is $O(\Delta')$.

- ***Cost of intra-cluster and inter-cluster communication***

Cost of inter-cluster communication increase if the number of clusters increase or the size of clusters decrease. Decrease in the size of clusters will reduce the cost of intra-cluster communication. Let, the total number of clusters in the network be denoted as cls_num. Also assume that hlim and clim denote the maximum distance of a cluster member from its cluster-head in terms of number of hops and maximum number of nodes in a cluster, respectively. Then,

$$cls\_num \times clim = N \quad (8)$$

i.e. $cls\_num = N / clim$

Cost of inter-cluster communication is given by O(cls_num). Cost of intra-cluster broadcast and unicast communication are O(clim) and O(hlim) respectively. hlim is less than or equal to the hop count H of the network. If clim is set to $\sqrt{N}$, then cost of both inter-cluster communication and intra-cluster broadcast becomes $O(\sqrt{N})$. On the other hand, if clim is set to $N^{1/3}$, then cost of inter-cluster communication and intra-cluster broadcast are $O(N^{2/3})$ and $O(N^{1/3})$, respectively. So, clim is the handle that is used to obtain a trade-off between the costs of inter-cluster and intra-cluster communication.

8. Simulation Results

I evaluate the performance of FLB, using the network simulator ns-2. Except FLB, I implement the protocols tree-based broadcasting (TBB), reduction of broadcast traffic (RBT) approach, reliable broadcasting (RB) and density-based flooding (DBF). The ns-2 is a discrete event simulator developed by the University of California at Berkeley and VINT project [12]. For the purpose of studying multi-hop ad hoc networks, it has been modified and extended with mobile wireless modules by the CMU Monarch project [12]. This simulator has been used to evaluate the performance of ad hoc routing protocols. Each mobile node has a position and velocity. In different simulation runs, nodes move according to the “random waypoint”, “random walk” and “gauss-markov” model. In random waypoint model, each node begins operation by remaining stationary for PAUSE_TIME seconds (its value is mentioned in table 1). It then selects a random position in the space and moves to that position at a speed distributed uniformly between 0 and MAX_SPEED. When it reaches the destination, a new round of pause/ move is repeated. The random walk model was originally used to emulate the unpredictable movements of particles in physics, also referred to as Brownian motion. Random walk model is very similar to random waypoint mobility model because the node movements have strong randomness in both models. The random walk model may be thought of as a specific kind of random waypoint model with PAUSE_TIME 0 seconds. On the other hand, in gauss-markov mobility mode, the velocity of a node is assumed to be correlated over time and modeled as a gauss-markov stochastic process. The parameters of simulation are shown in table 5.

The performance metrics I observe are:-

- Broadcast cost – It is the normalized average cost to deliver a broadcast message to all nodes in the network. It is defined as TOT_MSG / (TOT_BRC_SRC * N) where TOT_MSG is the total number of messages transmitted by all nodes in the network, including the control messages, TOT_BRC_SRC is the total number of user messages generated by the broadcast sources and N is the total number of mobile nodes. TOT_MSG is also a metric of the bandwidth consumed in broadcast.
- Delivery ratio – It is defined as TOT_RECV / (TOT_BRC_SRC * (N -1)) where TOT_RECV is the total number of non-duplicate messages received by users. The delivery ratio reveals the robustness of the simulated protocol. In the ideal case, the delivery ratio will be 1.
- Delay - It is defined as (for all broadcast messages ∑ (MSG_END_TIME - MSG_START_TIME))/ (TOT_MSG) where TOT_MSG is the total number of broadcast messages transmitted. MSG_END_TIME is the timestamp when a broadcast operation completed i.e. reached to all nodes in the network. Similarly, MSG_START_TIME is the timestamp when a broadcast message was transmitted by its source i.e. when the broadcast operation initiated.

The performance of FLB is compared with the performance of some state-of-the-art broadcast protocols, namely RB, RBT, TBB and DBF. The corresponding graphical representations appear in figures 1 to 6.

I have already discussed the fact that in FLB, each node selects the most efficient uplink neighbor considering residual energy, strength of wireless bond between a node and its most efficient uplink neighbor, communication load and contribution in maintaining connectivity in the network. Only the selected uplink neighbors rebroadcast a message while the others drop the packet after receiving it. Hence, redundancy in FLB is 0 and the broadcast cost is much lesser compared to the other protocols mentioned above. TBB does not suffer from much redundancy because it is based on tree-structured nodes, but as the number of nodes increase, the phenomenon of link breakage becomes more frequent because more links are there to be maintained. As a consequence, the broadcast tree structure requires modification increasing the broadcast cost. On the other hand, links between a node and its most efficient uplink neighbor in FLB are stable, reducing the overhead of frequent re-election of most eligible uplink neighbor. The improvement can be noticed from figures 1 and 2 where broadcast cost is measured with respect to total number of nodes and number of broadcast source, respectively. It is quite evident that for all the above-mentioned protocols, broadcast cost increases with increase in number of nodes and broadcast sources, with the reason being increased signal collision in the network. But the dependence of broadcast cost on node mobility should be discussed separately. TBB creates a tree for broadcasting whose links break frequently if node mobility increases. This requires restructuring of the tree by exchanging some more messages. Hence, broadcast cost for TBB increases with average node velocity. But for others, the cost is steady. This is shown in figure 3.

Since, FLB is power aware, energy depletion in nodes is quite balanced. As a result, the chances of network partitioning get reduced. Also mobility awareness brings stability in relationship between a node and its most efficient uplink neighbor. All these contribute to produce packet delivery ratio as high as 99.98%. The delivery ratio increase for all the protocols, when the network scales large. This is because the network becomes dense with the increase of node number in a fixed size area and a mobile node is more likely to be covered by a broadcast relay gateway. In figure 5, delivery ratio is measured with respect to number of sources. As the number of broadcast sources increase, a huge number of messages need to be forwarded network wide. This, in turn, generates signal contention and collision resulting in the drastic drop in delivery ratio. Since FLB is power and mobility aware and does not suffer from redundancy, it can efficiently resist the drop for a longer time duration than RB, RBT, TBB and DBF. The phenomenon is illustrated in figure 5. Figure 6 illustrates the dependence of delivery ratio on average node velocity. Since broadcast cost increases in TBB with increase in node velocity, delivery ratio decreases with node velocity due to signal collision and high rate of energy depletion of nodes. For the other protocols the delivery ratio remains steady with node mobility.

Table 5
Simulation Parameters

Parameter	**Value**
Network Area	500 × 500 m^2 in first ten runs, 1000 × 500 m^2 in next ten runs, 1000 × 1000 m^2 in last ten runs
Transmission Range	10 – 50 m in first ten runs, 30 – 100 m in next ten runs, 10 – 100 m in last ten runs
Interval between consecutive HELLO messages	20 seconds for first ten simulation runs, 30 seconds for next ten and 45 seconds for last ten simulation runs
Number of nodes	30 - 300
MAC layer	IEEE 802.11g
PAUSE_TIME	20 seconds
Traffic type	Constant bit rate (128 kbps/second)
Maximum number of retries before an acknowledgement is obtained	4
Packet Size	64 bytes in first ten runs, 128 bytes in next ten runs, 256 bytes in last ten runs (in different simulation runs)
Bandwidth	1- 4 Mbps in first ten runs, 2 – 7 Mbps in first ten runs, 1-10 Mbps in last ten runs
Mobility model	Random waypoint mobility model in first 10 runs, Random walk mobility model in subsequent 10 runs and Gaussian model in last 10 runs
Simulation Time	1000 seconds for each run

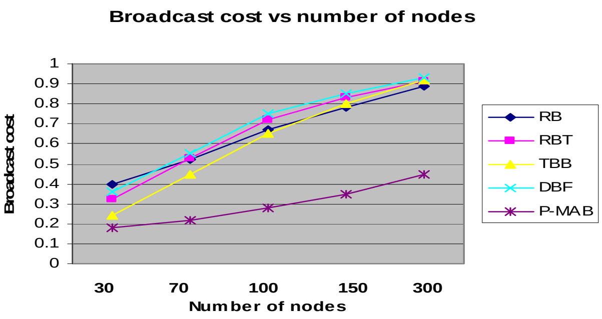

Figure 1: Graphical demonstration of broadcast cost vs number of nodes

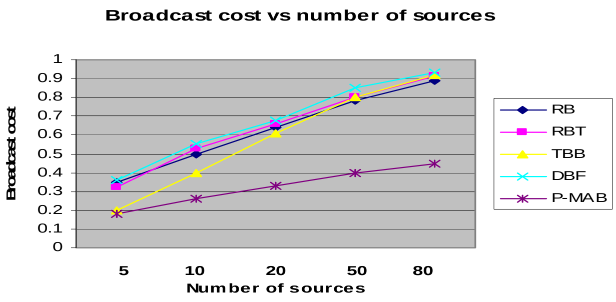

Figure 2: Graphical demonstration of broadcast cost vs number of sources

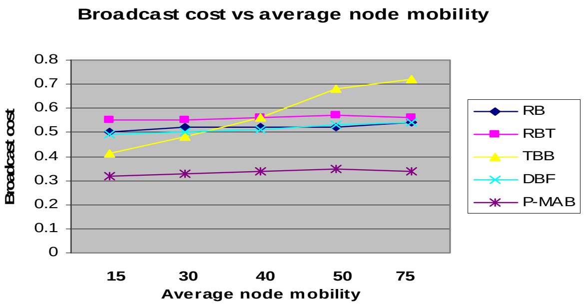

Figure 3: Graphical demonstration of broadcast cost vs average node velocity in meter/second

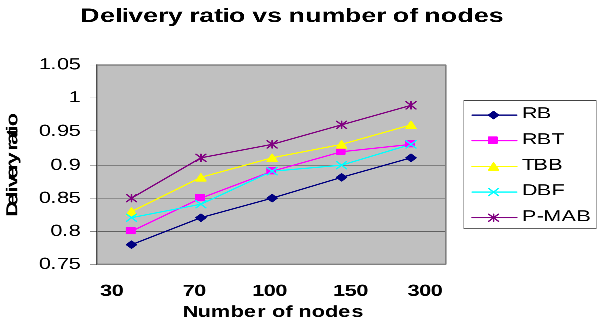

Figure 4: Graphical representation of delivery ratio vs number of nodes

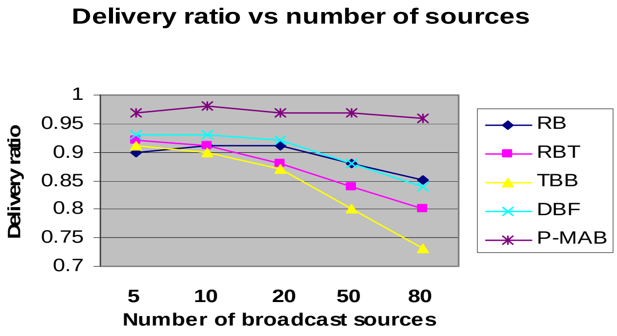

Figure 5: Graphical representation of delivery ratio vs number of source

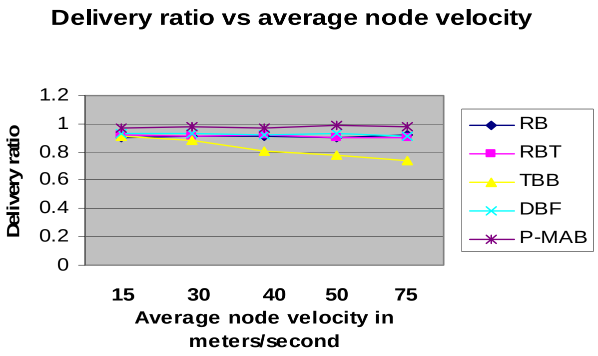

Figure 6: Graphical representation of delivery ratio vs average node velocity

9. Conclusion

This paper presents a new approach for efficient broadcasting in mobile ad hoc networks. The proposed protocol called FLB is both power and mobility aware. Each node selects its most efficient uplink neighbor and receives broadcast message from only that neighbor. It minimizes the broadcast redundancy and also saves the network bandwidth. Most efficient uplink neighbor is elected by considering residual energy and link stability. This brings power and mobility awareness in the protocol.

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