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Route Robustness of a Multi-Meshed Tree Routing Scheme for Internet MANETs

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Abstract: We propose a layer 2 routing and forwarding scheme called Multi-Meshed Tree (MMT) routing for MANETs connected to Internet. The specifications of this scheme were drawn from unique features of Internet MANETs. Evaluation of the robustness of routes in this scheme is provided along with the route failure notification delays, which is an important performance parameter of this scheme. Where available we have substantiated our results with simulation data. The results clearly show the significance of the redundant routes offered by MMT.

I. INTRODUCTION

Mobile Ad hoc NETworks (MANETs) connected to Internet would be an attractive option to Wireless Local Area Networks (WLANs) and cellular networks as they combine the advantages of WLANs in terms of low deployment and call costs, and a wider coverage without much infrastructure. We call MANETs, tethered or connected to Internet as tMANETs. The downside of using tMANETs instead of WLANs and cellular networks are 1) lack of Quality of Service (QoS) support, 2) network joining delays especially for users roaming with active calls 3) higher probability of connection/call loss. These disadvantages are due to the ad hoc nature of the network. In this work, we provide the design for a layer 2 routing and forwarding scheme, which supports QoS, facilitates quick joining and provides robust connectivity through route redundancy in tMANETs. However, in this article we assess the proposed scheme for its route robustness and delays for route failure notification. Route failure notification time is a very important performance parameter in the proposed scheme as it determines the delay to switchover to backup routes on route failures and hence affects the route robustness of the proposed scheme. It also affects QoS as packets during the time the notification is being forwarded will be directed to the old route and lost thereby.

II. RELATED WORK

A number of efficient routing schemes have been proposed and investigated for standalone MANETs of which [3, 4] are accepted RFC documents and [5] is a very popular routing protocol. Subsequently when MANETs were being investigated to extend wireless Internet or to provision for QoS, the prospective candidate routing protocols were the ones already proposed for standalone MANETs, with appropriate adaptations to connect to Internet or support QoS [10-12, 14, 15, 17]. Several of these focus on an IP based solution [7, 8, 13], [16] has an approach based on the layer 2 and attempts collision reduction to improve QoS. [1, 2] address quick handoff in MANETs and Mobile Networks, where quick joining is essential for quick handoff. Our focus in this work is to support QoS via route robustness and improve joining time for new mobiles in tMANETs. For this purpose, we use some features of a tMANET, which are distinct from a standalone MANET. They are 1) connectivity to Internet, resulting in a major traffic flow from/to Internet; 2) limited number of hops that can be supported from the gateway connecting to Internet; 3) and total number of mobiles that can be supported on a tMANET as mobiles closest to gateway providing forwarding services are a serious bottleneck [6]. The proposed routing scheme was designed using these features to advantage, and hence has a different approach and results show that this approach is indeed successful in providing robust routes, improving connectivity and has low route failure notification delays which facilitates quick switchover to backup routes and thereby improves QoS.

III. PROPOSED DESIGN

We propose a layer 2 routing and forwarding scheme, which we aptly name as “Multi Meshed-Tree” (MMT) routing. To our knowledge for the first time a novel approach, which is a combination of a tree and a mesh, is being used efficiently for routing – an approach which is crucial to provision QoS, improve connectivity and route robustness in tMANETs. We now define some terminology and explain the design of MMT, using figure 1.

Information flow to/from a mobile is along the branches of a tree, which is the route to the mobile. Routes to a mobile are defined by nodeIDs allocated to a mobile, and these are registered with the gateway (wire connected to Internet).

Meshed tree: The branches of a tree mesh to provide multiple routes or route redundancy to a mobile. For example in figure 1, mobile G has routes [AG1, C, G] and [AG1, B, G], because branches from C and B meet at G – accordingly it has nodeIDs [131] and [123]. A mobile can have ‘M’ maximum number of routes and hence ‘M’ nodeIDs. A mobile uses one of the nodeIDs as the primary - normally with the least hops and best available bandwidth2, the rest are stored in order of preference. These routes are continually updated. Mobiles not willing to participate in routing are leaf nodes of the tree.

Multi-Meshed Tree: A more robust route redundancy is provided by using multiple gateways and allowing the trees originating from these gateways to mesh as shown in figure 1 (distinct colors are used for each tree). Mobiles ‘B1’ and ‘Q’ have routes from AG1 and AG3.

NodeID: Let the nodeID of a mobile ‘n’ hops away from a gateway be MIDn. Then MIDn = [A1, A2……A k……A n+1] where, Ak ∈ {0, 1……9}, [A1] is the gateway nodeID and [A1, A2……Ak] is the nodeID of the (k-1)th mobile enroute.

1 In this work we have not focused on selecting disjoint routes.
2 Bandwidth reservation and QoS effects have been submitted and accepted for publication in PIMRC 2005.
A. Mobile Registration

Starting at access gateway, AG1 advertises its nodeID ‘1’. First hop mobiles listen and request AG1 to be connected. AG1 then allocates them a nodeID, which is derivative of it’s ID - for example in figure 1, mobile ‘A’ is allocated nodeID 11, ‘B’ has nodeID 12, and ‘C’ has nodeID 13. First hop mobiles then advertise their nodeIDs, and second hop mobiles join in and are given nodeIDs, which are derived from their predecessor nodeIDs. Mobiles continually listen to nodeIDs of their neighbors and accordingly acquire nodeIDs to get better routes. Hence, nodeIDs are dynamic and routes are dynamic. All mobiles with nodeIDs derived from an access gateway register with it along with their home IP address and Care-of-IP address (CoA) acquired in the new network. MMT imposes a hop-limit to restrict number of wireless hops to preserve QoS. This is easily achieved by restricting digits in the nodeIDs.

B. Operation

Packet Forwarding: IP packets arrive at a gateway with the mobile’s CoA. The gateway selects the primary nodeID of the mobile, encapsulates the IP packet in a layer 2 frame, sets destination address as mobile’s primary nodeID and source address as it’s nodeID and forwards the frame. For example, an IP packet for mobile G when framed by AG1, has source address ‘1’ and destination address ‘131’. This frame is picked up by all first hop mobiles i.e. A, B, and C but is forwarded only by mobile ‘C’ with nodeID ‘13’. Before forwarding, ‘C’ changes source address in frame to ‘13’. (change of source address is done by all forwarding mobiles). Thus the source address in frames serves as implicit advertisement for that mobile/gateway. This applies to frames going upstream or downstream. This considerably reduces periodical broadcasts of ‘hello’ messages. Besides data frames, any control frames carrying a nodeID in the first field of the frame can serve as an advertisement.

Advertisements: As mentioned above data frames going upstream or downstream serve as advertisement for mobiles/gateway forwarding them. If there are no data frames to forward for an advertisement interval ‘τ’, then mobiles/gateway will send out a short advertisement frame.

Implicit Acknowledgements: A mobile that has forwarded a frame listens to mobiles downstream or upstream, which is supposed to forward it further. If it does not hear the frame being forwarded for a certain ‘ack’ interval, it will resend the frame, assuming frame was lost or faced collisions. It will repeat this ‘retry’ times, at the end of which it reports a ‘route failure’ to the gateway.

Route failures and repairs: A mobile that does not hear from its predecessor or successor for an interval of ‘3τ’ (3*advertisement interval) reports a failure of that route of the mobile to gateway. The gateway then removes that failed route (i.e. the corresponding nodeID) for the mobile and for all successor mobiles whose nodeIDs were derived from the failed nodeID. On failing to hear any activity from their predecessor or successor, a mobile reaches one of following conclusions; that either it has moved or its predecessor/successor has moved or failed.

Figure 2: Route failure notification

In figure 2, mobile R has a nodeID derived from T and a nodeID derived from H. As R moves along the dotted arrow, it looses route 132111 (via T). It will report loss of this route to gateway using nodeID 1222 (via H). Gateway will then stop using all nodeIDs derived from 132111, and use the alternate nodeIDs in all cases. As R moves on it will acquire a route 1111 via I. Route 132111 could have failed due to the failure of routing mobile T also.

Though bandwidth reservation mechanism has been incorporated in the MMT, we do not provide details of this, as the focus of this paper is primarily on evaluating the route robustness of MMT.

IV. PERFORMANCE

The primary performance parameters in MANETs are mobile joining time, network settling time, end-to-end message delivery delay, end-to-end data throughput, route availability and route failure notification time. We estimate route failure notification delays and route robustness in this article. Route failure notification time is the time taken by a mobile to identify failure of one of its routes and inform the gateway to use another backup route. Network settling time, is an important parameter and comprises of the route failure notification time and the time taken to re-establish the broken or new routes. However, in MMT due to redundant or backup routes, there is no time wasted on re-establishing broken routes hence this time is the same as ‘route failure notification’ time. Route availability can be used to measure

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the robustness (availability) of routes and in turn the robustness of the proposed routing and forwarding scheme.

A. Route Failure Notification Time

A mobile which notices route failure reports to the gateway via its secondary or backup route. There is however a non-zero probability that a mobile does not have any secondary or backup routes. This can happen if the density of mobiles is very low or highly non-uniform. We assume this probability is negligible.

Route failure notification process is initiated by a mobile after 3 advertisement intervals during which it has not heard from its predecessor or successor. Hence, the time taken for route failure notification is given by

\[
T_{RF,N}= [3*\tau] + [\xi(n)*\tau] + [\xi(n)* (\tau_{\text{trans}} + \tau_{\text{prop}})]
\]

(1)

Where \(\tau\) is the advertisement interval, \(n\) is the number of hops the reporting mobile is away from the gateway and \(\xi(n)\) is the average number of retransmission to get a control message to the gateway successfully. If the reporting mobile is \(n\) hops away from the gateway, the route failure notification failure to reach the gateway, it takes at least \(n\) messages from the reporting mobile to the gateway. However, there is a probability that a message will not get through because of collisions, link conditions and intermediate node mobility. Each mobile will make 2 retries to send the message. Hence \(\xi(n)\) has to be calculated considering these factors and its derivation is given in the next section. \(\Gamma\) is the processing delay at each mobile. \(\tau_{\text{trans}}\) is transmission delay per frame and \(\tau_{\text{prop}}\) is propagation delay per frame. In equation 1, there are 3 contributing components, one due to identification of route failure, which depends on advertisement intervals, the second due to processing delays in mobiles and the third is due to transmission and propagation of frames. Depending on the relative values for these contributing components, any component could be predominant in this equation. In this article we provide some results highlighting the dominant effects of processing delays.

A.1 Processing Delays

A mobile or gateway is normally processing jobs. When a frame arrives, the frame has to wait for some time before it gets processed and then transmitted. The delays so incurred by frames depend on CPU processing capacity of mobile or gateway and the rate at which jobs arrive at mobiles (gateway) and can be modeled using a simple M/G/1 queue process, where total waiting time is given by

\[
\Gamma = \frac{1}{\mu + \sigma}
\]

(2)

where \(\sigma\) the waiting time and can be obtained using Pollaczek-Khinchin equation as given below

\[
\sigma = \eta(1/\mu + \sigma^2) / 2(1 - \eta / \mu)
\]

(3)

\(\eta\) is the arrival rate of jobs per seconds, \(\mu\) is service rate of CPU in the mobile (gateway), \(\sigma^2\) is the variance.

A.2 Calculation of \(\xi(n)\)

To determine the delays incurred in transmitting a packet over ‘n’ wireless hops it is required to calculate the average number of packets that get transmitted (retransmitted) over the ‘n’ hops. In this section, we calculate the average number of transmissions before a route_failure_notification message sent by a mobile reaches the gateway. The process is explained below in figure 3.

In figure 3, \(n\) stages are shown between gateway and mobile forwarding route_failure_notification message. At each stage a mobile make 3 tries to forward the message to the next mobile towards the gateway. If at a stage a mobile fails to forward the message within the 3 tries, it will abort the retry process and drop the packet.

Let the probability of success for a message in one try be \(p\) wherein are factored collisions, link conditions, and node mobility effects. The probability that a message sent by a mobile ‘n’ hops away from the gateway reaches the gateway successfully with ‘n’ messages only i.e. at all stages the message was transmitted successfully at the first try is given by \(p^n\). Similarly, we can calculate the probability that the message sent by the mobile reached the gateway in exactly \(n+1\) messages or \(‘n+2\) messages etc. The table below gives the probabilities for the numbers of transmissions to successfully deliver a message to the gateway. The maximum number of transmission in one attempt can be ‘3n’ transmissions, where at each of the ‘n’ stages 3 tries were attempted and success achieved at the third try.

<table>
<thead>
<tr>
<th>(n+i) Distribution of messages</th>
<th>(\text{Probability of success})</th>
</tr>
</thead>
<tbody>
<tr>
<td>(n)</td>
<td>1 tr at each of the ‘n’ stages</td>
</tr>
<tr>
<td>(n+1)</td>
<td>2 trs at one stage and 1 tr at n-1 stages</td>
</tr>
<tr>
<td>(n+2)</td>
<td>(2 trs at 2 stages and 1 tr at n-2 stages) or (3 trs at 1 stage and 1 tr for the rest)</td>
</tr>
</tbody>
</table>
| \(n+3\) | (2 trs at 3 stages and 1 tr at n-2 stages) or (3 trs at 1 stage, 2 trs at another stage and 1 tr at the rest) | \(C_n^3(1-p)^3p^{n-1} + n(1-p)^{n-1} = C_n^3(1-p)^np^n + nC_n^2(1-p)^2p^{n-2}\)

*tr- transmission

From table 1, generalizing the probability of success with only \((n+i)\) messages over ‘n’ hops is

\[
P_{n+i} = \left[ C_n^i + \sum_{k=0}^{m} C_n^{i-k} (1-p)^k \right](1-p)^np^n
\]

(4)

where \(P_{n+i}\) is the success probability in \(n+i\) transmissions, \(m\) is the biggest value which satisfies \(2m \leq i\), and is given by \(\lceil i/2 \rceil\) and \(k\) identifies the number of stages with at least 3 transmissions. Hence ‘k’ is less than ‘n’ and \(C_n^k = 0\) for \(k > n\).

From equation 4

\[
\xi(n) = \sum_{i=0}^{n} (n+i)P_{n+i} / \sum_{i=0}^{2n} P_{n+i}
\]

(5)

where ‘i’ can take a maximum value of 2n and the denominator normalizes \(\xi(n)\) to the success probability.
In this section, we assess the availability of a route by assessing the availability of each hop of the route. We use the term ‘stage’ instead of hop, as at a stage there is a primary route and backup routes.

Table 2: Parameters for Route Availability

<table>
<thead>
<tr>
<th>Number of routes available</th>
<th>R</th>
</tr>
</thead>
<tbody>
<tr>
<td>Types of link failure faults</td>
<td>M</td>
</tr>
<tr>
<td>Average time taken for a node to enter in the routing range of a mobile</td>
<td>1/µ secs</td>
</tr>
<tr>
<td>Average time taken for a node to leave the routing range of a mobile</td>
<td>1/λ secs</td>
</tr>
<tr>
<td>Rate of link failure</td>
<td>δ per sec</td>
</tr>
<tr>
<td>Rate of link revival</td>
<td>Φ per sec</td>
</tr>
<tr>
<td>Time taken to switch over to a new route</td>
<td>Ψ secs</td>
</tr>
</tbody>
</table>

Let i ∈ I = {0, 1, ….. R} is the number of available routes and j ∈ J = {0, 1, ….. M} is the types of faults that can make a route at any stage unavailable. The tuple {i, j}, i ∈ I, j ∈ J identifies a stage which has ‘i’ routes with the possibility of ‘j’ failures. In figure 4 a Continuous Time Markov Chain (CTMC) model [18, 19] to evaluate availability of one stage of a route is shown. After obtaining the availability of one stage we compute the availability of a route by cascading ‘n’ stages for ‘n’ hops that makeup the route.

From the state transition diagram of figure 4, the rate transition matrix Q as shown below can be obtained.

\[
Q = \begin{pmatrix}
    0 & 1 & 1 & 2 & 2 & 3 & 3
    \mu & \psi & \delta & \psi & \delta & \psi & \delta
    \end{pmatrix}
\]

The stability equations for a rate transition matrix are

\[
\pi Q = 0 \quad \text{and} \quad \Sigma = 1
\]

where \( \pi = [\pi_0, 0, \pi_1, 0, \pi_1, 1, \pi_2, 0, \pi_2, 1, \pi_3, 0, \pi_3, 1] \). From this we can obtain the steady state probabilities in each of the 7 states, from which the availability of one stage in a route is given by

\[
A_i = \sum_{n=0}^{\infty} \pi_n, i = 0, 1, 2, 3
\]

Cascading ‘n’ stages the availability of a route with ‘n’ stages can be calculated as \( [A_i]^n \).

**Route Failure Notification Time**

Route_failure_notification latency was calculated using equation 1, and values from table 3. In table 3, \( \tau_{trans} \) is the transmission time for a 64 byte control frame. We also evaluated route_failure_notification latency using an Opnet simulation model of tMANET with 3 access gateways with 30 mobiles and 50 mobiles. Comparison of results obtained via analytical and simulation models are provided in graphs 1 and 2.

**Performance Results**

We have restricted most of our study to mobiles within 7 hops from the gateway as it is difficult to assure QoS guarantees if the number of wireless hops is high, especially when traffic aggregates near gateways and creates a bottleneck [6].
Graph 4 shows the failure probability of the notification messages for various values of $\rho$. At 7 hops, there is a probability of 0.17 that a link failure message never makes it to the gateway. When the link conditions are good i.e. $\rho=0.9$ the failure probability is negligible. The set of plots in graph 4 were obtained using equation 4, where the failure probability will be 1 minus the success probability.

**Route Availability**

Table 4 gives the parameter values that were used for the calculation of route availability. Route availability was evaluated for various mobile arrival rates ($\mu$) and departure rates ($\lambda$) and also for varying link qualities ($\delta$). The arrival and departures were varied proportionally and some interesting observations made when the relative mobility of the mobiles was reduced.

<table>
<thead>
<tr>
<th>R</th>
<th>M</th>
<th>$\mu$/sec</th>
<th>$\lambda$/sec</th>
<th>$\delta$/sec</th>
<th>$\phi$/sec</th>
<th>$\psi$/sec</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>1</td>
<td>0.05, 0.025</td>
<td>0.01, 0.005</td>
<td>0.005, 0.01</td>
<td>100</td>
<td>1000</td>
</tr>
</tbody>
</table>

Graph 5 shows the route availability, when the mobiles had 3 routes, one primary and two backup. A mobile 7 hops from the gateway has route availability of 0.88 for a poor link ‘$p_{link}$’ ($\delta=0.01$/sec) and 0.92 for a good link ‘$g_{link}$’ ($\delta=0.005$/sec). This was recorded for $\lambda=0.01$/sec and $\mu=0.05$/sec, which we call normal mobility conditions and indicated by plots labeled ‘n_mob’. We reduced $\lambda$ and $\mu$ proportionally to 0.005/sec and 0.025/sec respectively (plots labeled ‘l_mob’ for ‘low mobility’), which resulted in the route availability for the 7th hop mobile drop to 0.8 and 0.75 for a good link and a poor link respectively. This is because when the mobility rate drops it becomes comparable to the link failure rate, and the link failures predominate. During the steady state analysis it was observed that with lower mobility rates the system seemed to reside more in states 2,0 and 1,0 (see figure 4). (In the graph the plots for n_mob_p_link and l_mob_g_link coincide and are not seen distinctly.

From our simulation studies with 3 access gateways and 30 mobiles, it was noted that we did not have mobiles which were farther than 5 hops from a gateway and most mobiles had 3 routes. This would result in a route availability of 0.91 to 0.94 for normal mobility, 0.87 to 0.92 for low mobility for the 3 route case.

To illustrate the significance of the backup routes proposed in MMT, graph 6 shows the plot for 2 routes and 1 route compared with 3 routes. For the 3 and 2 route cases we have shown the plots for $g_{link}$ and $p_{link}$ but for the one route case, there was hardly any difference because when the link fails, the recovery is completely dependent on $\phi$, the link revival rate and not on the route switchover rates. When the mobiles have 2 routes, the route availability is till around 0.7 for mobiles 7 hops from the gateway, but for the one route case, the route availability drops exponentially with the number of hops a mobile is away from the gateway. However the simulations showed that most mobiles acquired more than 3 routes and in very few cases some mobiles had 2 routes, for a short duration. Under such circumstance good route availability can be guaranteed with MMT for tMANETs within the limitations of the simulation scenario. However this depends also on the density and the mobility patterns of...
the mobiles, which factors have not been considered in this study.

B.1 Number of Routes

From the simulations conducted with 30 and 50 mobiles with 3 access gateways, it was found that in the 30 mobiles case, there were 25 mobiles with 3 routes and 5 mobiles with 2 routes. For the 50 mobiles case, on average there were 47 mobiles with 3 routes and 3 mobiles with 2 routes. However for the 50 mobiles case we had mobiles which were 7 hops away but for the 30 mobiles case most mobiles were within a 5 hop limit. This shows the capability of the MMT to provide redundant routes and thereby enhancing the route robustness of the tMANET.

VI. CONCLUSIONS

The proposed MMT routing scheme provides very good route robustness. With 3 gateways it is able to support most mobiles within 5 hops, provided we restrict the number of mobiles to 30. From the simulation statistics, most of these mobiles easily acquired 3 routes and on very rare occasions a mobile had 2 routes. The route availability plots show that for 3 or 2 routes the route availability is as high as 0.8-0.92 for 5 hop mobiles. However lack of redundant routes deteriorates the route availability considerably. Redundant routes supported by MMT thus result in high route availability. We also evaluated the route notification delay, a very important performance parameter for MMT based routing, both from analytical and simulation models and have shown the low values for this latency, which proves the enhanced route robustness of MMT.

REFERENCES