

# RELIABLE AND EFFICIENT PACKET FORWARDING BY UTILIZING PATH DIVERSITY IN WIRELESS AD HOC NETWORKS

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## ABSTRACT

*It is critical to provide high-rate, reliable and energy efficient wireless communications in mobile ad hoc networks. The use of path diversity is a promising way to achieve this objective. However it requires careful cross-layer design. In this paper, we present a new cross-layer approach based on AODV and 802.11 MAC to utilize the local path diversity.*

## INTRODUCTION

Providing high-rate, reliable and energy efficient wireless communications in mobile ad hoc networks is challenging. A wireless link may easily suffer channel variations due to fading, shadowing, interference, user mobility as well as node failures. The effects of channel variations on routing and forwarding can be roughly decomposed into two categories with different timescales, flow level link breakage and packet level transmission failures.

Flow-level link breakage can be caused by user mobility and node failure (e.g., power-off). When a link breaks, routing re-discovery is necessary to complete data delivery. Re-routing is costly since it is usually flood-based and system-wide in mobile ad hoc networks. Most of the traditional multi-path routing schemes [3] [4] [5] were proposed to address the flow-level link breakage.

Recently, small scale channel variations, which are normally on the packet level, draws more and more attention. Due to time-varying fading, shadowing and interference, a packet may fail in transmission from one node to its intended neighbor with non-negligible probability. To reliably forward the packet, it may take several times to transmit, which introduce undesired delay as well as the waste of energy. Furthermore, when a wireless link experiences long-duration fading and a packet fails in transmission over certain times, the link may be falsely considered as broken even as the receiver is still in the average transmission range of the transmitter. False alarm of link failure will unnecessarily result in end-to-end route re-discovery [10]. As

demonstrated by [12], TCP, which is widely implemented in wired networks, performs very bad in mobile ad hoc networks because of the link error, frequent route breakage as well as out-of-order delivery [12].

One of useful approaches to combating small-scale channel variations is the use of path diversity in the link layer. Considering there are multiple next-hop nodes which have routes to the destination, the source or an intermediate node, may choose one of the alternative next-hop nodes which have good instantaneous link qualities to forward an arriving packet. Note that it is necessary for routing layer and MAC layer to work cooperatively to exploit the benefits of opportunistic packet forwarding. Traditional routing protocols [3] [4] [5] [6] and MAC protocols [1] cannot work well to utilize the path diversity because these schemes are designed separately with each other. To utilize the path diversity in the link layer, several papers [7] [8] [9] [10] have been presented recently to address related cross-layer-design issues.

However, some fundamental problems are still not well addressed. Firstly, it is desirable to use a good metric [11] and a good distributed algorithm to evaluate the "cost" of a path. The "hop count" used in the traditional routing schemes may not be a good one since it does not consider packet failures and necessary link-layer retransmissions, thus may not reflect the actual cost.

Secondly, it is desirable that all the alternative paths have the similar cost. Imagine that if the average costs of delivering a packet from alternative next-hop forwarding nodes to the destination are much higher than that of the primary forwarding node, it is better to retransmit failed packet to the primary forwarding node rather than anycasting the packet to one of the alternative nodes.

The other open issues include the out-of-order delivery and inter-flow contention introduced by utilizing the path diversity. The out-of-order delivery is harmful, especially for TCP traffic. The inter-flow contention can decrease the channel efficiency. These two problems are not easy to resolve. However, if we use the local path diversity rather than the system-wide path diversity, we may alleviate these

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problems.

With all the aforementioned tradeoffs in mind, in this paper, We limit the alternative forwarding nodes of current hop to those which are neighboring to the primary forwarding nodes of both the last hop and the next hop. By counting the local path diversity gains, a new distributed routing scheme is proposed to find the most cost efficient primary path in the sense that the average times of packet transmission (in the link layer) to reliably forward packets from the source to the destination is smallest. After a primary path is discovered, we provide a cooperative forwarding scheme, which is based on 802.11 MAC, to utilize the local path diversity in the MAC layer. So packets can be opportunistically forwarded to one of the alternative next hops according to the instantaneous link qualities.

In this way, we utilize the path diversity to reliably forward packets with the least cost while alleviating the out-of-order delivery problem and the multiple flow contention problem which are present in traditional path routing and forwarding schemes. Our analytical results show our scheme can significantly reduce end-to-end delay and improve end-to-end throughput.

The rest of the paper is organized as follows. Section II illustrates our motivation. Section III presents our routing scheme. Section IV discusses the cooperation of the MAC layer. The performance is evaluated in Section V. Finally, Section VI concludes our paper.

## ILLUSTRATION

In this section, we detail our motivation by an example. Fig. 1 shows a grouped distributed ad hoc networks. From the source to the destination, there are two virtual paths. Virtual path 1 consists of  $S \rightarrow G1\{1\} \rightarrow G2\{2\} \rightarrow D$ . Virtual path 2 consists of  $S \rightarrow G3\{3, 4\} \rightarrow G4\{5, 6, 7\} \rightarrow D$ . There is only one candidate forwarding node in each hop along virtual path 1. However, there are two candidate forwarding nodes, i.e., node 3 and 4, in the first hop of virtual path 2 and there are three candidate forwarding nodes, i.e., node 5, 6 and 7, in the second hop of virtual path 2. Obviously, virtual path 2 is more robust and the cost of packet forwarding is less in comparison with virtual path 1.

There are two basic issues needed to be addressed. The first issue is to find out the most cost efficient virtual path, in which each hop has a primary forwarding node and several alternative forwarding nodes. The second issue is how to enhance the 802.11 MAC to provide opportunistic MAC layer anycasting under the guidance of routing preference. For example, the source should forward packet to either node 3 or node 4 but not node 1. Node 3 or node 4 should

TABLE I. Notation

Notation	Meaning
$N_i$	The set of the neighbors of the primary forwarding node of the hop $i$
$PF_i$	The primary forwarding node of the hop $i$
$AP_i$	The set of all the candidate forwarding nodes of the hop $i$
$f_{i,j}$	The average fade probability of the link $(i, j)$
$C_i$	The cost of data forwarding from the source to hop $i$
$c_{i,i+1}$	The cost of data forwarding from the $i^{th}$ hop to its next hop
$P_{i,j}$	The probability that a packet is forwarded via node $j$ given it is forwarded via hop $i$

know there are three candidate forwarding nodes (i.e., node 5, 6 and 7) in the next hop and should choose one of candidate forwarding nodes with good instantaneous link qualities to deliver an arriving packet.

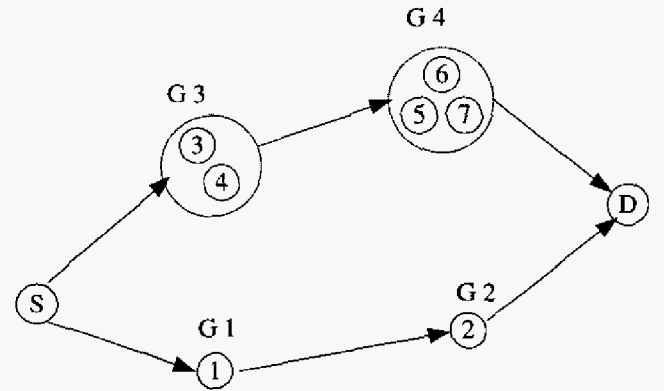


Figure 1. An example of cooperative routing and forwarding

## AD HOC ON-DEMAND ROUTING

We base our routing scheme on AODV [2]. We assume each node sends hello messages periodically to maintain local connectivity. The hello message contains the IP addresses of its neighbors and the average fade probabilities of corresponding links. Thus each node keeps two hop information which includes the addresses of its first hop neighbors and the average fade probabilities of the links between this node and its first hop neighbors, the addresses of its second hop neighbors and the average fade probabilities of the links between the first hop neighbors and the second hop neighbors. Table I shows some notations we used in this paper.

### A. ROUTING DISCOVERY

Whenever a source node needs to communicate with another node, it initiates the route discovery process if it has no routing information in its table for that node. Similar to

TABLE II. RREQ sent by the primary forwarding node of hop  $i$

source address
source sequence number
broadcast id
destination address
destination sequence number
IP address list and packet forwarding probability list of all candidate forwarding nodes of hop $i - 1$ in which the first item is that of the primary forwarding node
cost from the source to the hop $i - 1$

AODV, the source node initiates route discovery by broadcasting a route request (RREQ) packet to its neighbors. The RREQ sent by the primary forwarding node of hop  $i$  contains the fields shown in Table II.

The difference between RREQ of our scheme and that of AODV is the last two fields. Since the average (re)transmission times needed to successfully forward a packet from one node to its neighbor is link-quality dependent, hop count cannot accurately represent the cost of forwarding a packet along a route path. Thus we use the average times of packet forwarding (including failure times) rather than hop-count to represent the cost to reliably transmit packets from the source to the destination.

To calculate the average cost of forwarding a packet between two neighboring hops, say hop  $i - 1$  and hop  $i$ , the information of  $AF_{i-1}$ ,  $P_{i-1,j}$  ( $j \in AF_{i-1}$ ) and  $AF_i$  is required. The primary forwarding node of hop  $i$  (except the destination) does not know all the alternative forwarding nodes of hop  $i$  when receiving RREQ because the primary forwarding node of hop  $i + 1$  is unknown. The cost of data forwarding from the hop  $i - 1$  to the hop  $i$  is left to the primary forwarding node of the hop  $i + 1$  to calculate. The primary forwarding node of the hop  $i + 1$  knows alternative forwarding nodes of hop  $i$  by checking the available two hop information. The IP address list and packet forwarding probability list of all candidate forwarding nodes of hop  $i - 1$  is required by the primary forwarding node of hop  $i + 1$  to calculate the cost of packet forwarding from hop  $i - 1$  to hop  $i$  and the packet forwarding probabilities of all candidate forwarding nodes of hop  $i$ , so they are included in RREQ of hop  $i$  for re-broadcasting.

The primary forwarding node of hop 0, i.e., the source sets the second last field of RREQ as the broadcast IP address and the last field as 0. The primary forwarding node of hop 1, i.e., the neighbor of the source sets the second last field of RREQ as the source IP address and set the last field as 0. The method for the primary forwarding nodes in the following hops to calculate the cost from the source to the last hop is shown as follows. The cost from the source to

the hop  $i$  is

$$C_i = \sum_{j=0}^{i-1} c_{j,j+1}, \quad i \geq 1 \quad (1)$$

$$c_{i,i+1} = \sum_{j \in AF_i} P_{i,j} \frac{1}{1 - \prod_{k \in AF_{i+1}} f_{j,k}} \quad (2)$$

where  $AF_i = N\{i - 1\} \cap N\{i + 1\}$ . For all  $j \in AF_i$  and  $i \geq 1$ , there exists

$$P_{i,j} = \sum_{m \in AF_{i-1}} P_{i-1,m} (1 - f_{m,j}) \prod_{l \in AF_i, o(l) > o(j)} f_{m,l} \quad (3)$$

where  $o(l)$  is the relative forwarding priority of node  $l$  among candidate forwarding nodes of hop  $i$ , which may be derived based on the average link quality. For example, the lower average fade probability, the higher priority. When  $i = 0$ , all packets are transmitted from the source, so  $P_{0,0} = 1$ .

Normally an intermediate node will update the last two fields of RREQ, re-broadcast RREQ and keep track of necessary information in order to implement the reverse path setup, as well as the forward path setup that will accompany the transmission of the eventual RREP:

- Destination IP address
- Source IP address
- Broadcast\_id
- Expiration time for reverse path route entry
- Source node's sequence number
- IP address list of all candidate forwarding nodes of the last hop in which the first item is that of the primary forwarding node.
- IP address list of all candidate forwarding nodes of the next-to-last hop in which the first item is that of the primary forwarding node.
- Cost from the source to the last hop.

Notice that a node may receive multiple copies of the same RREQ from various neighbors. When an intermediate node receives a new RREQ with the same broadcast\_id and source\_address, it drops the redundant RREQ if the cost from the source to the last hop (calculated in the current hop) is higher than the recorded one. If the cost is smaller than the recorded one and if the RREQ arrives before the intermediate node receives RREP, the intermediate node takes the same operation as it does when it initially receives the same RREQ, i.e., updating the last two fields of RREQ, re-broadcasting RREQ and keeping track of necessary information. If the cost is smaller than the recorded one and if the RREQ arrives after the intermediate node receives an RREP, the intermediate node will create a new RREP

TABLE III. Format of RREP received from hop  $i + 1$ 

IP address list of all candidate forwarding nodes of hop $i$
source address
destination address
destination sequence number
IP address list of all candidate forwarding nodes of hop $i + 1$
cost from hop $i$ to the destination

and send it to the neighbor from which the new RREQ is received.

The destination creates a RREP and propagates the RREP to the source when receiving the first RREQ. When it receives further RREQ, it creates a new RREP and propagates the RREP to the neighbor from which it receives the new RREQ only if the new route path has smaller cost.

An intermediate node may receive more than one RREPs. It propagates the later RREPs along the updated reverse path since the new path has smaller cost.

The operations to set up reverse path and forward path are similar as AODV except that all the alternative forwarding nodes also need to set up the forward path. Each candidate forwarding node of hop  $i$  (it is still numbered starting from the source node) will receive a RREP, which contains the information shown in Table III, from the primary forwarding node of hop  $i + 1$ . Notice the RREP in the original AODV is unicast. The primary forwarding node of each hop in our scheme uses MAC layer multicast to send RREP to all candidate forwarding nodes of the last hop. Only the primary forwarding node should transmit the RREP to the last hop. With IP address list of all candidate forwarding nodes of hop  $i + 1$ , all the candidate forwarding nodes of hop  $i$  can set up forward routing entries.

In the AODV, if the RREQ's sequence number for the destination is smaller than that recorded by the intermediate node, the intermediate node can send a reply packet (RREP) back to its neighbor from which it receives the RREQ. We keep it as an option.

Once the source receives a RREP, it can start to transmit data. The source may receive another RREP with lower cost. In this case, the source may choose the new path to transmit data in the future.

## B. ROUTE MAINTENANCE

After the route discovery completes, the routing table entries are created as shown in table IV.

When an alternative forwarding node of hop  $i$  joins, the primary forwarding node  $i + 1$  will help the new node to create a routing entry for packet forwarding. Each candidate forwarding node of hop  $i - 1$  will add the newly joining node as another next hop forwarding node. When an alternative

TABLE IV. Structure of routing table entries

destination address
destination sequence number
IP address list of all candidate forwarding nodes of current hop
IP address list of all candidate forwarding nodes of next hop
IP address of the primary forwarding node of the second next hop
cost from the current hop to the destination
expiration.timeout

forwarding node of next hop leaves, it will be deleted from the route entry. When the primary forwarding node leaves, it handovers the functionality of local connectivity maintenance to another alternative forwarding node.

## COOPERATIVE FORWARDING

The basic idea of our cooperative forwarding protocol is as follows. When the source intends to send a packet or an intermediate node prepares to forward a packet, it checks the routing table and gets the list of candidate forwarding nodes of the next hop. Before transmission of the data packet, the source or the intermediate node multicasts (in the MAC layer) a channel probing message to all candidate forwarding nodes of the next hop. Each candidate forwarding node evaluates the instantaneous link quality based on the received channel-probing message. The candidate forwarding node with channel quality better than a certain level is granted to access the medium. Considering more than one candidate forwarding nodes may have good link qualities and are ready to receive data, a coordinating rule should be applied to avoid collisions. The channel-probing message includes a list of the media access priority of each candidate forwarding node. According to the announced channel access priority list, the qualified candidate forwarding node with the highest priority is ensured to access the channel first.

Now, we discuss how to implement the cooperative forwarding scheme over the CSMA/CA MAC. In the 802.11, the handshake of RTS and CTS is necessary for collision avoidance prior to the transmission of a long packet. Since the RTS used in 802.11 MAC is a unicast message in that only one receiver is targeted at. In our protocol, we use multiple candidate receiver addresses in the RTS and request those receivers in the receiver list to receive the RTS and measure the channel quality simultaneously. The wireless shared media with omni-directional antenna makes this mechanism possible without incurring much overhead.

A candidate forwarding node evaluates the channel condition based on the physical-layer analysis of the received RTS message. If the channel quality is better than a certain level and its NAV is zero, the forwarding node is allowed to transmit a CTS after deferring certain time. To avoid

collisions when two or more candidate forwarding nodes are qualified to receive data, a service rule is applied. The listing order of candidate forwarding nodes in the RTS announces the priority of the media access. Different Inter-Frame Spacings (IFSs) are employed to prioritize the candidate forwarding nodes. For example, the IFS of the  $n^{th}$  candidate forwarding node equals to  $SIFS + (n - 1) * Time\_slot$ . The candidate forwarding node with the highest priority among those who have capability to receive data packet would reply CTS first. Since all candidate forwarding nodes are within the one-hop transmission range of the sender and the carrier sensing range is normally larger than two hops of the transmission range, the CTS should be powerful enough for all other qualified candidate forwarding nodes to hear or sense. These lower-priority candidate forwarding nodes would yield the opportunity to the one transmitting CTS first.

If a lower priority qualified candidate forwarding node cannot hear or sense the CTS, it may send its own CTS before the higher priority one completes transmission of the CTS, thus causing a collision. However, this does not interfere with the correct operation of the proposed protocol. The sender can detect the collision and tell which candidate forwarding node of the next hop is the first one to reply the CTS. The sender will immediately send a unicast RTS to the qualified next-hop forwarding node who sends the CTS first after the collision ends.

## PERFORMANCE ANALYSIS

We present two sets of performance results. Firstly, we provide a simple model to analytically evaluate the packet delivery ratio, the packet forwarding cost and end-to-end packet transmission delay in a group-distributed chain network, where each group consists of several nodes. This simplified model demonstrates the potential of our approach. The second set presents simulation results based on ns-2, which includes more detailed protocol setup.

### A. ANALYSIS FOR A GROUP-DISTRIBUTED CHAIN NETWORK

Consider a group-distributed chain network as shown in Fig. 2. There are  $n$  intermediate forwarding groups between the source and the destination. The number of group members in each group is  $m$ . The fade probability of each link is  $p_f$ . The maximal retransmission number is  $\alpha$ . The packet transmission time of each hop is  $T$ .

The average packet delivery ratio is

$$P = (1 - p_f^{m\alpha})^n (1 - p_f^\alpha) \quad (4)$$

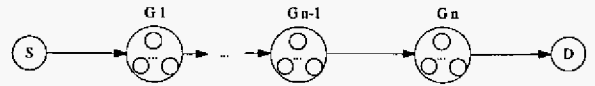


Figure 2. Group-distributed chain network

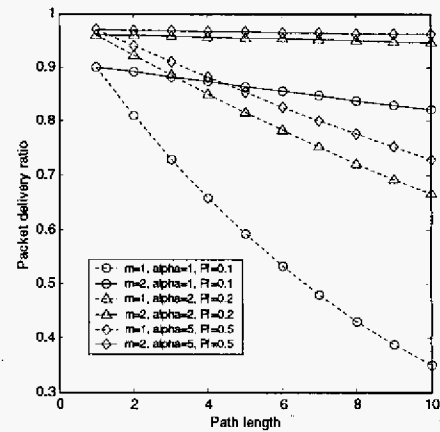


Figure 3. Packet delivery ratio

The average cost to successfully forward a packet is

$$C = n \sum_{i=1}^{\alpha} i (1 - p_f^m) p_f^{m(i-1)} + \sum_{i=1}^{\alpha} i (1 - p_f) p_f^{i-1} \quad (5)$$

The average delay for a successfully delivered packet is

$$D = CT \quad (6)$$

Fig. 3 presents the analytical results for packet delivery ratio. It is observed that the more alternative forwarding nodes, the higher packet delivery ratio. It also shows the longer path, the higher gains by using our scheme. Fig. 4 shows the analytical results for average cost to forward a packet given it has been successful delivered. It indicates that the gains of our scheme is high even with a small number of alternative forwarding nodes in each hop. Since the end-to-end packet transmission delay observes the same trend as that of the cost, we can easily find that our scheme reduces the end-to-end packet transmission delay significantly.

### B. SIMULATION RESULTS

In this section, we use ns-2 as the simulation tool to evaluate the performance of our protocol and compare it with the scheme of base rate IEEE 802.11 MAC plus single path routing. The topology we use is still group-distributed chain topology. The distance of each hop is 220m. The physical propagation model we use is Ricean fading model. The Ricean parameter  $K$  is set to 5 and the maximal velocity is set to 2m/s. The data packet size is set to 1000 bytes in all simulations and each reported result is averaged over

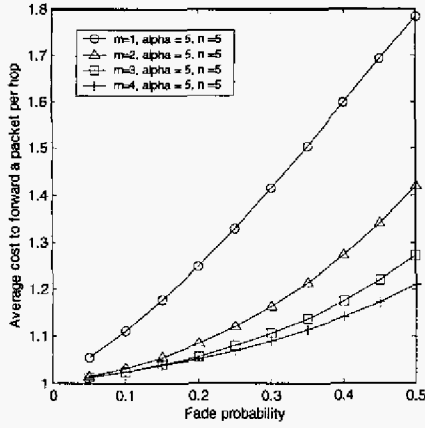


Figure 4. Average cost to forward a packet

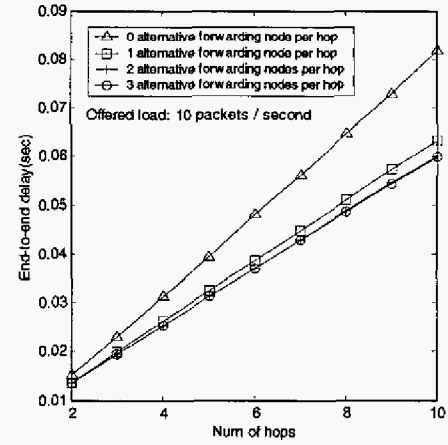


Figure 6. UDP delay when the offered load is 10 packets/sec

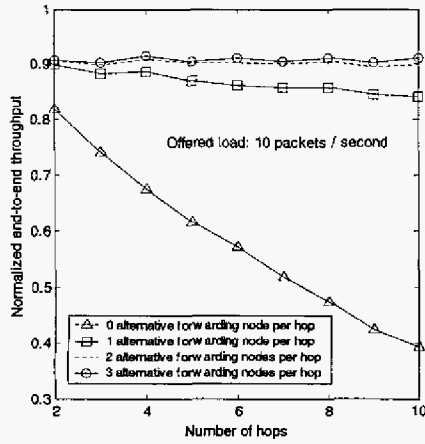


Figure 5. UDP throughput when the offered load is 10 packets/sec

10 300-second simulation results. Finally, all throughput results we provided are end-to-end data throughput.

As shown in Figs. 5, 6, 7, 8, 9, and 10, our approach can improve end-to-end throughput and reduce end-to-end delay significantly when input traffic is UDP. The normalized throughput is the ratio of total packets received by the destination divided by total packets sent by the source. Fig. 11 shows the TCP performance of our scheme. Since TCP is very sensitive to packet losses and our approach can improve the end-to-end reliability greatly, our approach outperforms the basic scheme which does not use the alternative forwarding nodes significantly.

## CONCLUSION

In this paper, we provide a scheme to utilize the local path diversity in improving the reliability and efficiency of packet forwarding in the multihop ad hoc networks. We build our scheme over AODV routing and 802.11 MAC.

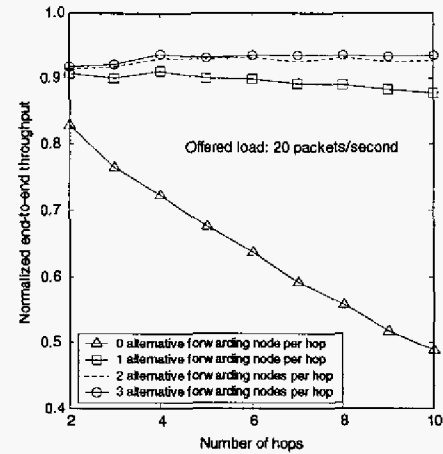


Figure 7. UDP throughput when the offered load is 20 packets/sec

Our analytical results and simulation results show that the packet delivery ratio, the energy efficiency, and the end-to-end throughput can be improved significantly, by the optimized cross-layer design.

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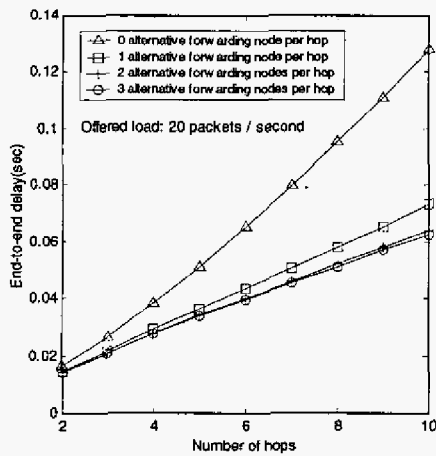


Figure 8. UDP delay when the offered load is 20 packets/sec

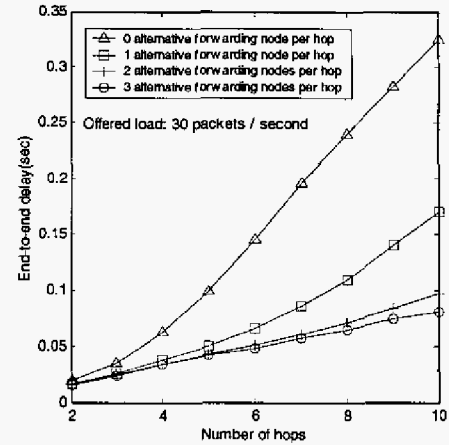


Figure 10. UDP delay when the offered load is 30 packets/sec

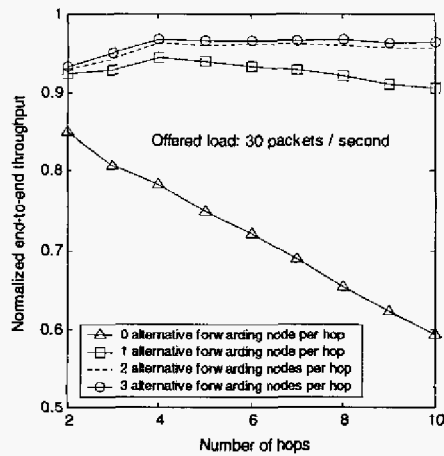


Figure 9. UDP throughput when the offered load is 30 packets/sec

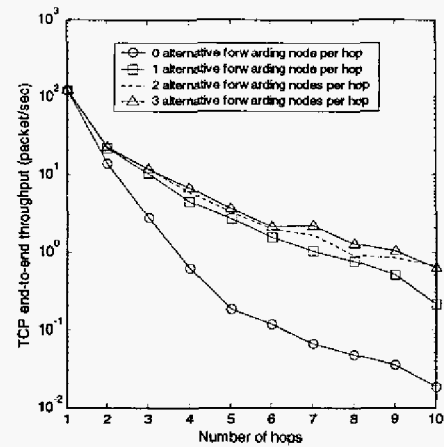


Figure 11. TCP throughput

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