Performance Analysis and Improvement of Express Forwarding in Wireless Mesh Networks

Jiazhen Zhou and Kenneth Mitchell
University of Missouri - Kansas City
Email: {jzmpc, mitchellke}@umkc.edu

I. Introduction

Metropolitan Wi-Fi based wireless mesh networks are being deployed in large cities such as Philadelphia, Houston, Taipei and Hongkong, to provide convenient Internet access for government and public users. However, since IEEE 802.11 was originally designed for single-hop communications, there are significant problems when it is used in multi-hop networks, among them are inefficient use of the medium, unfairness for long-hop flows [1], and high delay that makes it difficult to ensure QoS for nodes that are far from the gateways. Express forwarding [2], which has been proposed to the IEEE 802.11s Task Group, is a possible strategy for solving these problems.

The key idea of express forwarding is that the receiving node of a frame will not automatically backoff. Instead, it forwards the frame immediately toward the destination node.

As shown in [3] and [2], express forwarding is a good method to provide QoS since it can shorten the end-to-end delay especially for long-hop flows. However, existing work is limited to simulation studies, which prevents us from obtaining better insight on the benefits and disadvantage of express forwarding. More importantly, as shown in our work, express forwarding can be explored for improving the throughput and fairness.

The purpose of this work is to give a higher-level analysis of the benefits of express forwarding schemes. As seen from the definition, the intention of "express forwarding" is to build an "expressway" in mesh networks, which should have much higher efficiency and capacity than a "local road" built on the traditional backoff-before-forward mechanism. However, it still waits to be explored how effective an "expressway" can be built, especially when a single channel is used .

II. Basic Scenario

As the first step, a basic scenario has been studied: there are K nodes in a chain topology, with node 1 being closest to the gateway. Only the transmissions among mesh routers are considered, and the communications between mesh clients and mesh routers are omitted since they use different frequencies/channels. All K nodes are either neighbors or hidden terminals to each other. We assume an ideal collision avoidance mechanism. Also note that the carrier sense range is equal to the transmission range, thus there can be only one node transmitting at any time. Detailed analysis for this part can be found at: http://j.web.umkc.edu/jzmpc/ExpFrdBasic.pdf.

A. Analysis of effective throughput

To extend this work to a general topology, we take into account possible interruptions of express forwarding, and denote the probability that an intermediate node forwards a frame immediately as δ.

For $k = 1..K$, state k means the flow out of node k is transmitting, state 0 means all K nodes are in backoff. For the saturated load problem, it can be shown that a Markov chain can still be constructed. When each node has the same backoff rate, it can be shown that **each node gets the same portion of time (H_{EF}) to transmit to its next hop** despite the fact that an express forwarding can be interrupted. Denote μ and β as the rate for transmission and backoff respectively, we have:

$$H_{EF} = \frac{\beta}{\mu + \sum_{k=1}^{K} \sum_{i=0}^{k-1} \delta^i \beta}. \quad (1)$$

At each intermediate node, how to schedule the relayed and originating traffic is another important factor that affects throughput, fairness, and efficiency of the network. Two typical scheduling schemes proposed together with express forwarding are the priority queue scheme [3] and the single FIFO queue scheme [4].

The **effective throughput** for node k is defined as the traffic initiated by node k that eventually arrives at the gateway. For the priority queue scheme, *EffThr*$_k$ = $H_{EF}\delta^{K-k}$. For a FIFO queue, the unlimited local traffic will take almost all of the throughput at each node, thus node 1 achieves $H_{EF}\frac{1-\delta^K}{1-\delta}$ as it uses all of

Schemes	Efficiency	Total Effective Throughput	Fairness Index
EF-PQ	1 - $\pi_{EF}[0]$	$H_{EF}\frac{1-\delta^K}{1-\delta}$	≈ 1
EF-FIFO	$H_{EF}\frac{1-\delta^K}{1-\delta}$	$H_{EF}\frac{1-\delta^K}{1-\delta}$	$\frac{1}{K}$
TF-PQ	1 - $\pi_{TF}[0]$	H_{TF}	$\frac{1}{K}$
TF-FIFO	H_{TF}	H_{TF}	$\frac{1}{K}$

TABLE I
COMPARISON OF FORWARDING SCHEMES

the throughput won by the upstream nodes through express forwarding. Other nodes virtually get no effective throughput.

For the traditional backoff-before-forward scheme, if a priority queue scheme is employed, the throughput of flow K is H_{TF}, and those of other flows are 0. If a single FIFO queue scheme is applied, only flow 1 can get effective throughput (H_{TF}). Here

$$H_{TF} = \frac{\beta}{\mu + K\beta} \tag{2}$$

B. Comparison of fairness, efficiency and total effective throughput

The **total effective throughput** is defined as the summation of effective throughput of all nodes in a mesh network. The **efficiency of mesh networks** is defined as the *portion of time used to transmit frames that successfully arrive at the destination.*

To measure the fairness of different scheduling schemes, Jain's fairness index [6] is used.

The comparison of different forwarding schemes is shown in TABLE I. Here "EF" represents express forwarding, "TF" means the traditional backoff-before-forward scheme. "PQ" and "FIFO" represent the priority queue and First-in-First-out queue scheme respectively. The effective throughput has been normalized with respect to the maximum continuous transmission rate.

From the above table it can be concluded that **the priority queue based express forwarding scheme has the best fairness, efficiency, and effective throughput**. The underlying reasons are:
(1) The express forwarding scheme enables each node equal chance to transmit frames to the destination rather than to the next hop. Thus the spatial bias is removed.
(2) The Priority queue scheme will prevent the already generated upstream frames from being dropped, thus the medium can be used more effectively.
(3) The upper bound of the total effective throughput for express forwarding can be derived as $\frac{2}{K+1}$, while for the traditional forwarding scheme it is $\frac{1}{K}$. Obviously express forwarding can guarantee better system throughput.

III. ONGOING/FUTURE WORK

A. Analysis on general topology

As shown above, express forwarding can help remove spatial bias in the basic scenario. However, it might not be as effective in a general topology since uneven interference will cause uneven throughput and new bias. As a first step of this work, the behavior of express forwarding will be modeled and the effectiveness of providing fairness and improving efficiency will be studied. Based on the analysis, methods about removing the negative effect of uneven interference through modifying current MAC protocols will be studied. For example, the random backoff behavior can be replaced by synchronized backoff and transmission.

B. Delay Analysis

Closed form expressions of delay similar to [5] are to be explored. The effectiveness of using express forwarding to provide QoS will be analyzed in detail.

C. Comparison with using IEEE 802.11e

The effectiveness on providing QoS guarantees and improving fairness will be compared between IEEE 802.11e and express forwarding.

REFERENCES

[1] S. Xu and T. Saadawi. " Does IEEE 802.11 MAC Protocol Work Well in Multi-hop Wireless Ad Hoc Networks?", *IEEE Communication*, June 2001

[2] M. Benveniste and K. Kaustubh, "Performance Evaluation of 'Express Forwarding' for a Single-Channel Mesh", *IEEE Doc 802.11-07-2454r1*, September 2007.

[3] A. Acharya and S. Ganu and A. Misra, "DCMA: A Label Switching MAC for Efficient Packet Forwarding in Multihop Wireless Networks" . *Selected Areas in Communications, IEEE Journal on*, vol. 24, no. 11, pp. 1995 - 2004, Nov. 2006

[4] D. Raguin and M. Kubisch and H. Karl and A. Wolisz, " Queue-driven cut-through multiple access in wireless ad hoc networks", *IEEE Wireless Communications and Networking Conference (WCNC)* vol.3, pp. 1909 - 1914, March, 2004

[5] J. Zhou and K. Mitchell, "A Delay Based Multipath Optimal Route Analysis for Multi-hop CSMA/CA Wireless Mesh Networks", *International Teletraffic Congress (ITC) 20*, Ottawa, June 17 - 21, 2007

[6] R. Jain, D.M. Chiu and W. Hawe, "A Quantitative Measure of Fairness and Discrimination for Resource Allocation in Shared Systems", *DEC Research Report TR-301*, 1984