The Head-of-Line Blocking Problem on Exposed Terminals in MANETs

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***Abstract*— In Mobile Ad Hoc Networks (MANETs), the hidden and the exposed terminal problems affect the throughput of the Medium Access Control (MAC) protocols. Several MAC schemes have been proposed to solve these problems by allowing the exposed terminals to send their packets concurrent with the on-going transmission. Due to their locations, the exposed terminals are likely to have data packets for neighbors that are temporarily unavailable to receive. This leads to the so-called head-of-line (HOL) blocking problem. In this work, we propose the Exposed Terminal Scheduling (ETS) technique to solve the problem. In the ETS scheme, all nodes collect the local topology and transmission information to make sure that they will not send to those temporarily unavailable nodes. The ETS Shuffle (ETSS) scheme is proposed to mitigate the problem when such local topology and transmission information are unavailable. Simulation results are presented to support the claimed benefits of the proposed techniques.**

I. Introduction

Mobile Ad Hoc Networks (MANETs) have been studied extensively recently due to their potentials of being deployed in various scenarios such as technical conferences, trade shows, exhibitions, and emergency communications. A MANET usually contains a collection of mobile hosts (or nodes) that are spread out in a region, in which these nodes roam and perform different communication tasks. Some of the unique properties of MANETs include the lack of central control and random interconnection topology [1].

Since information packets need to be delivered from one node to another through the use of the wireless communication channel, a Medium Access Control (MAC) scheme is required. The goal of MAC schemes is to use the channel efficiently and to maintain fair channel usage among competing nodes. MAC schemes such as ALOHA [2] and Carrier Sensing Multiple Access (CSMA) [3] have been proposed for wireless networks. However, some of these techniques suffer the hidden and the exposed terminal problems, as briefly summarized below [4]:

The hidden and the exposed terminal problems arise in the communications among nodes of a non-fully connected network. The hidden terminals are those nodes within the transmission range of the receiver but out of the range of the sender (i.e., they are "hidden" from the sender). When a CSMA-based MAC scheme is used, the hidden terminals may send their data (since they cannot hear the transmission from the sender), destroying the on-going reception at the receiver. In the illustrative network shown in Fig. 1, node H is a hidden terminal of the communication between nodes S and D. In Fig. 1, the large solid circle represents the transmission range of the sender, node S. The dashed circle represents the transmission range of the receiver, node D.

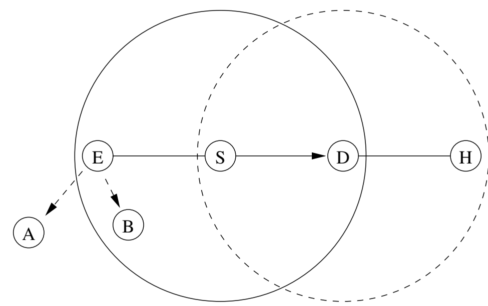

Fig. 1. Illustrations of the hidden and the exposed terminals.

Similarly, the exposed terminals are those nodes that are within the transmission range of the sender but out of the range of the receiver. Therefore, node E is an exposed terminal with respect to the communication from node S to node D.

In order to protect the on-going transmission and improve channel spatial re-use, the hidden terminals should not send on the channel and the exposed terminals should be allowed to re-use the channel. Some techniques achieve these goals, e.g., Receiver-Initiated Busy Tone Multiple Access (RI-BTMA) [5], Dual Busy Tone Multiple Access (DBTMA) [6], and Power Controlled Dual Channel (PCDC) medium access protocol [7]. Note that the exposed terminals are effectively not allowed to send data packets in IEEE 802.11 Distributed Coordination Function (DCF) [8].

With the use of the schemes such as RI-BTMA, DBTMA, and PCDC, the exposed terminals are free to transmit. Such transmissions will in fact increase the spatial re-use of the wireless channel. Unfortunately, even when the exposed terminals are allowed to transmit, they may be blocked by the head-of-line packets. This is because such packets may be destined to those nodes within the range of the current sender, and the intended receivers are unavailable to receive them. This is called the head-of-line (HOL) blocking problem.

In this work, we propose the Exposed Terminal Scheduling

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(ETS) technique to solve the problem. In the ETS scheme, all nodes collect the local topology and transmission information to make sure that they will not send to those temporarily unavailable nodes. The ETS Shuffle (ETSS) scheme is proposed to mitigate the problem when such local information is unavailable. Simulation results are presented to support the claimed benefits of the proposed techniques.

The paper is organized as follows: in Section II, we overview related work. The ETS and the ETSS schemes are presented in Section III. The performance evaluation results are provided in Section IV. We summarize and conclude this work in Section V, stating some possible future directions.

II. Related Work

In [9], Ray et al. investigated the Masked Node problem. The masked nodes are defined as those nodes within the communication range of the sender and the receiver but not overhearing the RTS/CTS packets. Such nodes are unaware of the on-going transmission. Any new transmission from such nodes may collide with the on-going communications. Different to [9], we focus on the exposed terminals that are allowed to send information in this work.

In order to improve the throughput and the fairness among contending nodes in MANETs, Eshet and Liang proposed the Randomly Ranked Multiple Slots (RRMS) scheme [10]. The RRMS scheme makes use of mini-slots and sequences of pseudo random numbers to maximize spatial reuse and to divide the throughput fairly among contending nodes. The RRMS scheme was further extended into the RRMS-BT scheme that used a receiver busy tone.

Shukla et al. proposed a method to mitigate the HOL blocking problem [11]. In this scheme, an exposed node initiates a parallel transmission by simply aligning its data transmission with the ongoing transmission. One problem with such an approach is that the transmission of the exposed terminal may still be sent to a blocked receiver, wasting the transmission.

In [12], Liu et al. investigated the starvation of low-priority traffic due to the high traffic load of the high-priority traffic flows. A "Courtesy Piggybacking" technique was introduced to exploit the channel dynamics and stochastic traffic features and to alleviate the conflict. The key feature is to let high-priority traffic to help the low-priority traffic by sharing unused residual bandwidth with courtesy. Practical methods were presented to estimate the ratio of unused-to-used residual bandwidth of the high priority traffic.

There are several works focusing on stochastic link failure [13], [14]. In [14], Kazantzidis and Gerla proposed to use the fragment acknowledgment and link-failure message (used for unicast traffic in IEEE 802.11 DCF [8]) to produce link-by-link (source, destination) pair throughput measurement. Then the sources send different traffic flow according to the permissible throughput estimate. Our approach is different to these in that we focus on the status of the intended receiver of the exposed terminals.

In [15], Bhagwat et al. proposed a Channel State Dependent Packet (CSDP) scheduling for networks with infrastructure such as base stations. The CSDP scheme defers the transmission to a certain terminal when the communication link associated with it is temporarily broken. Similar approaches were employed in [16], [17]. These schemes were designed for infrastructure-based WLAN and for good/bad two-state channel conditions. In this work, we focus on how to allow the exposed terminals to increase spatial re-use of the channel. Our approach is to identify the blocked potential receivers from other receivers.

Finally, our approach is similar to the approach employed in [18]. The main difference is that the scheme in [18] was designed for nodes with directional antenna. When directional antenna is used, a node may be permitted to send in some certain directions but not others.

III. The ETS and the ETSS Schemes

We present the details of the ETS and the ETSS schemes in this section. The ETS scheme requires additional information on two-hop neighborhood, especially the neighbor list of the current senders. The ETSS scheme, however, does not need any of such information. Instead, it uses a shuffle technique to mitigate the HOL blocking problem caused by the unavailability of an exposed terminal's intended receiver.

A. The ETS Scheme

In the ETS scheme, we assume that nodes broadcast their neighbor list to all immediate neighbors. Such broadcasts are similar to the HELLO messages used to maintain link states and can be scheduled periodically with an interval T. Adding randomness among the broadcasts from different neighbors will reduce potential collisions.

Denote the neighbor set of a node, u, as $\mathcal{N}(u)$. We assume that each node u has the knowledge of $\mathcal{N}(v)$ for each $v \in \mathcal{N}(u)$. In addition, each node u maintains a list of senders in its neighborhood as $\mathcal{S}(u)$, $\mathcal{S}(u) \subseteq \mathcal{N}(u)$.

We use node u to illustrate the ETS scheme. Node u maintains two queues: one for available receivers (AR); the other for blocked receivers (BR). We assume that the First-In-First-Out (FIFO) strategy is used when a data packet is added to a queue. Other queueing techniques might be used as well.

When a data packet arrives, node u checks the intended (one-hop) receiver of the packet. Denote the receiver as node v. The packet is put into the AR queue if node u does not find any node belonging to both $\mathcal{S}(u)$ and $\mathcal{N}(v)$, i.e.,

$$\mathcal{S}(u) \cap \mathcal{N}(v) = \emptyset \ . \tag{1}$$

Equation (1) represents that, to the best knowledge of node u, node v is not blocked to receive.

On the other hand, if there exists at least one node belonging to both $\mathcal{S}(u)$ and $\mathcal{N}(v)$, i.e., (1) is not satisfied, the packet will be stored into the BR queue.

Node u updates the two queues when it overhears the start of a new transmission or the end of a transmission. Basically, when a new transmission starts, those data packets in the AR

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queue that are intended to a node that is the neighbor of the new sender will be moved to the BR queue. On the other hand, when a transmission ends, those data packets in the BR queue that are intended to a node that is the neighbor of the sender, but not neighbors to any other local senders, will be moved to the AR queue.

Node u always picks the head packet of the AR queue whenever it gets a chance to access the channel.

B. The ETSS Scheme

In order to mitigate the HOL blocking problem without adding extra overhead and complexity to the data link layer, we propose the ETSS scheme herein. In the ETSS scheme, only one queue is maintained. When the channel request (such as the Request-To-Send, RTS, packet in [4]) is unsuccessful for a data packet, the data packet is inserted to the end of the queue and the next data packet in the queue with a different intended destination is chosen and processed. Such a "shuffle" technique is likely to initialize a transmission without requiring extra state information exchange among neighboring nodes.

IV. Performance Evaluation

We used Matlab to construct a simulator and to evaluate the performance of the proposed techniques. Traffic generations are periodic unless specified otherwise. All traffic has been normalized against the data rate of the channel. Therefore, traffic load of 1 means that the traffic will saturate the channel.

In the following performance evaluations, we ignore potential packet collisions that are normally present at data link layer. We argue that such collisions will degrade the throughput performances of regular scheme and the ETS/ETSS scheme with similar ratio. Therefore, the conclusions observed from this section still hold even if we consider packet collisions.

We simulate two network scenarios: a fixed network and a random network. The ETS scheme is used in the fixed network scenario and the ETSS scheme is used in the random network scenario. We ignore the neighbor list broadcast overhead in the ETS scheme. Such random broadcasts take place very rarely and only add a small amount of overhead to the total traffic. In some routing schemes, these broadcasts may be piggybacked on the HELLO message broadcast as well.

A. Fixed Network

In this subsection, we investigate the performance of a fixed network as shown in Fig. 2. There are five nodes staying on a line. Node 2 has traffic to send to nodes 1 and 3. Node 4 only has traffic to send to node 5. Note that both nodes 2 and 3 are in the transmission range of node 4. Denote the traffic from node i to node j as $\lambda_{i,j}$, where $1 \leq i, j \leq 5$.

In Fig. 3, we show the throughput of several individual traffic flows. The traffic load is set and changed in the following way: $\lambda_{4,5} = 1$, $\lambda_{2,1} = \lambda$, and $\lambda_{2,3} = 1 - \lambda$. The change of λ represents different portion of traffic from node 2 for node 1. From Fig. 3, we can see that the use of the ETS scheme increases the throughput of both flow $2 \rightarrow 1$ and

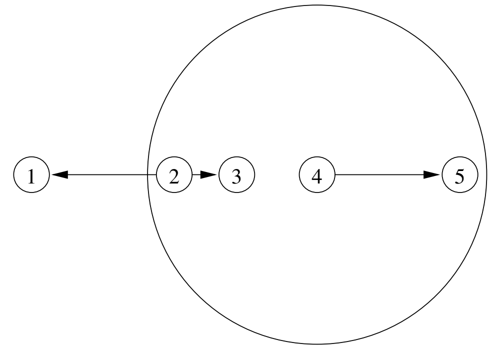

Fig. 2. Illustrations of one-dimension fixed network.

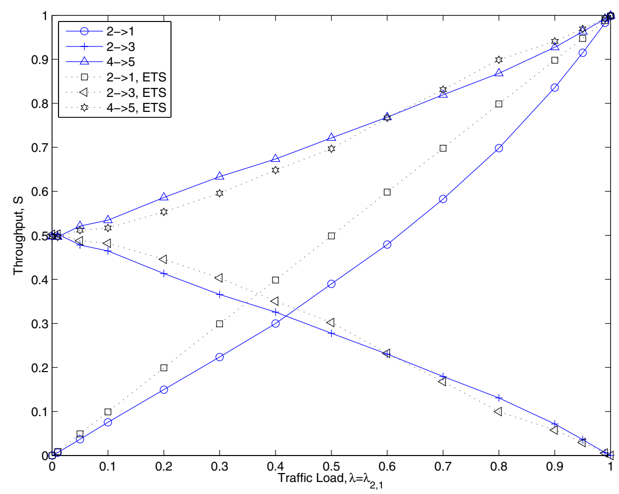

Fig. 3. Throughput of different traffic flow for one-dimension fixed network.

$2 \rightarrow 3$ significantly, with the throughput of data flow $4 \rightarrow 5$ slightly lowered. The throughput increase of flow $2 \rightarrow 1$ is more significant.

One other noticeable result is that, as $\lambda_{2,1}$ increases, the throughput of $2 \rightarrow 3$ with the ETS scheme becomes slightly lower than that without ETS, leading to the throughput of $4 \rightarrow 5$ slightly higher when ETS is used. The cross-over takes place at $\lambda = 0.6$. Similar results may be observed in Figs. 4 and 7.

We present the total throughput sent by nodes 2 and 4, respectively, in Fig. 4. We can see that throughput increase of node 2 depends on λ. The increase is higher, at about 20%, when λ is around 0.5, i.e., when node 2 has relatively equal traffic for nodes 1 and 3.

In Fig. 5, we fixed the traffic load $\lambda_{2,1} = \lambda_{2,3} = 0.5$ and changed the traffic load $\lambda_{4,5}$. The network supports all traffic when $\lambda_{4,5} < 0.5$. As $\lambda_{4,5}$ further increases, the network without the ETS scheme suffers the unfairness problem, with the throughput of node 4 higher than 0.5 while throughput from node 2 to nodes 3 and 1 suffers significantly. With the help of the ETS scheme, the traffic from node 2 to node 1 is fully supported (0.5) and the throughput from node 2 to node 3 slightly increases. Note that the total throughput of $2 \rightarrow 3$

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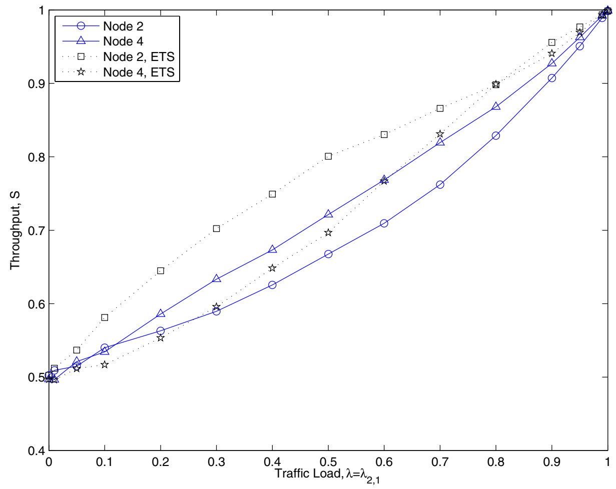

Fig. 4. Throughput of nodes 2 and 4 for one-dimension fixed network.

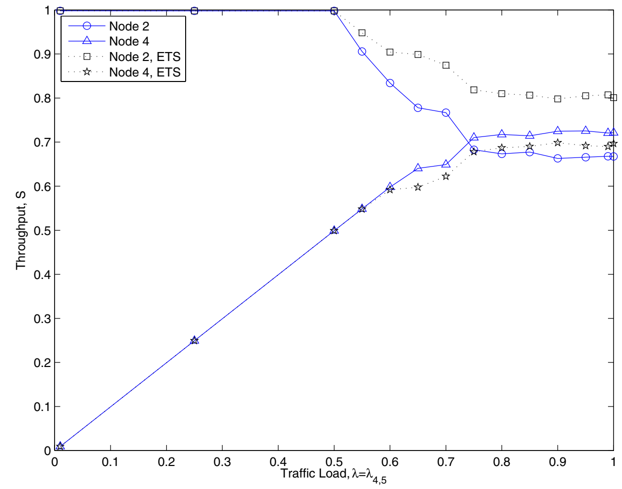

Fig. 6. Throughput of nodes 2 and 4 for one-dimension fixed network.

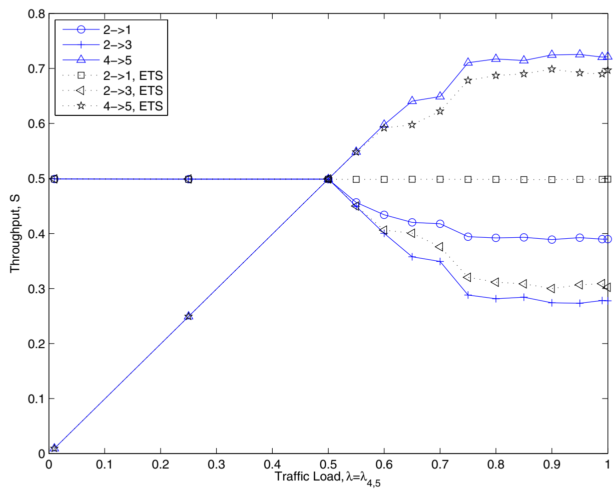

Fig. 5. Throughput of different traffic flow for one-dimension fixed network.

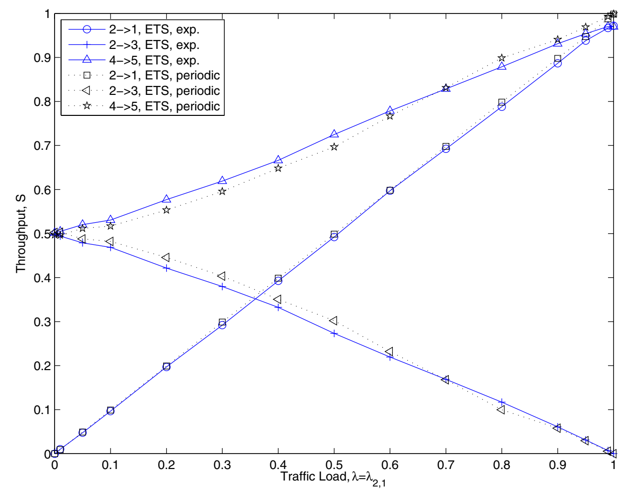

Fig. 7. Throughput of different traffic flows with different arrival pattern.

and $4 \rightarrow 5$ is at most 1 due to the local contention.

The total throughput of nodes 2 and 4 with or without the ETS scheme are compared in Fig. 6. With the ETS scheme, the throughput of nodes 2 and 4 stays at about 0.7 when λ is large. When ETS is used, a throughput increase of node 2 can be observed and that of node 4 stays at similar level. Note that the ETS scheme degrades the fairness between nodes 2 and 4. This, however, is mainly caused by the increase of node 2's throughput but not the decrease of node 4's throughput.

We compare the performance of periodic data packet arrival and Poisson packet arrival (with the same average arrival rate) in Fig. 7. This figure corresponds to Fig. 3. It can be observed that these two sets of results are very similar to each other, suggesting that the arrival pattern does not change our observations above.

B. Random Networks

In Fig. 8, random networks were investigated. The number of nodes in a 600×600 m^2 area is $N = 20$, 40, and 60, respectively. The transmission radius of each node is 100 m. The throughput of the entire network is depicted as a function of increasing traffic load, λ, that is generated from each pair of neighbors. The throughput of a network with ETSS scheme implemented is always higher than that of a network without ETSS. The performance gain depends on N, or node density. As N increases, the chance of initiating concurrent transmissions from the exposed terminals is higher, resulting in higher throughput. When N is 80, the performance gain is about 30%.

In order to compare the difference of throughput by different flows, we compare the standard deviation, σ, of throughput in Fig. 9. Some increases of σ caused by the ETSS scheme can be observed in Fig. 9, with the increase being more noticeable as N increases. Note that our focus in this paper is the aggregate throughput of the competing nodes in MANETs. With the use of the ETS and the ETSS schemes, spatial re-use in MANETs can be increased. Some insights on throughput and fairness can be obtained by comparing Figs. 9 and 6. Namely, the

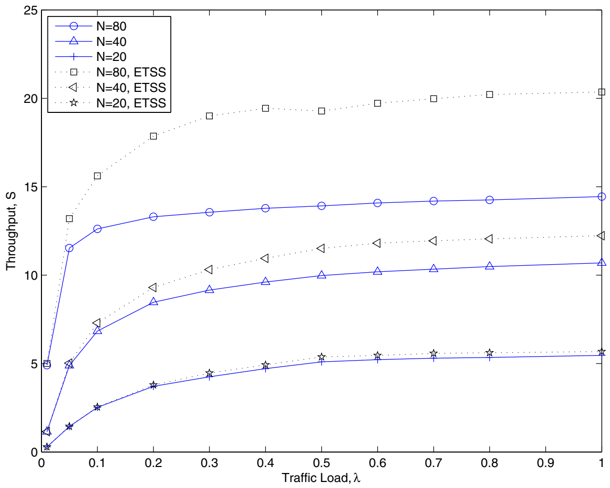

Fig. 8. Throughput of random network.

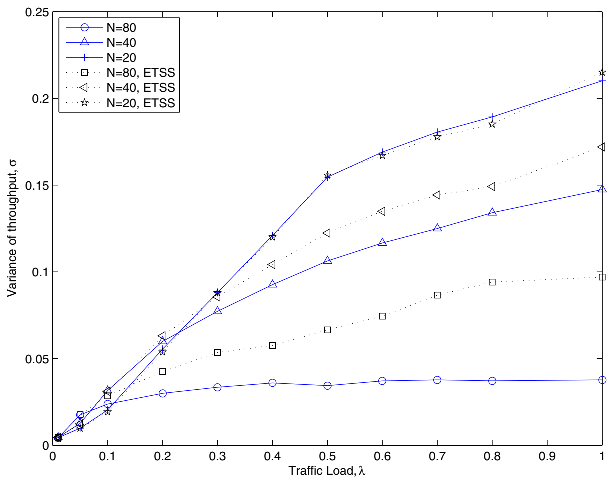

Fig. 9. Standard deviation of throughput of random network.

increase in standard deviation of throughput among different traffic flows is mainly caused by the throughput increase of some traffic flows.

V. Concluding Remarks

In medium access control (MAC) of MANETs, the hidden terminal and the exposed terminal problems render a low throughput of contending nodes in the network. Several MAC schemes have been proposed to solve these problems. Unfortunately, the potential transmissions of such exposed terminals will not succeed when the intended receivers are in the range of the current sender.

In this work, we have proposed and investigated a simple yet efficient way to take full advantage of such MAC schemes, making sure that such exposed terminals will re-use the channel. Our technique is to distinguish different status of the receivers of the exposed terminals. While some of the potential receivers in the exposed terminal's neighborhood may be blocked by the current sender, other receivers may be able to receive.

Our simulation results show that our technique improves the throughput by 10-30%. Some degradations of fairness among different users has been observed. This, however, is mainly due to the throughput increase of some nodes, by taking full advantage of the opportunity for transmission. In the future work, we plan to investigate the effect of partial information of topology and transmission schedule on the ETS scheme and to derive an analytical model for the proposed schemes.

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