Avoiding Bottlenecks Due to Traffic Aggregation at Relay Nodes in Multi-hop Wireless Networks

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Abstract— ***In multi-hop wireless networks all nodes are potentially routers, forwarding traffic on behalf of other users. Some scenarios (e.g. gateways to Internet, mesh networks) may lead to some nodes forwarding more traffic than others. When using IEEE 802.11 with RTS/CTS, these relay nodes become a significant performance bottleneck in the network. Previous research has attempted to overcome this bottleneck by giving priority to the relay nodes and implementing congestion control schemes. We propose a new scheme where a relay node avoids congestion by only responding to RTS frames when its receiving and forwarding rates are balanced. This avoids adverse affects of significant changes to the RTS/CTS scheme, and (as shown by simulations) provides significant throughput increases over ordinary RTS/CTS and almost equivalent throughput/delay as the other proposed schemes.***

I. INTRODUCTION

Multi-hop wireless communication is a flexible paradigm to rapidly deploy and to extend the coverage of dynamic networks such as ad hoc wireless networks, mesh networks and sensor networks. In multi-hop wireless networks, a source node may not be able to directly communicate with its destinations and may rely on intermediate nodes to transmit data. To share the common wireless channel, nodes may use random medium access control (MAC) protocols, such as IEEE 802.11 [1], to contend for the opportunity to send data. Random MAC protocols are robust due to their distributed nature, however the mechanism of random channel contention often results in significant wastage of resources [2-4]. One property of random MAC protocols is to statistically provide equal chances of accessing a common channel for contending nodes. This property is desirable if traffic is evenly distributed among these nodes, as they would have equal chances to transmit data. However, this property can lead to inefficient channel sharing in some practical cases where multiple traffic flows are destined to a common node, for example, in mesh networks, where nodes would share a common gateway, and in sensor networks, where nodes send data to sinks. In these scenarios, traffic may aggregate at intermediate (relay) nodes, where contention between multiple sending nodes and a relay node would result in insufficient share for the relay node to forward its received data. This problem becomes more severe when the number of sending nodes and traffic load increase, resulting in performance degradation and, as a consequence, traffic congestion at the relay node.

Given that contention at relay nodes is a significant cause of performance degradation, various techniques [3-6] have been proposed to prioritize relay nodes' access to the channel or to reduce possible contentions. These approaches (described further in Section II.A) modify the operation of IEEE 802.11 RTS/CTS and backoff scheme to give the relay nodes greater opportunity to transmit. However, in addition to adverse affects of the RTS/CTS modifications, the transmission chance may still be limited in most cases, meaning the relay node cannot forward all packets, leading to congestion [4].

The congestion problem in a multi-hop wireless environment is addressed in several works with approaches from different layers [4, 7, 8] (described further in Section III.A). However, these schemes have drawbacks such as inefficient handling of traffic bursts and ignoring the contention at the MAC layer.

To resolve the problems of inefficient contention and congestion, we propose a new approach of allowing relay nodes to maintain the balance of its relaying activities, rather than aggressively compete against other nodes for channel access. By balancing its receiving rate close to forwarding rate, a relay node can efficiently contend for channel access, ensure that it is able to forward the arriving packets, and achieve its optimum performance. The balance is achieved by the relay node dropping RTS frames if the receiving rate is too high. We evaluate our scheme by simulations and show that our scheme, compared to 802.11 RTS/CTS, can improve the throughput by up to 100% and reduce delay in some scenarios.

The rest of this paper is organized as follows. In Section II, we review the 802.11 RTS/CTS scheme and explain how the traffic aggregation bottleneck occurs. Our new scheme is proposed in Section III, and simulations are used to analyse the performance in Section IV. Finally, we present conclusions and ideas for future work in Section V.

II. TRAFFIC AGGREGATION AT RELAY NODE

In this section, we briefly explain IEEE 802.11 with RTS/CTS scheme [1], which we assume is the baseline protocol used for multi-hop wireless networks[1]. We then explain how the traffic aggregation bottleneck arises when RTS/CTS is used.

A. IEEE 802.11 with RTS/CTS

The IEEE 802.11 MAC protocol [1] specifies how nodes share access to a common wireless medium. The protocol is based on Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) and applies the RTS/CTS access scheme to reserve the channel before transmitting data. In the RTS/CTS scheme, a node having a frame ready to transmit waits for a random period (according to a binary exponential backoff

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[1] Although there are many alternate MAC protocols for multi-hop wireless networks, it is reasonable to assume 802.11 RTS/CTS or its variances will be used in these networks due to its simplicity and widespread deployment.

algorithm) and then, if the channel is idle, begins the transmission procedure. The backoff algorithm reduces the probability multiple nodes repeatedly send at the same time and provides each node statistically equal chance of access the medium. The transmission procedure involves a four-way handshake (see Figure 1): Request To Send (RTS) sent to the intended recipient; Clear To Send (CTS) returned to the sender; the DATA frame being sent; followed finally by an ACKnowledgement. Both RTS and CTS frames contain the time required to complete the data transmission so that other nodes hearing these frames defer access for the indicated time. The RTS/CTS scheme reduces possible transmission collisions to collision of RTS or CTS frames, which are small in size, rather than collision of DATA frames, which are typically long in size. Although RTS/CTS introduces additional small overheads, this scheme is useful for reducing the number of hidden terminals [9], which may lead to significant performance loss in a multi-hop wireless network.

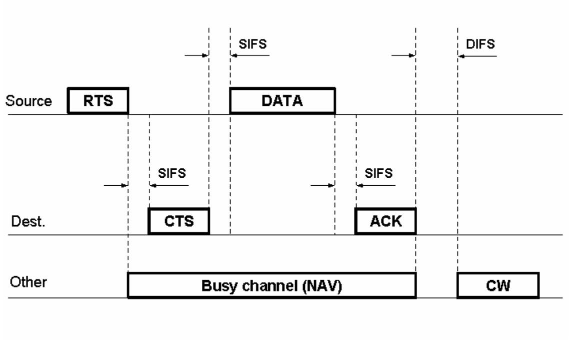

Figure 1: IEEE 802.11 with RTS/CTS scheme

B. Degradation of performance at relay node

In order to show how aggregation of traffic at a relay node leads to performance degradation in the network, we will describe a simple scenario, where the network topology is shown in Figure 2. There are N-1 source nodes sending data to M destinations via a single relay node. Assume the 802.11 RTS/CTS scheme is used, meaning all nodes within hearing distance equally share access to the channel.

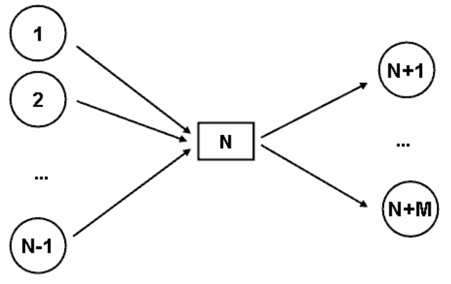

Figure 2: Multiple sources relay data through one relay node

Statistically, if the total sending rate of all source nodes is less than half of the channel capacity C, then the relay node effectively can use the “other half” of the channel capacity to forward data. Total throughput measured at M destination nodes is equal to the forwarding throughput of the relay node. This results in the maximum achievable throughput of C/2, i.e. neither source nor relay nodes must queue packets.

When the total sending rate of all source nodes is more than half of the channel capacity, the relay node will not be able to forward all packets it receives. Therefore the throughput, which is dependant on the forwarding rate of the relay node, will be less than the maximum throughput. At an extreme, with a high total sending rate, the relay node only has access to its share of C/N. This results in a forwarding rate, and throughput of C/N, much less the maximum achievable throughput when N is non-trivial.

It is clear that with several source nodes with moderate sending rates, the relay node becomes a bottleneck in network performance. This is due to the statistically equal access to the channel attributed to all nodes (sources and relay). Therefore, in order to maximize the relayed traffic, and hence network throughput, the traffic from sources should be limited to a level that the relay node can forward.

III. BALANCE RELAYING RATES TO IMPROVE SATURATED THROUGHPUT

A. Fast-relaying and congestion control

Berger et al. [3] and Zhai et al. [4] have addressed the problem of providing priority access to relay nodes in multi-hop wireless networks. Two schemes called *quick-exchange* and *fast-forward* are introduced in [3]. Quick-exchange permits a relay node to piggyback small payload packets in ACK frames of the RTS/CTS scheme. This is particularly suited to applications that have bi-directional data flows (e.g. TCP ACKs) as two DATA frames (the original, plus the piggybacked frame) can be sent within one channel reservation. For larger payloads, the fast-forward scheme can be used. This gives the relay node priority to extend channel reservation by using the ACK frame as an RTS frame. Zhai et al. [4] propose the OPET scheme as another method to give priority to the relay node. OPET allows a relay node to compete for channel access with an initially smaller contention window (CW). As specified in 802.11 RTS/CTS, all nodes must wait for a backoff period, which depends on the CW, before occupying the channel. By giving the relay node a potentially smaller backoff period, it obtains higher priority in winning access to the channel.

These fast-relaying schemes provide the relay node with better opportunity to forward packets. However, a shortcoming of these schemes is they may cause higher possibility of collisions in contending for the channel if there are multiple relay nodes competing for the channel. For example, consider Figure 3 where the *fast-forward* [3] is applied for nodes 1 and 3, which relay data from nodes 2 and 4, respectively, to node 0. After receiving data, relay nodes 1 and 3 do not follow the normal backoff procedure but immediately send a RTS to node 0. Thus these two requests would collide at a high probability if sources 2 and 4 transmit at high rates. In the OPET scheme, assigning a smaller initial CW for relay nodes (compared to the default CW used by other nodes) gives them higher priority, but unfortunately the probability of collisions may be very high if there are multiple relay nodes competing with the same small CW. Furthermore, packets may queue up then be dropped at the relay node, thus Zhai et al. [4] suggest to apply an additional congestion control mechanism.

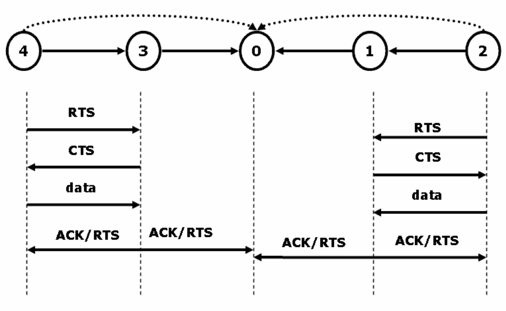

Figure 3: Possible collision with fast-forward

Congestion is observed at the network layer when the data queue builds up at a relay node. To resolve the congestion, Sundaresan et al. [7] propose to compute appropriate sending rates based on feedback from intermediate and receive nodes. However, as the channel may fluctuate over short periods of time, the feedback information, which is piggybacked on data packets that often traverse multiple hops, may not accurately reflect the current channel conditions. Zhai et al. [4] propose *backward-pressure scheduling* to keep sources from sending more packets than the relay nodes can support. A threshold, which is one queued packet per flow at each intermediate node, is applied to restrict transmission of sources. Congestion notification (Negative CTS frames) will propagate hop-by-hop to source nodes. This mechanism does not require explicit feedback (from congested node), which may contribute more traffic to the network. Nevertheless, the main disadvantage of this scheme is it inefficiently handles channel fluctuation and burst traffic. For example, the channel at relay node may be temporarily unavailable to forward but available to receive, resulting in at most one packet per flow is queued. Consequently, the relay node can forward only queued packets when the channel becomes available to send, then it must wait for the arrival of the next packets. It would be more desirable in this case to have more packets in the queue, thus more packets could make use of the good channel conditions.

B. Rate balance scheme

To overcome drawbacks of the existing schemes, we propose a new relay mechanism that permits a relay node to decide how it receives or forwards data to maintain the balance of relaying activities. The reasoning behind the balance strategy is a relay node can at most forward all received packets, thus by maintaining the balance, the relay node efficiently contends for the channel, performs at its best performance and avoids any congestion. Contention is efficient in the sense that the channel is equally divided for receiving and forwarding packets. The highest performance is achieved as the relay node forwards all packets that arrive. Congestion does not exist since the balance condition ensures that data queue at relay node does not arbitrarily increase.

We propose a rate balance scheme that controls the rate of incoming and outgoing traffic. The rates are computed at the network layer, and if there is an imbalance, the relay node temporarily ceases receiving packets. Packet reception is resumed once queued packets are sent. Denote r_{in} the receiving rate and r_{out} the forwarding rate[2]. The relay rate balance condition is satisfied with constraint Δr if:

$$\frac{r_{in} - r_{out}}{r_{out}} \le \Delta r \qquad (1)$$

The value of Δr should be close to zero in order to maintain the balance. The larger the value of Δr, the higher the difference between r_{in} and r_{out} (the more incoming traffic is favored in occupying channel) and as a consequence, the more packets will be queued at the relay node.

The interval Δt, which is used to measure the rates, also has a significant impact on the balance condition. Typically, the length of Δt is several times the time required to transmit a data packet. If Δt is too small, r_{in} and r_{out} will fluctuate greatly as only a few packets are counted. Consequently, the difference between these rates will become too large and it is difficult to keep Δr close to zero. With an appropriate Δt, the rate balance scheme can satisfy two contradicting requirements of (i) keeping a small difference between these rates to improve performance and, (ii) allowing relatively large difference between these rates (i.e. a large queue size in a short period of time) to handle traffic burst, which could be spread over Δt while averaging r_{in} and r_{out} on that interval. This advantageous capability cannot be found in a scheme that controls only the number of packets in the data queue.

Instead of allowing relay nodes to aggressively contend for the channel as implemented in existing schemes, which would potentially cause collisions, in our new scheme, relay nodes manage the balance of receiving and forwarding rates. However, the balance is achieved at the cost of more time required by relay nodes to increase their forwarding rate.

Another advantage of our scheme is its flexibility in setting control parameters, which could either be r_{in}, r_{out}, Δr or Δt. Our balance mechanism also implicitly provides hop-by-hop congestion feedback by dropping channel requests frames. Therefore, a node can only send as many packets as relay nodes can support, resulting in the stability of activities of nodes.

C. Controlling CTS response in 802.11 RTS/CTS

To allow a relay node to control its receiving rate, we propose to apply a simple modification of the receiving process in the 802.11 RTS/CTS scheme. From Section II.A the RTS/CTS scheme only allows the DATA frame to be send if a CTS frame is received. In our scheme, with the relay node monitoring its receiving and forwarding rates, it will only

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[2] Both r_{in} and r_{out} are only traffic that is forwarded by the relay node; it doesn't include traffic destined to or originating from the relay node.

respond to a RTS if the balance condition is maintained. In other words, if the relay node is receiving too much data, it will not send a CTS, effectively limiting the sending rate of the sources. This approach requires no modifications to the 802.11 frames and it is possible to have a network where most nodes implement the original 802.11 scheme, as long as the relay nodes implement our modified scheme. This is of benefit in that the enhancements can be deployed incrementally.

IV. EVALUATION AND SIMULATION RESULTS

In Section III we identified the advantages and disadvantages of the approaches for improving performance at the relay node, and proposed a scheme where the relay node balances its transmit/receive rates by its responses to RTS frames. Our scheme does not increase the possibility of collisions since it does not aggressively contend for the channel. In addition, we apply a rate balance scheme, which is more efficient in handling traffic bursts. One key criteria for the effectiveness of this scheme is that it provides improved performance over 802.11 RTS/CTS and performs at a level similar to that reported in [3, 4]. In this section we use simulations to evaluate our scheme in terms of average throughput and delay.

A. Simulation Setup

The aim of our simulations is to compare the network performance using 802.11 RTS/CTS (basic scheme) and our scheme (called rate balance) in selected scenarios (which are explained in the corresponding sections).

We perform the evaluation using Glomosim [10] with the following parameter values fixed across all simulations: the propagation path-loss model is two-ray; radio model is noise accumulation; channel bandwidth is 2Mbps; nodes use static routing with pre-computed routes; source nodes generate CBR/UDP sessions sending 1000-byte packets at various rates, which increase until network traffic is saturated.

For each scenario, we run 20 simulations (with different random seeds) for 60 simulated seconds. We plot simulation results of total end-to-end throughput and average delay versus total rate of CBR sessions. We plot performance of the RTS/CTS (basic) scheme with a dashed line and performance of our scheme (rate_balance) with a solid line.

B. Relaying performance

In the first scenario we are interested in seeing the difference between basic and our scheme in a simple network topology with up to five source nodes all sending data to a single destination via a relay node (as depicted in Figure 2, M = 1). The number of source nodes is varied to illustrate how the number of sources impacts on performance.

With the basic scheme, total throughput decreases when the number of sources increases (Figure 4). With our scheme, the total throughput significantly increases independent of the number of sources. This improvement is achieved by maintaining the rate balance, which allows the relay node to control its receiving rate and to increase its sending rates, keeping the total throughput close to the achievable throughput that the channel can support. However, higher average delay is observed using our scheme, which follows the strategy of giving more *time* instead of *higher priority* to the relay in order to counterbalance the forwarding rate. Therefore, packets spend more time queueing at the relay.

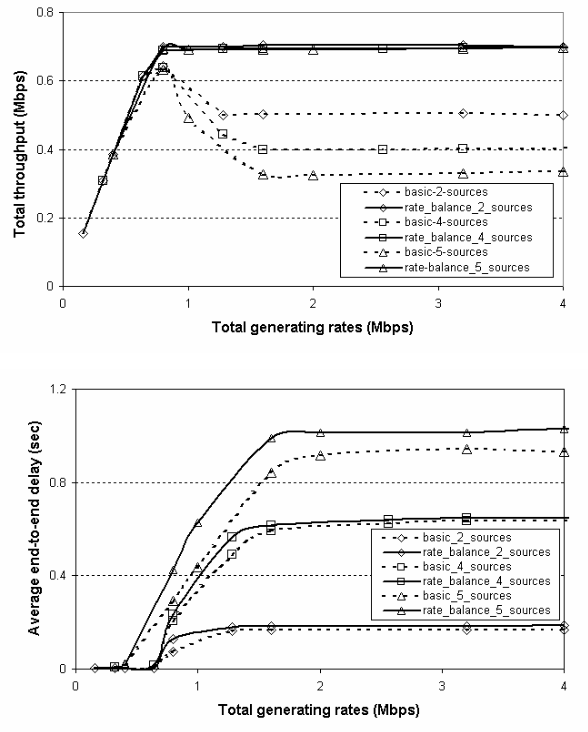

Figure 4: Relaying throughput and average end-to-end delay

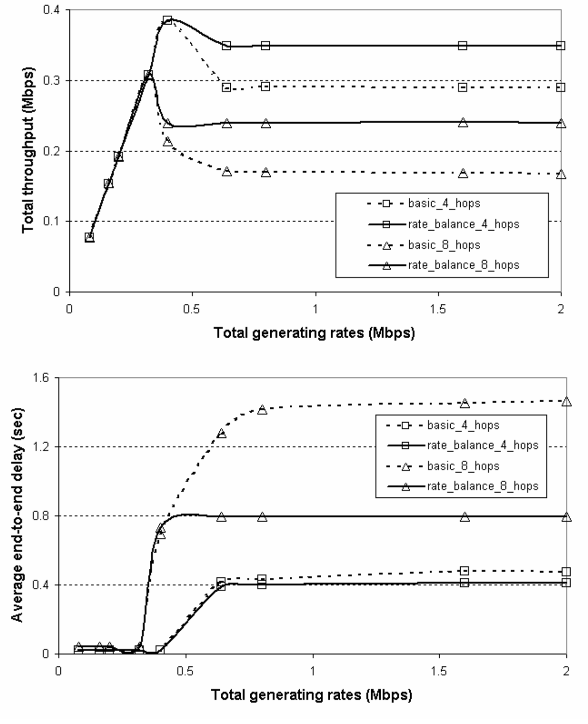

Figure 5: End-to-end throughput and delay in chain topology

C. *Relaying in chain topology*

In the second scenario, we are interested in comparing the difference in performance between basic and our scheme in a chain topology. Multi-hop transmission in such scenario is reported inefficient when increasing the number of hops [2]. We setup a chain topology and number of hops is selected to be 4 and 8 hops to give an indication of how the throughput decreases as the number of hops increases.

Simulation results (Figure 5) show that higher throughput is achieved in the two cases (20% and 40%, respectively) with smaller average end-to-end delay. The rate balance scheme is able to limit the traffic flows to a level that subsequent relay nodes can forward, therefore, improving overall performance. Interestingly, although the first relay node possibly increases the delay using our scheme, the end-to-end delay is reduced since the first relay node appropriately regulates the traffic.

D. *Multi-hop traffic aggregation*

In this scenario, we are interested in comparison between basic and our scheme in a more realistic situation where there are multiple sources sending data to a common destination through multiple relay nodes. In the simulation scenario, twenty nodes are uniformly distributed in an area of 1000x1000m^2; they are sparse enough so that multi-hop transmission (up to 4 hops) is required to send data. A set of 10 nodes is selected to be source nodes, which generate CBR sessions to send data to a destination.

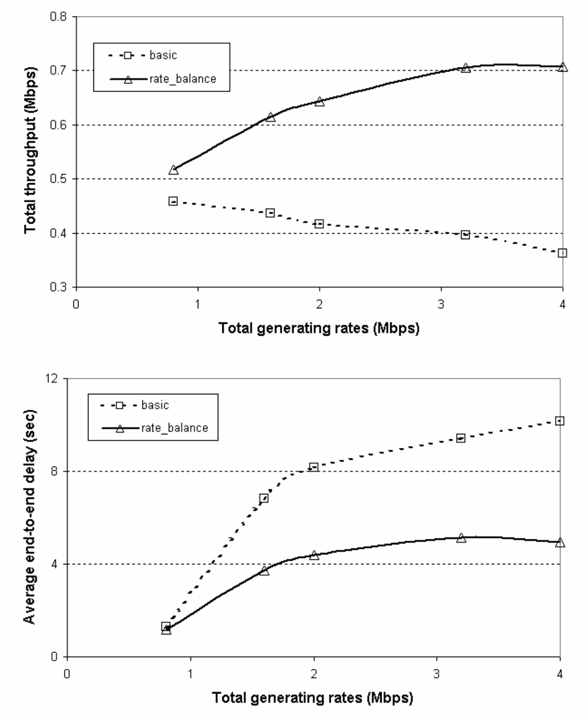

Figure 6: Aggregated average end-to-end throughput and delay

When the traffic rates at source nodes increase, the total average throughput decreases when basic scheme is used on its own (Figure 6). Some sessions are starved when sending rates are relatively high. With our scheme, the total average throughput is up to 95% higher and all sessions could send their data with lower average delay. Again, by maintaining the balance of transmitting and receiving rates, relay nodes could efficiently control traffic at appropriate level that nodes in network can support, thus overall performance is improved.

V. CONCLUSIONS

Often multi-hop wireless networks will contain nodes that relay more traffic than others, e.g. in mesh networks or mobile ad hoc networks with gateways to external networks. When using a random MAC protocol such as IEEE 802.11, these relay nodes can become a bottleneck in the network, in that they struggle to obtain opportunities to forward packets (since they must compete on an equal level to other nodes). This in turn can create congestion in the network. In this paper we propose a scheme where the relay node balances its receiving and transmitting rate to implicitly control the sending rate of source nodes by not responding to RTS frames (essentially giving it time in order to forward packets). The rate balance scheme provides greater and more flexible control than queue length based control as it can better handle changes in the channel conditions. Analysis of several scenarios with relay nodes has revealed that our proposed scheme provides significant throughput enhancement over 802.11 RTS/CTS, even in the cases when there are many hops. Another advantage of our scheme is the relative minor changes to 802.11 RTS/CTS that are necessary, therefore, our scheme can be deployed in multi-hop wireless networks with relative ease.

In our scheme, the relay node drops RTS frames without regard to the source of these frames once the rate balance condition is violated. As an area of future work we intend to investigate whether or not this results in unfairness in sharing the channel, and how to address this (e.g. integration with fair schedulers and flow control mechanisms). In addition, we will investigate our scheme in the presence of other congestion control schemes, e.g. TCP.

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