An Adaptive Resource Control Mechanism in Multi-hop Ad-Hoc Networks

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Abstract. This paper presents an adaptive resource control mechanism for multi-hop ad-hoc network systems, which avoids bottleneck problems caused by the node-fairness property of IEEE 802.11. In our proposal, the feedback information from the downstream bottleneck, derived from Request-To-Send (RTS) and Clear-To-Send (CTS) messages is utilized to control the Transmission Opportunity (TXOP) limit of the upstream nodes for traffic balancing. The proposed mechanism is modelled control-theoretically using the 20-sim control system modelling tool, which has the advantage that results can be obtained in a fast and efficient way. Compared to systems without resource control, a higher throughput and lower delay can be achieved under a variety of traffic load conditions as well as in dynamic network environments.

Key words: resource control; multi-hop; 802.11; RTS/CTS; TXOP;

1 Introduction

IEEE 802.11 [1] based Wireless Local Area Networks (WLANs) are in widespread deployment nowadays. In the 802.11 Medium Access Control (MAC), the Distributed Coordination Function (DCF) is the key mechanism to provide shared access in an ad-hoc mode. In most scenarios, the equal access as provided by the DCF is desirable. However, in certain multi-hop wireless networks, the fairness among contending nodes will lead to undesirable situations where packets may get lost at bottlenecks even after having gone through the initial hops already. In this paper, we consider multi-hop ad-hoc network scenarios, in which certain nodes happen to function as bottlenecks, forwarding packets received from a number of upstream nodes towards other stations. In 802.11 DCF ad-hoc network systems, a certain bottleneck obtains an equal capacity share as any one of its upstream nodes in the same interference domain; however, it has to support the traffic from all of them. This leads to a very high queue length of the bottleneck, eventually also buffer overflow, and in any case, long delays.

In order to combat this packet loss problem in multi-hop ad-hoc networks, an adaptive resource control mechanism is proposed to provide efficient use of the limited channel capacity by applying controlled access differentiation. The mechanism utilizes information in the Request-To-Send/Clear-To-Send (RTS/CTS) message exchange, and

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is generally applicable to access mechanism using RTS/CTS. The proposed resource control mechanism is modelled with a control-theoretic modeling approach, and the system performance is evaluated using the 20-sim tool [15].

The contributions of this paper are as follows: (i) We introduce an adaptive resource control mechanism, in which there is no modification to the IEEE 802.11 standard frames, no control overhead in the frame structure, and no need for a centralized controller. (ii) The designed mechanism is modelled in a control-theoretic way. The control model is hierarchically structured and formalized, and results can be obtained much more quickly and efficiently compared to an ns-2 simulation. (iii) Experimental results show that the new mechanism is able to provide fair and efficient capacity use, avoids packet loss at intermediate bottlenecks, achieves fairly low queuing delay, and quickly adapts to network environmental changes.

The remainder of the paper is organized as follows. Section 2 introduces background and related work. Section 3 discusses the objectives of the TXOP control, and describes the new control mechanism for multi-hop ad-hoc networks. Section 4 presents a control-theoretic model for the proposed mechanism modeling. Section 5 shows experimental results, and in Section 6 the paper is concluded.

2 Background and related work

RTS/CTS is an optional four-way handshaking mechanism adopted by the 802.11 DCF to reduce data frame collisions caused by the hidden terminal problem. The RTS and CTS are short frames exchanged prior to data transmission between a pair of source and destination nodes. Before transmitting a packet, an RTS will be broadcasted comprising the destination address and the expected data duration information. Besides the intended destination, this RTS packet can also be received by all other nodes in reach of the source node, so that they will refrain from accessing the medium during the period that the source will be transmitting. To acknowledge the receipt of an RTS, the destination node replies with a CTS packet, which is also a broadcast packet including the data duration information. Therefore, with the RTS/CTS mechanism applied, other nodes within the range of both the source and the destination will not disturb the medium for the intended packet transmission time until the following acknowledgement (ACK).

In order to support Quality of Service (QoS) in WLANs, an Hybrid Coordination Function (HCF) has been proposed and incorporated in [1]. The TXOP limit is one of the QoS differentiation parameters specified in 802.11 HCF, which is defined as the time interval during which multiple packets are allowed to be transmitted consecutively by one station per successful channel access. However, the problem is how to set the TXOP for good performance and fairness trade-off. To overcome the problem of selecting a fixed TXOP setting, in this paper the TXOP limit is made adaptive.

In [2], a control-theoretic model has been designed for 802.11 ad-hoc networks, in which a chosen TXOP limit is studied to improve the system performance. However, the dynamic adaptation of the TXOP parameter according to the current network situation is not done. An adaptive TXOP allocation is achieved in [3, 4] to improve the system efficiency. However, in [3, 4] a centralized controller, known as the Hybrid Coordinator (HC) is required, which is not applicable in distributed wireless ad-hoc networks. A resource allocation protocol has been described in [5] to provide a QoS service in 802.11 networks, which allows each individual node to adjust its TXOP limit when it wins a channel contention. However, each node has to monitoring the MAC-level queue continuously in order to obtain the queue length and packet arrival information. The work [6] proposed an adaptive resource control mechanism in 2-hop ad-hoc networks, which can not be applied in multi-hop network scenarios, because the TXOP limit of the bottleneck node is set to a fixed value.

Our proposed resource control is based on an improved Additive Increase Multiplicative Decrease (AIMD) algorithm, in which the TXOP decrease ratio can be dynamically adapted according to the current network condition. A lot of work has been done in order to provide solutions for the AIMD improvement. Yang and Lam [7] presented a relationship between the increase rate and decrease ratio parameters to produce TCP-friendly flows. These parameters can be further dynamically adjusted based on current network condition for smooth multimedia streaming [8]. However, all their work is limited to TCP congestion control. In TCP, each sender limits its sending rate as a function of perceived network congestion in order to resolve the packet loss problem; this leads to underutilization of the limited channel resource in wireless environment [9]. There are different techniques proposed to adapt the standard TCP to wireless networks [10, 11]. However, TCP modifications or other link layer solutions are required. In [12], a congestion control mechanism combined with random access MAC has been proposed to improve network utilization in multi-hop wireless networks. However, an enhanced carrier-sensing technique is required to provide full awareness of a link's neighbor set.

In this paper a new resource control mechanism based on TXOP adaptation is proposed. It is able not only to avoid congestion at bottleneck nodes, but also to ensure high network throughput. Furthermore, our mechanism requires no modification to the IEEE 802.11 frames and no control overhead as well.

3 Resource control objectives and designed mechanism

Section 3.1 discusses the objectives of resource control. Section 3.2 presents our resource control strategy for multi-hop ad-hoc networks, and in Section 3.3, the TXOP value assignment method is introduced.

3.1 Resource control objectives

The objectives of the resource control design for multi-hop ad-hoc networks are as follows:

(1) *Fairness:* Ideally, a fair capacity sharing among all flows, regardless of the number of hops is desired. However, in wireless ad-hoc network systems, only local information can be utilized by each node since global knowledge of the entire network is not available. With our resource control mechanism applied, an equal sharing of the channel capacity among all the nodes on each individual hop can be achieved.
(2) *Maximizing the network throughput:* It has been shown in [14] that higher network throughput can be achieved by adopting a larger TXOP limit, leading to less frequent channel competition. However, in multi-hop ad-hoc networks, packet loss

occurs at bottlenecks if all the nodes transmit with the maximum TXOP value. As a result, the resource capacity consumed on the initial hops will be wasted. Therefore, TXOP control is required to provide more efficient use of the channel capacity, meanwhile ensuring the network throughput.

(3) *Avoiding bottleneck overflow:* All incoming packets can be fully forwarded by each bottleneck node, i.e., no packet loss at bottlenecks.
(4) *Minimizing the queuing delay:* The queue lengths at each node within the network should be as small as possible.
(5) *Being adaptable in dynamic network environments:* The resource control system should react on network changes quickly.

3.2 Resource control strategy

The key idea of our TXOP control is that upstream nodes transmitting through the same downstream bottleneck adjust their TXOP limits based on the feedback information obtained from the bottleneck node. Note that in the following, we will express the TXOP value in terms of number of packets that can be transmitted within the chosen TXOP (as alternative notion of time).

For simplicity, the proposed TXOP control mechanism will be presented by considering a simple 2-hop network scenario, as depicted in Fig.1. A bottleneck node B forwards packets received from a number of n sources towards other destinations. Sources and the bottleneck are all within reach of each other; hence, share the same bandwidth capacity during communication.

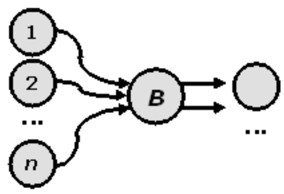

Fig. 1. Bottleneck in a 2-hop adhoc network

The detailed TXOP control procedure is illustrated in Fig.2. We see in Fig.2(a) that in case one of the source nodes i ($i = 1, 2, \ldots, n$) wins a channel competition, an RTS packet will be sent including its current expected Packet Transmission Duration information, PTD_i, from which the number of packets intended to transmit, T_i can be computed, relying on a fixed data rate assumption. Note that T_i is determined by the number of queued packets in the buffer of node i, q_i and its TXOP limit, i.e., $T_i = \min(q_i, TXOP_i)$. After receiving this RTS, a CTS packet will be broadcast by B, also including the PTD_i. Therefore, all the source nodes that have seen this CTS are informed about the number of packets that will arrive at B, A_B, in source i's current channel access. By this means, the source nodes can accumulate all the A_B based on a number of consecutive CTS received from B in order to obtain the total number of packets arrived at B, $\sum A_B$, until B wins a channel access. As soon as the bottleneck B obtains a chance to transmit, the number of packets that will be transmitted by B, T_B, can be calculated by the sources as well according to the broadcasted RTS from B, as shown in Fig.2(b). After comparing $\sum A_B$ with T_B, the TXOP limit of each source i, $TXOP_i$, can be adapted accordingly. If the total number of packets that arrived at B is equal to the amount that can be currently transmitted, i.e., $\sum A_B = T_B$, the bottleneck B is considered to be lightly loaded, so that each source will try to increase the $TXOP_i$. As a result, more packets are sent to B, which leads to a larger $\sum A_B$. In case

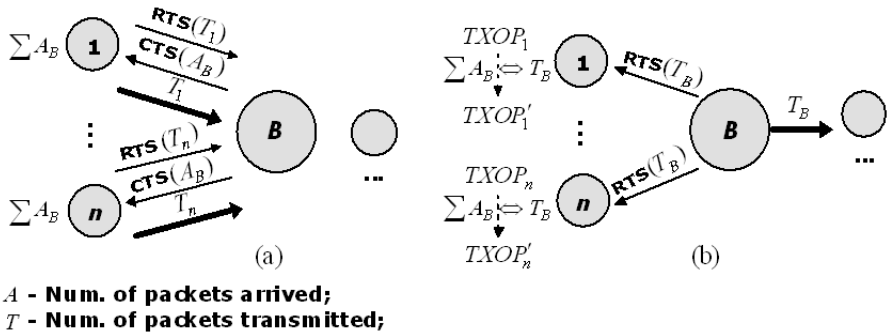

Fig. 2. TXOP control procedure

the overall feedback value $\sum A_B$ is larger than T_B, $TXOP_i$ will be decreased, leading to fewer packet arrivals at B, so that the queue of the bottleneck will be emptied, during which each source will keep its current $TXOP_i$ until the bottleneck B becomes lightly loaded again. The specific algorithm proposed for TXOP value assignment will be discussed in Section 3.3.

With this feedback TXOP control strategy applied, fairness between two consecutive hops will be achieved, regardless of the number of nodes competing for bandwidth at each hop. The use of the RTS/CTS message for feedback realizes this control strategy at no additional cost in terms of bits to be transmitted and no protocol changes!

3.3 TXOP value assignment

In order to provide fairness among the nodes on each individual hop in multi-hop ad-hoc networks, a variation on the Additive Increase Multiplicative Decrease (AIMD) mechanism known from TCP congestion control is used to adapt each source i's TXOP value. AIMD has been proven in [13] to be able to provide fairness among sources. The $TXOP_i(\alpha, \beta)$ control algorithm is expressed as follows:

$$TXOP_i' = \begin{cases} TXOP_i + \alpha, & \sum A_B = T_B \text{ (lightly loaded at } B\text{)}, \\ TXOP_i \cdot (1 - \beta), & \sum A_B > T_B \text{ (over loaded at } B\text{)}, \\ TXOP_i, & \sum A_B < T_B \text{ (queue emptying at } B\text{)}, \end{cases} \tag{1}$$

where α and β are control gains used to determine the increase rate and decrease ratio of $TXOP_i$, respectively, and $TXOP_i'$ [1] denotes the value of source i's TXOP limit after control. Note that in order to drain the queue of the bottleneck B, the current $TXOP_i$ will be kept unchanged in case $\sum A_B < T_B$. We only increase $TXOP_i$ when $\sum A_B = T_B$, since B's queue can then be perceived to be emptied.

The problem now focuses on how to choose proper control gains α and β. We assign α to 1 to achieve a slow increase of the TXOP value, so that large system variation can be avoided. As an improvement on the original AIMD, an adaptive control gain $\hat{\beta}$ is dynamically computed according to the current traffic load condition of the bottleneck

[1] $TXOP_i'$ can be a real number if fragmentation is applied during packet transmission in practice.

B, leading to a more efficient use of the channel capacity. In case $\sum A_B$ is larger than T_B, the following total number of packets that may arrive at B, $\sum A'_B$ will be controlled to be equal the number of packets that can be transmitted by B minus the amount currently stuck in B's queue, that is,

$$\sum A'_B = T_B - (\sum A_B - T_B). \tag{2}$$

Moreover, the TXOP limit of each source i determines the number of packets that will arrive at B, therefore, the control gain $\hat{\beta}$ used to control $TXOP_i$ is applied to $\sum A_B$ as well:

$$\sum A'_B = \sum A_B \cdot (1 - \hat{\beta}). \tag{3}$$

According to (2) and (3), the control gain $\hat{\beta}$ can then be calculated as follows:

$$\hat{\beta} = \frac{2 \cdot (\sum A_B - T_B)}{\sum A_B}. \tag{4}$$

In most cases, each source i can determine its TXOP limit using the derived $\hat{\beta}$. However, in dynamic network environment the bottleneck B may become overloaded when a group of source nodes join into the network simultaneously. As a result, the $TXOP'_i$ for the following packet transmission will be controlled to be smaller than 1 or even be negative according to the adopted $\hat{\beta}$. In this case, we assign $TXOP'_i$ to 0, so that the transmission of the sources can be temporary suspended until all packets arrived at B are perceived to be successfully transmitted ($\sum T_B = \sum A_B$), and then the $TXOP'_i$ will be reset to 1. Note that with this source nodes' transmission suspension method applied, the bottleneck can also obtain more opportunities to access the medium to empty its queue.

4 Resource control system modeling

In ad-hoc network systems, all the nodes within reach of each other compete for medium access in a distributed manner without any central coordination function. We abstract from this random access method, and implement the proposed resource control mechanism in a basic control-theoretic way. To model the TXOP control process, we adopt a discrete (integer) time scale as presented in Fig.3, in which t represents a discrete time instant, and the following time interval is denoted by $I_t = [t, t+1]$. It is assumed that all the nodes within the network may get a chance to transmit once in each time interval I_t for simplicity.

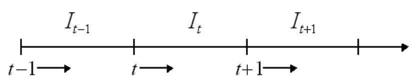

Fig. 3. Timing scheme for control system modeling

According to the discrete timing scheme, a basic control-theoretic modeling framework is designed and illustrated in Fig.4. The TXOP control mechanism described in Section 3 is modelled in the "TXOP control" module. It is clear that the number of packets transmitted by B in current time interval I_t, $T_B(t)$ and the accumulated packet arrivals $A_B(t)$ are used by each source

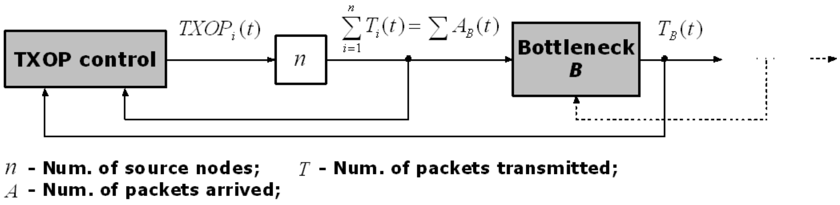

Fig. 4. The basic control-theoretic modeling framework

i to control its TXOP value. Note that the TXOP adaptation behaviour of n homogeneous source nodes is identically controlled by the feedback from B, therefore, we only model it once using the "TXOP control" module, as shown in Fig.4. By multiplying the adapted $TXOP_i(t)$ with n, we obtain the total number of packets transmitted by n sources in the current interval I_t, $\sum_{i=1}^{n} T_i(t)$ (assuming saturated sources). It is equal to $\sum A_B(t)$, which will further impact the bottleneck B's following packet transmission.

Note that our control-theoretic model can be easily extended by adding more steps in terms of hops, and then the TXOP limit of the bottleneck B will also be controlled by its downstream node. Moreover, we can also have more source and bottleneck nodes on each individual hop. Therefore, using the control-theoretic model the presented TXOP control mechanism can be studied under various network topologies.

The detail of each source i's "TXOP control" module is depicted in Fig.5. Following

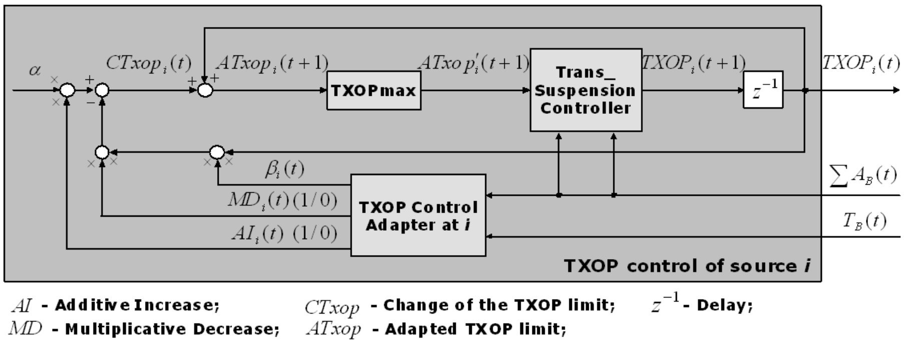

Fig. 5. Source i's "TXOP control" module

the control rule presented in (1), the TXOP Control Adapter function block activates either the TXOP Additive Increase (AI) or the Multiplicative Decrease (MD) process by setting the corresponding output, i.e., $AI_i(t)$ or $MD_i(t)$, to 1 according to the perceived $\sum A_B(t)$ and $T_B(t)$ at t. Note that if the TXOP limit of source i is determined to be unchanged in the following time interval I_{t+1}, both $AI_i(t)$ and $MD_i(t)$ will be set to 0. Furthermore, in case the current $MD_i(t)$ is 1, the current $\hat{\beta}_i(t)$ will be calculated based on (4), otherwise, it is assigned 0. The change of $TXOP_i(t)$ after control, $CTxop_i(t)$, can then be derived as follows:

$$CTxop_i(t) = \begin{cases} \alpha, & \sum A_B(t) = T_B(t), \\ -\hat{\beta}_i(t) \cdot TXOP_i(t), & \sum A_B(t) > T_B(t), \\ 0, & \sum A_B(t) < T_B(t). \end{cases} \tag{5}$$

Based on the $CTxop_i(t)$, the adapted TXOP limit of source i for the following interval I_{t+1}, $ATxop_i(t+1)$, can be expressed as:

$$ATxop_i(t+1) = TXOP_i(t) + CTxop_i(t). \tag{6}$$

In addition, a general TXOP upper limit, $TXOP_{max}$, has to be applied to restrict each source i's channel occupancy in time interval I_{t+1}, $ATxop'_i(t+1) = \min(ATxop_i(t+1), TXOP_{max})$.

The transmission suspension method described in Section 3.3 is implemented in the Trans_Suspension Controller function block, as shown in Fig.5. If the value of $ATxop'_i(t+1)$ is not smaller than 1, the output TXOP limit of source i in I_{t+1}, $TXOP_i(t+1)$, is equal to the input $ATxop'_i(t+1)$, otherwise, it will be assigned to 0, that is:

$$TXOP_i(t+1) = \begin{cases} ATxop'_i(t+1), & ATxop'_i(t+1) \geq 1, \\ 0, & ATxop'_i(t+1) < 1. \end{cases} \tag{7}$$

Note that in case of $ATxop'_i(t+1) < 1$, $TXOP_i(t+1)$ will be kept to 0 until all the packets arrived at B in I_t, $\sum A_B(t)$, have been successfully transmitted, and then $TXOP_i(t+1)$ will be reset to 1, following (5).

The queue dynamics of the bottleneck B is illustrated in Fig.6. The queue length of

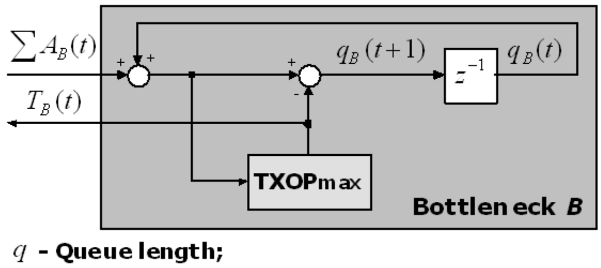

Fig. 6. The bottleneck module

B at $t+1$ is equal to that at the current t plus the total number of packets arrived, and minus those can be transmitted within I_t:

$$q_B(t+1) = q_B(t) + \sum A_B(t) - T_B(t). \tag{8}$$

Note that to ensure the current $T_B(t)$ to be no more than the adopted $TXOP_{max}$, the TXOP_{max} function block is applied as well.

Using the described basic TXOP control model, the introduced TXOP control mechanism can be studied in a simple and explicit way. As a further step, this basic model is embedded into the control-theoretic framework introduced in [2] in order to include random access behaviour, in order to be able to also do the performance evaluation of the TXOP control in IEEE 802.11 DCF applied multi-hop ad-hoc network systems. The corresponding experimental results are presented in Section 5.2.

5 Experimental results

The adaptive resource control mechanism introduced in Section 3 is studied using the software package 20-sim [15]. A multi-hop network scenario is designed, as shown in Fig.7. There are two intermediate bottleneck nodes IB_1 and IB_2, each of which forwards packets received from a number of n sources towards other stations via the same bottleneck B. Note that we model intermediate bottlenecks using the bottleneck module presented in Fig.6, in which the TXOP control module presented in Fig.5 is embedded instead of the TXOPmax function block. We assign the system parameter $TXOP_{max}$ to 10, which is used for B's packet transmission per successful channel acquisition. Note that the value of the $TXOP_{max}$ can be chosen according to the delay and delay jitter requirements of different network systems. Furthermore, a saturated network condition is assumed, so that the TXOP limit of each source node will always be reached per channel access.

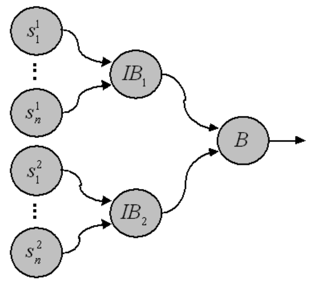

Fig. 7. Designed multi-hop network scenario

Note that the proposed mechanism is also applicable in many other network topologies, e.g., more nodes functioning as the second-hop bottlenecks instead of just B. In case there are more downstream nodes available, multiple TXOP adaptation processes can be maintained at a node based on feedback information from the corresponding receivers.

5.1 Results without random access

The performance of the resource control mechanism is evaluated using the basic control model without random access, as explained in Section 4. We consider a non-static network situation in which the intermediate bottleneck IB_2 with n sources joins the network after time interval 200. Note that in what follows, we denote the group of all sources sending to IB_j as $S_j = \{s_1^j, \ldots, s_n^j\}$ $(j = 1, 2)$. For the parameter setting $n = 3$, the corresponding system response is depicted in Fig.8, where the performance shows the adapted TXOP limits of IB_1 and its sources S_1 at each time epoch t. Since in the first 200 time intervals there is only one intermediate bottleneck in the network, all packets from IB_1 can be forwarded by the bottleneck B, hence, the TXOP value of IB_1 always reaches $TXOP_{max}$. After n sources of IB_2 joining into the network, the $TXOP_{IB_1}$ will be controlled to be smaller, leading to a decrease of the TXOP limit of s_i^1 $(i = 1, 2, \ldots, n)$. It can also be observed in Fig.8 that the TXOP control system reacts on network condition changes quickly, so that the system becomes stable again within a few time intervals. Note that the TXOP values of all the sources and intermediate bottlenecks are adapted based on the algorithm presented in Section 3.3.

We continue now to study the average number of packets transmitted by the second-hop bottleneck B, T_B, per access opportunity for varying number of sources of each intermediate bottleneck, n. Simulation results in Fig.9 show that the average throughput T_B decreases when the group of sources S_2 are added into the network. This is due to

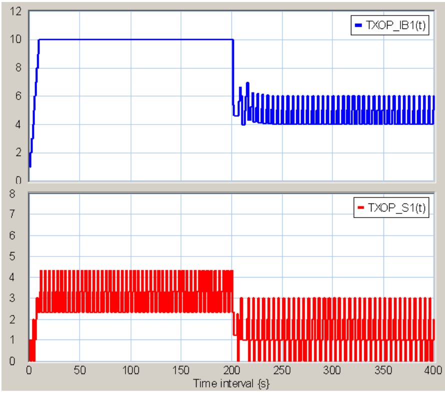

Fig. 8. TXOP limit as a function of time under non-static network conditions

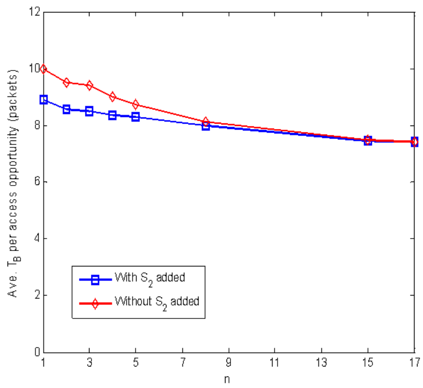

Fig. 9. Average T_B per access opportunity

the fact that the adding of the sources and the corresponding node IB_2 increases the variation of the TXOP control. We also see in Fig.9 that the average throughput T_B decreases slightly with increasing n, however, it can still remain above 7 in both cases with and without S_2 added, because the source nodes' transmission suspension method (described in Section 3.3) plays a key role under larger n settings. Note that in Fig.9-13, only discrete data points have been computed; lines are drawn to ease interpretation.

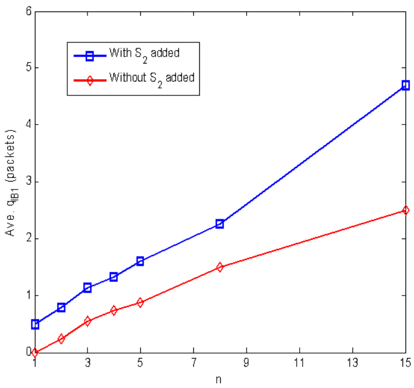

Fig. 10. Average queue length at IB_1

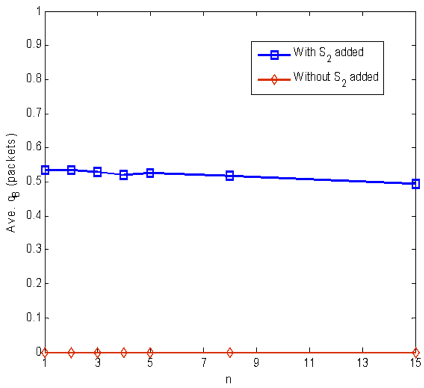

Fig. 11. Average queue length at B

The average queue length of IB_1, denoted as q_{IB_1}, is shown in Fig.10. We see that adding the group of sources S_2 increases the average q_{IB_1}, owing to the capacity share of IB_2. When n grows, the average queue length of IB_1 becomes higher, however, that of B can always be kept around 0.5 as a result of IB_1's TXOP control in the case with S_2 added, as shown in Fig.11. Note that without the sources S_2, the average q_B will be equal to 0. That is because if only IB_1 functions as the intermediate bottleneck, the $TXOP_{max}$ restricts its packet transmission, so that all packets arrived at B can be completely forwarded per access opportunity.

5.2 Results with random access

Using the control-theoretic IEEE 802.11 DCF model presented in [2], we study the resource control mechanism in an ad-hoc network system with random access considering the multi-hop scenario illustrated in Fig.7. All the sources and bottlenecks are within reach of each other, hence share the same radio bandwidth, and compete for channel access in a distributed manner. The system parameters of the 802.11 DCF are specified the same as reported in [2].

To evaluate the efficiency of the proposed algorithm, the overall control model is simulated using the 20-sim tool. Experiments are designed to compare the simulation results with and without the TXOP control mechanism applied. In the non-TXOP control case, three bottleneck nodes use a TXOP limit of $TXOP_{max}$, whereas all the sources are assumed to have their TXOP limits pre-configured to $TXOP_{s\_ini}$, which is a static value that can not be further adapted. Unless otherwise specified, all (mean) values of the following simulation results and the corresponding 95% confidence intervals are obtained by performing 10 simulations runs of 30000 time intervals.

Based on the parameter setting $n = 2$, i.e., there are two sources for each intermediate bottleneck, the expected throughput of the bottleneck B is shown in Fig.12. We

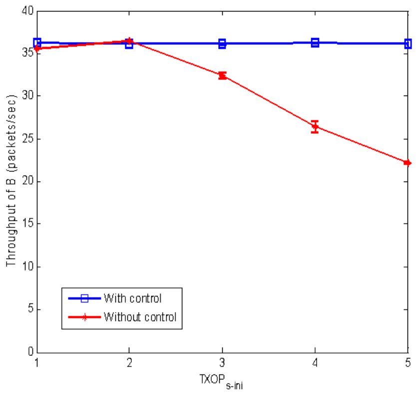

Fig. 12. Expected throughput of B

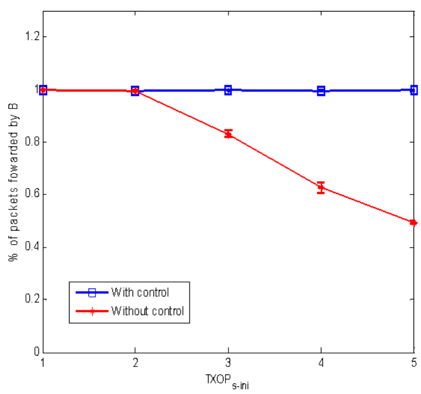

Fig. 13. Fraction of packets forwarded by B

observe that without feedback control for TXOP, the throughput of B slightly increases by enlarging the $TXOP_{s\_ini}$ from 1 to 2. This is because with a larger $TXOP_{s\_ini}$, more packets are allowed to be transmitted per access opportunity, so that the channel competition occurs less frequently. As the value of $TXOP_{s\_ini}$ is further increased, the throughput of B becomes lower due to the fact that more capacity is consumed on the first two hops, which leads to an overloaded B with its queue length building up. As a result, packets arriving at B can not be all forwarded, as shown in Fig.13. The fraction of packets forwarded by B is defined as B's total number of packet transmissions divided by the number of packets transmitted by all the sources within the simulation duration.

Correspondingly, in the scenario with TXOP control, the throughput of B can be kept above 35 packets/sec, without packet loss at B, regardless of the initial settings of the TXOP value, $TXOP_{s\_ini}$, as presented in Fig.12 and Fig.13, respectively. This is due to the fact that with the proposed TXOP control strategy implemented, the $TXOP_{s\_ini}$ are adapted efficiently.

Finally, Fig.14 shows the expected overall bottleneck queuing delay, which is defined as the average time that a packet waits in the queue of both the intermediate bottleneck and the bottleneck B before it is successfully forwarded. Note that simulation results presented in Fig.14 are obtained with 95% confidence intervals smaller than 7% of the mean value. We see that when $TXOP_{s\_ini}$ grows, the bottleneck queuing delay increases to infinity due to the overflow of the bottleneck B when the $TXOP_{s\_ini}$ is statically assigned. With TXOP control applied, a relatively low queuing delay can be achieved without being influenced by varying the $TXOP_{s\_ini}$. This is because the TXOP limit of the sources as well as the intermediate bottlenecks can be timely adapted, which avoids the building up of the bottleneck queues, and also ensures an efficient use of the bandwidth capacity.

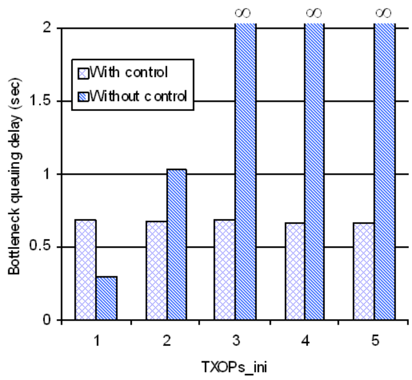

Fig. 14. Expected overall bottleneck queuing delay

6 Conclusion and future work

In this paper, a new resource control mechanism for multi-hop ad-hoc networks based on IEEE 802.11 has been presented. The RTS and CTS packets received from the downstream bottleneck are used as feedback to control the TXOP limits of the upstream nodes. The adaptive resource control requires no modification to the IEEE 802.11 standard frames, and there is no control overhead introduced in the frame structure. The proposed approach can be applied in real multi-hop ad-hoc networks without the intervention of a centralized controller. The resource control system has been modelled and evaluated in a control-theoretic way using the 20-sim tool. Experimental results show that the proposed mechanism is able to provide fair and efficient use of the limited channel capacity under a variety of traffic load conditions. Packet loss at bottleneck nodes can be avoided, meanwhile ensuring fairly low queuing delay. Furthermore, the resource control is adaptive in dynamic network environments, and the system is restabilized quickly.

The current work can be further extended by considering varying data rates and varying channel and traffic load conditions. Scenarios, in which certain downstream nodes are generating or taking in packets, will be considered as future work as well. Besides these, we will investigate a control-theoretic modeling approach for multi-hop ad-hoc networks in which each node is contending for channel access with only a subset of the set of nodes, i.e., each node has its own interference domain. Furthermore, the control model will be validated using the simulation platform OPNET, and different network topologies will be studied. Finally, we will do a number of comparative studies, thereby also including higher layer protocols, in order to investigate overall system behaviors.

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