Adaptive Contention Control for Improving End-to-End Throughput Performance of Multihop Wireless Networks

Daewon Jung, Jaeseon Hwang, Hyuk Lim, Kyung-Joon Park, and Jennifer C. Hou

Abstract

In multihop wireless networks, packets of a flow originating from a source node are relayed by intermediate nodes (relay nodes) and travel towards their destination along a multihop wireless path. Since the traffic forwarding capability of each node varies according to its level of contention, ideally, a node should not transmit more packets to its relay node than the corresponding relay node can forward. Instead, each node should yield its channel access opportunity to its neighbor nodes so that all the nodes can evenly share the channel and have similar forwarding capabilities. In this manner, nodes can utilize the wireless channel effectively, and further increase the end-to-end throughput of a multihop path. We propose a fully distributed contention window adaptation (CWA) mechanism, which adjusts the channel access probability depending on the difference between the incoming and outgoing traffic at each node, in order to equate the traffic forwarding capabilities among all the nodes in the path. We implement the proposed adaptive contention algorithm on Madwifi Linux kernel driver for Wi-Fi interface with Atheros chipset and carry out an empirical study in our division building. The experiment results demonstrate how the proposed mechanism can improve end-to-end throughput performance in the multihop wireless networks.

Index Terms

Multihop wireless networks, CSMA/CA, contention control, adaptive algorithm.

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I. INTRODUCTION

Multihop wireless networks have received considerable attention in recent years, primarily because of their wide civilian use and military applications, and their capability to building networks without a pre-existing infrastructure. Multihop wireless networks consist of a number of either stationary or mobile wireless nodes, which serve as relays forwarding traffic from other nodes (as well as their own traffic) and maintain network wide connectivity. In other words, in multihop wireless networks, packets of a flow originating from a source node are relayed by intermediate nodes (relay nodes) and travel towards the destination along a multihop wireless path.

One of the critical performance metrics in multihop wireless networks is the network throughput, which heavily depends on the achievable channel capacity at each individual wireless link and the level of spatial reuse. Several PHY/MAC attributes in multihop wireless networks can be used in order to control channel access, reduce interference, and improve network throughput, among which the transmit power, the carrier sense threshold, and the channel access probability have been the main research topics.

In this paper, we consider the issue of improving the end-to-end throughput performance of IEEE 802.11 DCF-operated multihop wireless networks. The basic access method of the IEEE 802.11 DCF is carrier sense multiple access with collision avoidance (CSMA/CA). A node that intends to transmit first senses the channel and defers its transmission when the channel is sensed busy. When the channel is sensed to be idle for a specific time interval, called *distributed inter-frame space (DIFS)*, the sender chooses a random back-off timer, which is uniformly distributed in $[0, \mathrm{CW}-1]$, where CW is the contention window size. CW is initially set to its minimum value $\mathrm{CW}_{\min}$, and is doubled up to its maximum value $\mathrm{CW}_{\max}$ after each transmission collision. The back-off timer is decreased by one if the channel is sensed idle for one physical time slot, suspended if the channel is sensed busy. The node transmits its frame when the back-off timer reaches zero. Once the data frame is received without errors, the receiver sends an acknowledgment frame to the sender after a specified interval, called the *short inter-frame space (SIFS)*, which is less than DIFS. If an acknowledgment frame is not received, the data frame is presumed to be lost, and a retransmission is scheduled. Note that it has been shown in previous studies, e.g, [2], that the channel access probability is a function of CW, i.e., $2/(\mathrm{CW}+1)$ in an average sense, and thus we can control the channel access probability of each node via tuning the CW value.

In the context of IEEE 802.11 DCF-operated multihop wireless networks, we devise a contention window adaptation scheme that effectively adjusts the minimum CW size, $\mathrm{CW}_{\min}$, of the BEB mechanism in a distributed manner. In particular, we consider the following two major issues: (i) how does $\mathrm{CW}_{\min}$ affect the end-to-end throughput of a multihop wireless path? (ii) if it is insufficient for every node on a multihop wireless path to use a common, fixed $\mathrm{CW}_{\min}$ value, how does each node distributively adjust its $\mathrm{CW}_{\min}$ value? To address the first issue, we first motivate via simulation in Section II that the BEB algorithm with a common, fixed value of $\mathrm{CW}_{\min}$ is not sufficient to improve the end-to-end throughput of a multihop path. In order to resolve this issue and further improve the network throughput, we propose a fully-distributed contention window adaptation scheme. Specified in a set of iterative updating rules, the proposed scheme adaptively controls $\mathrm{CW}_{\min}$ by considering the level of traffic forwarding ratio. If the current ratio of incoming packets to outgoing packets is above/below a pre-determined forwarding capability (which is set to a value between 0 and 1) in a given interval, the $\mathrm{CW}_{\min}$ value will be set to a larger/smaller value in order to decrease/increase the channel access probability. We provide a convergence analysis of the proposed algorithm and evaluate its steady-state performance. We implement the adaptive contention mechanism on Linux kernel driver and carry out an empirical study in a multihop chain topology. The experimental results show that the proposed algorithm significantly outperforms IEEE 802.11 DCF in terms of the end-to-end throughput performance.

The rest of the paper is organized as follows: In Section II, we motivate our proposed work with an performance evaluation of a multihop wireless path. In Section III, we provide a summary of related work in the literature. In Section IV, we propose an adaptive contention algorithm for maximizing end-to-end throughput in multihop wireless networks. The empirical evaluation of the proposed contention algorithm follows in Section V. Finally, we conclude the paper in Section VI.

II. Motivation

To investigate how the contention among nodes affects the end-to-end throughput of a multihop wireless path, we perform a simulation for a chain topology with 7 nodes operating in the IEEE 802.11 DCF mode as shown in Fig. 1, where only the source node sends packets at a rate of 5 Mb/s to the destination node through intermediate nodes. In Fig. 1, adjacent nodes are within the transmission range of each other, and the carrier sense range is approximately twice of the transmission range. Nodes within a carrier sense range compete for the same channel and interfere with one another. In Fig. 1, the source node competes with two nodes (n_1 and n_2), while n_1 competes with three nodes ($source$, n_2, and n_3). Thus, the channel access probability for the source node will be approximately 1/3 while that for n_1 and n_2 will be 1/4 and 1/5, respectively. It is obvious that the traffic forwarding capabilities are not the same for nodes along a multihop path in the chain topology given in Fig. 1, due to the fact that each node has a different number of competing nodes.

One may think that there exists an optimal channel access probability (or equivalently, an optimal value of $\mathrm{CW}_{\min}$) that gives the maximal throughput of the multihop path. Fig. 2 shows the throughput performance when $\mathrm{CW}_{\min}$ = 16, 32, and 64. Note that each node has a common, fixed value of $\mathrm{CW}_{\min}$ in the first transmission attempt, and then the CW value is adapted in compliance with the BEB mechanism. The x-axis in Fig. 2 is the hop-count from the source, and thus the throughput at the last node (i.e., hop-count = 6) corresponds to the end-to-end throughput of the overall path. Several important observations can be made from Fig. 2:

- The throughput at the first hop is high, but rapidly decreases at the next hop under all the cases. For example, the throughput is reduced by half for $\mathrm{CW_{min}} = 16$. This throughput behavior implies that the first relay node (n_1) fails to forward all the packets received from $source$ to the next node (n_2), resulting in dropping a large amount of packets.
- The smallest $\mathrm{CW_{min}}$ does not give the highest end-to-end throughput even though it can achieve the highest throughput at the first hop. If one of the nodes accesses the wireless medium aggressively, other nodes have a less chance to access the channel. Thus, if the sender grasps the channel more often than the first relay node (n_1), the throughput of n_1 will further degrade. Consequently, the case for $\mathrm{CW_{min}} = 16$ gives the lowest end-to-end throughput with the highest throughput of the first hop.
- Starting from the third hop, the throughput of relayed traffic at each node does not decrease significantly and is approximately the same as the end-to-end throughput because the data rate is sufficiently reduced at the precedent nodes, and thus the contention among nodes is not severe.

Based on the above observations, we conclude that if nodes with a different traffic forwarding capability contend with each other with the same $\mathrm{CW_{min}}$ value, the node with the largest forwarding capability may utilize the wireless medium aggressively and eventually causes the decrease in the end-to-end throughput of the multihop path. Consequently, the BEB mechanism with fixed parameters does not resolve the *intra-flow interference* problem (i.e., the interference among packets of a connection that is routed on the same multihop path). Thus, we need to differentiate the channel access probability of each node by adjusting the CW size depending on the traffic forwarding capability.

Fig. 2 also shows the throughput result when the $\mathrm{CW_{min}}$ value of each node is adjusted by our proposed algorithm in Section IV. It is noticeable that the throughput achieved under the $CW_{\min}$ adaptation scheme does not vary with respect to the hop-count. This result implies that none of the relay nodes forwards excessive packets to its corresponding receiver. In summary, by differentiating the contention window size at each node, all the other nodes except the source are able to increase the traffic forwarding capability, which results in a significant increase in the end-to-end throughput.

As shown in the above example in Fig. 2, in order to improve the throughput of multihop wireless networks, we have to consider the following issues: (i) how to estimate the traffic forwarding capability at each node; (ii) how to differentiate the contention window size depending on the traffic forwarding capability; and (iii) how to increase the end-to-end throughput by regulating the throughput of traffic relayed at each hop in a distributed and scalable manner. We will deal with these issues in detail and propose a fully distributed, adaptive algorithm for controlling the contention window size in the next section.

III. RELATED WORK

Spatial reuse in wireless networks increases the overall network capacity by allowing concurrent transmissions that are spatially far enough not to interfere with each other. There exist abundant research results on how to exploit spatial reuse for improving the performance of wireless networks. We categorize these recent research efforts into the following three topics: tuning of the back-off parameters, transmit power control, and adjustment of carrier sense thresholds.

A. Tuning of the Back-off Parameters

In IEEE 802.11 DCF, the back-off parameters such as $CW_{\min}$ and $CW_{\max}$ are fixed, which is insufficient to guarantee a satisfactory performance under various network scenarios. To analyze the impact of the back-off parameters on network performance, Bianchi derived a two dimensional Markov chain model for the exponential backoff process [3]. Using this model, it was shown that the number of stations and the minimum CW size have significant impacts on the overall performance of IEEE 802.11 DCF. Bianchi and Tinnirello [4] proposed how to estimate the number of active stations using an extended Kalman filter in a WLAN. They showed that tuning of the MAC parameters can effectively improve the network performance when the number of active stations is properly estimated. Accordingly, extensive studies on improving network capacity by adapting back-off parameters have been carried out [2], [5], [6]. Cali *et al*. [2] proposed a distributed algorithm called IEEE 802.11+, which enables each node to estimate the number of contending nodes at any given time. They also derived an analytical model which gives a theoretical maximum bound on the network capacity, and tried to find the optimal CW value to achieve the theoretical throughput limit. Kwon *et al*. [5] proposed a *fast collision recovery (FCR)* protocol, which is a contention-based protocol that redistributes the back-off timer among all competing stations with an objective of reducing the idle back-off time.

Most existing CW tuning schemes assume a one-hop network topology such as an infrastructure WLAN and primarily consider how to adjust the contention window size of each node to maximize the number of concurrent transmissions without incurring severe collisions among the concurrent transmissions. To the contrary, we consider a multi-hop network topology, where intra-flow interference more significantly affects the end-to-end throughput performance. Our proposed CW adaptation scheme attempts to reduce unnecessary packet drops due to inter-flow interference and to improve the end-to-end throughput performance by differentiating the contention window sizes of relay nodes belonging to a same multi-hop path.

B. Transmit Power Control

The issue of power control has been extensively studied in the context of topology maintenance, where the objective is to preserve a graph-theoretic network connectivity, to reduce power consumption, and mitigate MAC-level interference [7]–[11]. Power control for the purpose of increasing spatial reuse and network capacity has been treated in the PCMA protocol [12], the PCDC protocol [13], and the POWMAC protocol [14]. In [12], Monks *et al.* proposed PCMA, in which the receiver announces its interference margin that it can tolerate on an out-of-band channel and the transmitter selects its transmit power that does not affect any ongoing transmissions. Muqattash and Krunz also proposed PCDC and POWMAC in [13], [14], respectively.

C. Carrier Sense Threshold Adjustment

The carrier sense threshold is also a key parameter for determining the level of spatial reuse. The impact of the carrier sense threshold on the network capacity has been studied in [15]–[19]. Zhu *et al.* [17] determined an optimal carrier sense threshold value which maximizes spatial reuse for several regular topologies. Based on the SINR required to sustain a predetermined transmission rate, Zhu *et al.* proposed in [18] a dynamic algorithm that adjusts the carrier sense threshold in order to set the SINR of each transmission to a given level. Vasan *et al.* [19] proposed an algorithm, called *echos*, to dynamically adjust the carrier sense threshold in order to allow more flows to co-exist in 802.11-based hotspot wireless networks. Yang and Vaidya [15] considered several factors such as MAC overhead, transmission rate, and network density in selecting optimal carrier sense threshold that maximizes the aggregate throughput.

IV. A CONTENTION CONTROL FOR MULTIHOP NETWORKS

In multihop wireless networks, the achievable throughput is limited by intra- and inter-flow interference. Specifically, flows that are routed along different paths within the interference range compete for the channel bandwidth, resulting in inter-flow interference. On the other hand, intra-flow interference results from consecutive packets in a single flow because the packets are spread over the route to their destination and interfere with each other. As each node is exposed to a different level of interference, it has a different traffic forwarding capability. We define the traffic forwarding capability α_i as the ratio of the rate of incoming and outgoing traffic at a node i:

$$\alpha_i = h_i^{out}/h_i^{in}.$$

If a node i can forward all the received packets to its neighboring node without packet loss, then α_i is equal to one. On the other hand, if node i receives a large number of packets but cannot forward them at the same rate as it receives, then α_i is less than one. If node i has the smallest forwarding capability α_i among the nodes on the multihop path, it may be a bottleneck relay node of the path. In this case, we have two choices to deal with this bottleneck problem: (i) node i may ask neighboring nodes to reduce the transmit rate because it cannot handle it; (ii) it may increase the channel access probability in order to relay more packets. In fact, if the node i increases the channel access probability, the neighbor nodes cannot help reducing the transmit rate because they are sharing the wireless medium with the node i.

We set the target traffic forwarding capability (denoted by α^*, $0 \ll \alpha^* < 1$) which each relay node is expected to have in a steady state. If the traffic forwarding capability of node i is less than α^*, the rate of traffic that the node i is relaying is smaller than that at which the node is supposed to relay. Such a node is granted to increase the channel access probability, attempting for access the wireless medium more aggressively. As a result, the neighbor nodes will have a lower possibility of gaining access to the wireless medium.

To differentiate the channel access probability, we propose to adjust the contention window size with respect to the traffic forwarding capability of each node. Instead of modifying the BEB algorithm in IEEE 802.11 DCF, we iteratively update $\mathrm{CW}_{\min}$ with the following rule:

$$\mathrm{CW}_{\min,i} \leftarrow \mathrm{CW}_{\min,i} + \gamma \ (h_i^{out} - \alpha^* \cdot h_i^{in}), \tag{1}$$

where γ is the step size. At each iteration, the increment in $\mathrm{CW}_{\min}$ is proportional to the discrepancy between the outgoing rate and the incoming rate scaled by the target traffic forwarding capability α^*. Note that in a steady state, α_i becomes α^*. [1]

The updated $\mathrm{CW}_{\min}$ is applied to the contention of packets that are being relayed at the node. However, for the contention of packets that are generated by itself, a pre-determined constant $\mathrm{CW}_{\min}$ is used because the forwarding capability of traffic whose source is itself cannot be determined. For example, when a node is generating a traffic flow and at the same time is relaying a traffic flow from a neighboring node, it should not use the $\mathrm{CW}_{\min}$ obtained by (1) for the generated traffic flow. Otherwise, it may happen that packets generated by itself is too aggressively transmitted with a small value of $\mathrm{CW}_{\min}$ that is computed by the forwarding capability of the relayed traffic. In what follows, we will first explain the detailed algorithm, and then show the convergence analysis of the proposed algorithm.

A. Adaptive Contention Algorithm

We devise a fully distributed contention window adaptation (CWA) algorithm for each node to independently and adaptively determine the minimum contention window size $\mathrm{CW}_{\min}$. The proposed adaptation rule in (1) needs neither the status information of neighboring nodes nor the topology information of the multihop path such as the total number of hops and the hop-count from the source. Algorithm 1 gives the pseudo-code of the contention window adaptation scheme. Each node periodically executes the algorithm and update its $\mathrm{CW}_{\min}$ at every T seconds.

[1] For notational simplicity, hereafter we use α for the target traffic forwarding capacity α^*.

The updated $\mathrm{CW_{min}}$ affects only new packet relays that start after its update. This means that this window adaptation scheme does not interfere the ongoing BEB process.

There are several points that are worthy of mentioning. First, in order to measure the rates of incoming and outgoing traffic, we count the number of packets for the time interval T. We have to consider two special cases: (i) when a node receives packets whose destination is itself; and (ii) when a node transmit packets whose source is itself. Whether or not to consider these cases may result in a large discrepancy between the amount of the incoming and outgoing traffic. Because these cases do not affect the forwarding capability (and hence the adaptation of $\mathrm{CW_{min}}$), we ignore them on lines 3 and 7 in Algorithm 1.

Second, on the lines 9–11 in Algorithm 1, an upper bound is placed on the rate of outgoing traffic. Even though there is no incoming packets, the packets accumulated in the buffer can be transmitted. For a short time interval, the outgoing rate could be higher than the incoming rate depending on the buffer size, and it may lead to a false decision in updating $\mathrm{CW_{min}}$ in (1). This is the reason that we limit the rate estimate of outgoing traffic up to that of incoming traffic.

Third, if the traffic load is sufficiently low and does not incur any packet loss, $\mathrm{CW_{min}}$ has the tendency to be large with the use of the adaptation rule in (1). On the other hand, it is also possible that a node cannot reach the target forwarding capability even though it eventually reduces $\mathrm{CW_{min}}$ to 1. Considering these two extreme cases, we have imposed an upper bound max_{th} and a lower bound min_{th} on $\mathrm{CW_{min}}$ on lines 15–19 in Algorithm 1.

B. *Convergence Analysis of the Proposed Algorithm*

Here, we give a convergence analysis of Algorithm 1. In our analysis, we deal with the channel access probability of each node instead of the CW size, which will be further corroborated in Remark 2. Consider a multihop wireless network consisting of a set of N nodes, denoted by $\mathcal{N} = \{1, 2, \cdots, N\}$. Similar to what has been done in [16], we derive the saturation throughput of each node. We simplify our analysis by assuming that the carrier sense threshold and the transmit power are the same for all the nodes, and the hidden node effect is not significant. We expect that our analysis can be extended to a more general scenario, which will be a subject of our future work.

Let p_i and q_i denote, respectively, the probability that node i transmits in any virtual time slot and the conditional collision probability of node i that there is at least one transmission in the time slot. Then, the conditional collision probability q_i can be expressed as

$$q_i(\mathbf{p}_{-i}) = 1 - \prod_{j \in C_i} (1 - p_j),$$

where C_i denotes the set of nodes whose simultaneous transmission will collide with node i, and $\mathbf{p}_{-i} = (p_1, \cdots, p_{i-1}, p_{i+1}, \cdots, p_N)$. Further, the average virtual time slot seen by node i, denoted by v_i, is

$$v_i = p_i \left[(1 - q_i)T_s + q_i T_c\right] + (1 - p_i)\left[(1 - q_i)\sigma + q_i T_b\right], \tag{2}$$

where T_s, T_c, T_b, and σ denote the durations of a successful transmission, a collision, a busy channel, and the idle slot time, respectively. Note that v_i corresponds to the average time duration of one transmission in consideration of transmission, collision, and idle times.

Now, we can obtain the saturation throughput of node i, denoted by $g_i(\mathbf{p})$, is defined by the ratio of the average amount of payload that is successfully transmitted to the average virtual time slot as follows:

$$g_i(\mathbf{p}) = \frac{l p_i \left(1 - q_i(\mathbf{p}_{-i})\right)}{v_i(\mathbf{p})}, \tag{3}$$

where $\mathbf{p} = (p_1, \cdots, p_N)$ and l is the payload size.

Let $h_i^{\text{in}}(\mathbf{p})$ and h_i^{gen} denote the incoming rate of node i and the data rate generated by node i, respectively. Further, $h_i^{\text{out}}(\mathbf{p})$ and $h_i^{\text{rel}}(\mathbf{p})$ denote the total outgoing rate and the relayed data of node i, respectively. Then, we have

$$h_i^{\text{out}}(\mathbf{p}) = \begin{cases} g_i(\mathbf{p}), & \text{if } h_i^{\text{in}}(\mathbf{p}) + h_i^{\text{gen}} \geq g_i(\mathbf{p}); \\ h_i^{\text{in}}(\mathbf{p}) + h_i^{\text{gen}}, & \text{otherwise,} \end{cases}$$

Note that the total outgoing rate (h_i^{out}) is equal to the summation of the incoming rate of node i and the data rate generated by node i (i.e., $h_i^{\text{in}}(\mathbf{p}) + h_i^{\text{gen}}$), but cannot exceed the saturation throughput of node i. When $h_i^{\text{in}}(\mathbf{p}) + h_i^{\text{gen}} \geq g_i(\mathbf{p})$, the incoming packets are dropped at node i as follows:

$$h_i^{\text{rel}}(\mathbf{p}) = \begin{cases} g_i(\mathbf{p})h_i^{\text{in}}(\mathbf{p})/(h_i^{\text{in}}(\mathbf{p}) + h_i^{\text{gen}}), & \text{if } h_i^{\text{in}}(\mathbf{p}) + h_i^{\text{gen}} \geq g_i(\mathbf{p}); \\ h_i^{\text{in}}(\mathbf{p}), & \text{otherwise,} \end{cases} \tag{4}$$

and

$$h_i^{\text{in}}(\mathbf{p}) = \sum_{j \in S_i} \beta_{ji} h_j^{\text{out}}(\mathbf{p}), \tag{5}$$

where S_i and β_{ji} denote a set of nodes sending traffic to node i and the fraction of $h_j^{\text{out}}(\mathbf{p})$ sending to node i, respectively. By (4) and (5), the updating rule for the channel access probability p_i is expressed as the following iterative algorithm:

$$p_i(t+1) = p_i(t) - \gamma \left\{ h_i^{\text{rel}}(\mathbf{p}(t)) - \alpha h_i^{\text{in}}(\mathbf{p}(t)) \right\}, \tag{6}$$

where the step size $\gamma > 0$ and the target traffic forwarding capability $0 < \alpha < 1$.

The rationale for introducing α (< 1) in (6) is as follows. Consider the case of $\alpha = 1$. Then, once $h_i^{\text{in}}(\mathbf{p}) + h_i^{\text{gen}}$ becomes smaller than $g_i(\mathbf{p})$, $h_i^{\text{rel}}(\mathbf{p}) = h_i^{\text{in}}(\mathbf{p})$ in (4), and p_i will be unchanged in (6) for $\alpha = 1$ and remain an unnecessarily large value, which makes node i under-utilized while unnecessarily decreasing the throughput of neighbor nodes. This situation results in degradation of the end-to-end throughput. In fact, $h_i^{\text{in}}(\mathbf{p}) + h_i^{\text{gen}} < g_i(\mathbf{p})$ corresponds to the unsaturated condition of node i. Hence, we hereafter assume that every node operates under the saturation condition, i.e., $h_i^{\rm in}(\mathbf{p}) + h_i^{\rm gen} \geq g_i(\mathbf{p})$ is satisfied, by a proper choice of $\alpha < 1$.[2] Now, (6) becomes

$$p_i(t+1) = p_i(t) - \gamma f_i(\mathbf{p}(t)), \tag{7}$$

where $f_i(\mathbf{p(t)}) = g_i(\mathbf{p(t)}) h_i^{\rm in}(\mathbf{p(t)})/(h_i^{\rm in}(\mathbf{p(t)}) + h_i^{\rm gen}) - \alpha h_i^{\rm in}(\mathbf{p(t)})$.

As the adaptation of the channel access probability is applied only to the contention of packets that are being relayed, we assume $h_i^{\rm gen} = 0$ for simplicity of the following convergence analysis.

Theorem 1 *The update algorithm in (7) converges to a unique equilibrium of* $\mathbf{p}^*$ *if*

$$\gamma < v_{\rm min}^2 / \left[l \left\{ 1 + (\alpha+2) S_{\rm max} \right\} \max(T_b, T_c) \right],$$

and

$$\sum_{k \neq i} \left| \frac{\partial}{\partial p_k} \left(g_i(\mathbf{p(t)}) + \alpha \sum_{j \in S_i} \beta_{ji} g_j(\mathbf{p(t)}) \right) \right| < \frac{\partial f_i}{\partial p_i} \quad \textit{for } \forall \mathbf{p} \textit{ and } \forall i,$$

where $S_{\rm max} = \max_i S_i$ *and* $v_{\rm min} = \min_{\mathbf{p},i} v_i$.

Proof: The proof is omitted here due to the page limit. The interested readers may refer to [1]. ■

As a more specific result that can be applicable in practice, we derive a sufficient condition on the convergence of (7) under a chain topology with the one-hop interference model. We assume the saturation condition on the source node of the chain.

Corollary 1 *Under a chain topology with the one-hop interference model and the assumption that* $|\partial g_i / \partial p_i| \gg |\partial g_i / \partial p_j|$, $j \neq i$, [3] $\mathbf{p}(t)$ *generated by (7) converges to a unique equilibrium of* $\mathbf{p}^*$ *if* $\gamma < v_{\rm min}^2 / \{ l(\alpha+3) \max(T_b, T_c) \}$, *where* $v_{\rm min} = \min_{\mathbf{p},i} v_i$.

[2]In fact, our simulation studies show that a value of α which is slightly smaller than one is sufficient to make every node operate under the saturation condition.

[3]This condition corresponds to the case when the effect of change in p_i on g_i is larger than that in p_j on g_i, which is usually valid in practice.

Proof: For a chain topology with N hops, let node i, $i = 0, 1, \cdots, N$ denote the ith node from the sender ($i = 0$ corresponds to the sender itself.) By (6), the attempt probability of the sender, p_0, will not be changed because there is neither relayed traffic nor incoming traffic at the sender. Hence, from the first condition of Theorem 1, the condition can be easily derived under the one-hop interference model with $S_{\max} = 1$. In the meanwhile, it is straightforward to show that the second condition in Theorem 1 is satisfied under the above assumption. ■

Note that $v_{\min}$ is not directly available in advance. However, we can get its lower bound by using its definition in (2). For example, $v_i > p_{min}\, T_c$ where p_{min} and T_c are readily available.

Remark 1 (Effect of α on throughput in chain topology) *Under a chain topology, let* $\mathbf{p}^*(\alpha)$ *denote the equilibrium of* $\mathbf{p} := (p_1, \cdots, p_N)$ *obtained by (7) for a given* α *(*$0 < \alpha < 1$*). Then, the maximum sustainable throughput of each node* i*, denoted by* $g_i(\mathbf{p}^*(\alpha))$*, will satisfy* $g_i(\mathbf{p}^*(\alpha)) = \alpha g_{i-1}(\mathbf{p}^*(\alpha))$*,* $i = 1, \cdots, N$*, from (7). For a given* α *slightly smaller than one, we will have* $\mathbf{p}^*(\alpha) \simeq \mathbf{p}^*(1)$*. Thus, if we let* $T(\alpha)$ *denote the maximum sustainable end-to-end throughput for a given* α*, then* $T(\alpha) = \min_i g_i(\mathbf{p}^*(\alpha)) = \alpha^N g_0(\mathbf{p}^*(\alpha)) \simeq \alpha^N g_0(\mathbf{p}^*(1)) = \alpha^N T(1)$*, which shows that the ratio of the end-to-end throughput obtained by (7) to its maximum is approximately* α^N*. Consequently, as long as (7) converges, we need to increase* α *in order to increase the end-to-end throughput .*

Remark 2 (CW size vs. attempt probability) *To comply with IEEE 802.11 Standards, we propose in Algorithm 1 a control mechanism for the CW size rather than the attempt probability. As previous studies have indicated [2], the relationship between the contention window size* CW_i *and the attempt probability* p_i *is given as* $p_i = 2/(CW_i{+}1)$*. Thus, the results in Theorem 1 can be re-derived for* CW_i *in a straightforward manner, by using* $\partial f/\partial CW_i = (\partial f/\partial p_i)(dp_i/dCW_i) = [-2/(CW_i + 1)^2](\partial f/\partial p_i)$.

V. Experimental Results

To evaluate the performance of our proposed CWA algorithm over the IEEE 802.11 DCF, we have implemented the proposed contention window adaptation mechanism in the MadWifi Linux kernel driver (version 0.9.1.2), which enables us to measure the rates of incoming and outgoing traffic and to adjust the minimum contention window size periodically. The multihop wireless paths with 5-node and 6-node are configured with 6 and 7 laptops, respectively, on the fourth floor in our department building. Each node is a Lenovo 300 N100 laptop equipped with a 3COM 802.11a/b/g wireless card (based on Atheros chipset). The wireless cards is configured to operate in IEEE 802.11a mode because the 5 GHz frequency band for IEEE 802.11a is less used in our building. We observe that each node can exchange packets only with its immediate neighboring nodes in our configuration. We use the *iperf* tool to generate UDP traffic flows and to measure the end-to-end throughput. The throughput of relayed traffic at each relay node is also measured by the *tcpdump* tool.

Recall that the main purpose of the proposed CWA mechanism is to prevent unnecessary packet losses due to a different forwarding capability of each relay node. If the contention among nodes is not severe in cases that the offered load is kept low by a traffic regulating load control or there exist a small number of TCP flows, the unnecessary packet losses would not be a dominant cause of the end-to-end performance degradation. To show the effectiveness of CWA in a throughput saturation environment, we do not consider lightly offered load cases in our experiments.

First, we evaluate the performance of IEEE 802.11 DCF with respect to the minimum window size $\mathrm{CW}_{\min}$ in 4-hop and 5-hop wireless paths. We vary the value of $\mathrm{CW}_{\min}$ to 16, 32, and 64. Table I shows the average and standard deviation of the end-to-end throughput. We observe that the change of $\mathrm{CW}_{\min}$ does not make a significant effect on the end-to-end throughput performance of the multihop paths as discussed in Section II (Fig. 2). This implies that it cannot improve the end-to-end throughput performance to assign a same value of $\mathrm{CW}_{\min}$ to all the nodes with a different forwarding capability on the multihop path.

To the contrary, the adaptive contention mechanism enables each relay node to independently adjust $\mathrm{CW}_{\min}$ depending on the forwarding capability, As a result, the end-to-end throughput is increased to 7.46 and 5.31 Mb/s in 4-hop and 5-hop paths, which correspond to about 40 and 112 % performance improvement, respectively.

A. Throughput decrease at relay nodes

To investigate the reason of the throughput decrease that happens at each relay node, we measure the rate of traffic being received and transmitted at relay nodes with the use of the tcpdump tool. Fig. 3 shows the rate of incoming traffic at each relay node in 4-hop and 5-hop paths. In Figs. 3 and 4, the vertical line indicates the 95 % confidence interval of each experiment. We observe that under the IEEE 802.11 DCF, the receiving rate at the first relay node is approximately twice and five times higher than that of the other relay nodes in the 4-hop and 5-hop wireless paths, respectively. This implies that the source node transmits so many packets excessively at a high rate, and the first relay node cannot forward them at the same rate as they are received. The reason is that the source node has the smaller number of neighboring nodes that it should compete with than the the first relay node, and thus, it has more channel access opportunities. For the proposed contention window adaptation mechanism, the throughput of relayed traffic is almost constant from the first node to the destination, because each relay node adjusts its contention level in order to equate the traffic forwarding capabilities among all the nodes on the path, resulting in the performance improvement of the end-to-end throughput in multihop wireless paths.

B. *Effect of α on throughput performance*

We investigate the effects of α on the end-to-end throughput performance. Recall that α is the target traffic forwarding capability, which each relay node is expected to have in a steady state. Fig. 4 shows the end-to-end throughput achieved by the proposed algorithm for α = 0.8, 0.85, 0.9, and 0.95 in the 4-hop and 5-hop paths. We observe that α makes differences of the converged value of $\mathrm{CW_{min}}$, and a larger value of α gives higher end-to-end throughput. However, the selection of α does not significantly affect the end-to-end throughput performance, because what is more important is a relative magnitude of $\mathrm{CW_{min}}$ among nodes rather than its absolute value. This is in part due to the BEB mechanism in IEEE 802.11 DCF. Note that we adjust the minimum window size $\mathrm{CW_{min}}$ rather than directly the window size CW in the contention mechanism. Under the BEB mechanism, the contention window size CW is initially set to $\mathrm{CW_{min}}$ and is doubled after each transmission collision. Once a node with a small $\mathrm{CW_{min}}$ experiences a collision, its contention window size CW could be much larger than that of other nodes.

C. *Variation of CW_{min} with respect to α*

Fig. 5 shows the variation of $\mathrm{CW_{min}}$ value at each relay node under the contention window adaptation mechanism in the 4-hop and 5-hop paths. The $\mathrm{CW_{min}}$ is initially set to 31. In the 4-hop path, the first relay node experiences the severe intra-flow interference and reduces its $\mathrm{CW_{min}}$ value as shown in Fig. 5(a) and (b) in order to have higher channel access rate, which enables it to forward packets at the same rate as they are received. The other relay nodes do not reduce their $\mathrm{CW_{min}}$, because the receiving rate of traffic is low enough to be forwarded without packet losses. In the 5-hop path, both the first and the second relay nodes reduce their $\mathrm{CW_{min}}$ value as shown in in Fig. 5(c) and (d). In the 5-hop path, the second relay node has hidden terminals (i.e., 4th and 5th), and its transmissions may be interfered with by those of the hidden terminals. Another parameter that affects the variation of $\mathrm{CW_{min}}$ is the target traffic forwarding capability α. We observe the larger α gives the smaller converged value of $\text{CW}_{\min}$ in Fig. 5.

D. Simulation results in a large network

To evaluate the performance of CWA in a larger network, we have also carried out ns-2 simulation in a random topology where 50 nodes are randomly placed in a 1500 x 1500 m area. [4] We vary the number of source-destination pairs from one to five pairs. Fig. 6 shows the throughput performance for IEEE 802.11 DCF with a fixed $\text{CW}_{\min}$ and the proposed CWA algorithm. The CWA algorithm gives the higher throughput than IEEE 802.11 DCF in all the cases. We observe that as the number of source-destination pairs increases, the level of the throughput improvement becomes more apparent.

VI. CONCLUSION

We have studied the issue of improving the end-to-end throughput performance of IEEE 802.11 DCF-operated multihop wireless networks. In particular, we have focused on the use of contention resolution algorithms, e.g., the BEB mechanism in IEEE 802.11 DCF. We have proposed a fully distributed contention window adaptation (CWA) scheme for tuning the minimum contention window size, $\text{CW}_{\min}$, in order to equate the forwarding capability of every node on a multihop wireless path, with the objective of improving the end-to-end throughput of the multihop path. We have derived a sufficient condition for the convergence of the proposed algorithm. We have implemented the contention window adaptation mechanism on Linux kernel driver and carried out an empirical study in a multihop chain topology. The experimental results have shown that the proposed scheme significantly outperforms the IEEE 802.11 DCF in terms of the end-to-end throughput performance.

[4]We have also performed extensive ns-2 simulations under a wide variety of network scenarios, which shows the 20–40% improvements of the proposed algorithm over the IEEE 802.11 DCF. However, due to the page limit, we do not include all the simulation results here. The interested readers may refer to [1].

References

[1] H. Lim, D. Jung, J. Hwang, K.-J. Park, and J. C. Hou, "Contention control for high end-to-end throughput performance of wireless mesh networks," in *Proc. of International Wireless Internet Conference (WICON)*, 2007.

[2] F. Cali, M. Conti, and E. Gregori, "Dynamic tuning of the IEEE the 802.11 protocol to achieve a theoretical throughput limit," *IEEE/ACM Transactions on Networking*, 2000.

[3] G. Bianchi, "Performance analysis of the IEEE 802.11 distributed coordination function," *IEEE journal of Selected Areas in Communications(JSAC)*, 2003.

[4] G. Bianchi and I. Tinnirello, "Kalman filter estimation of the number of competing terminals in an IEEE 802.11 network," in *Proc. of IEEE INFOCOM*, 2003.

[5] Y. Kwon, Y. Fanf, and H. Latchman, "A novel MAC protocol with fast collision resolution for wireless LANs," in *Proc. of IEEE INFOCOM*, 2003.

[6] H. Wu, Y. Peng, K. Long, S. Cheng, and J. Ma, "Performance of reliable transport protocol over IEEE 802.11 wireless LAN: Analysis and enhancement," in *Proc. of IEEE INFOCOM*, 2002.

[7] L. Li, J. Y. Halpern, P. Bahl, Y.-M. Wang, and R. Wattenhofer, "Analysis of a cone-based distributed topology control algorithm for wireless multi-hop networks," in *Proc. of ACM Symsposium on Princoples of Distributed Computing*, 2001.

[8] S. Narayanaswamy, V. Kawadia, R. S. Sreenivas, and P. Kumar, "Power control in ad-hoc networks: Theory, architecture, algorithm and implementation of the COMPOW protocol," in *Proc. of European Wireless 2002* , 2002.

[9] R. Ramanathan and R. Rosales-Hain, "Topology control of multihop wireless networks using transmit power adjustment," in *Proc. of IEEE INFOCOM*, 2000.

[10] V. Rodoplu and T. H. Meng, "Minimum energy mobile wireless networks," *IEEE J. Selected Areas in Communications*, vol. 17, no. 8, pp. 1333–1344, 1999.

[11] N. Li, J. C. Hou, and L. Sha, "Design and analysis of a MST-based distributed topology control algorithm for wireless ad-hoc networks," *IEEE Trans. on Wireless Communications*, vol. 4, no. 3, pp. 1195–1207, 2005.

[12] J. Monks, V. Bharghavan, and W.-M. Hwu, "A power controlled multiple access protocol for wireless packet networks," in *Proc. of IEEE INFOCOM*, 2001.

[13] A. Muqattash and M. Krunz, "Power controlled dual channel (PCDC) medium access protocol for wireless ad hoc networks," in *Proc. of IEEE INFOCOM*, 2003.

[14] A. Muqattash and M. Krunz, "A single-channel solution for transmission power control in wireless ad hoc networks," in *Proc. of Mobihoc*, 2004.

[15] X. Yang and N. Vaidya, "On the physical carrier sense in wireless ad hoc networks," in *Proc. of IEEE INFOCOM*, 2005.

[16] Y. Yang, J. C. Hou, and L.-C. Kung, "Modeling of physical carrier sense in multi-hop wireless networks and its use in joint power control and carrier sense adjustment," in *Proc. of IEEE INFOCOM Miniconferences*, 2007.

[17] J. Zhu, S. Roy, X. Guo, and W. Conner, "Maximizing aggregate throughput in 802.11 mesh networks with physical carrier sensoring and two-radio multichannel clustering," in *Proc. of Workshop on Pervasive Computing and Networking*, 2004.

[18] J. Zhu, X. Guo, L. Yang, and W. S. Conner, "Leveraging spatial reuse in 802.11 mesh networks with enhanced physical carrier sensing," in *Proc. of IEEE ICC*, 2004.

[19] A. Vasan, R. Ramjee, and T. Woo, "ECHOS: Enhanced capacity 802.11 hotspots," in *Proc. of IEEE INFOCOM*, 2005.

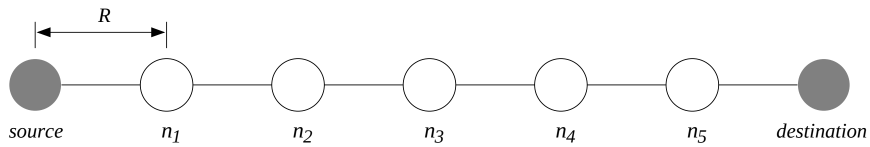


Fig. 1. A multihop wireless path consisting of a source node, a destination node, and five relay nodes.

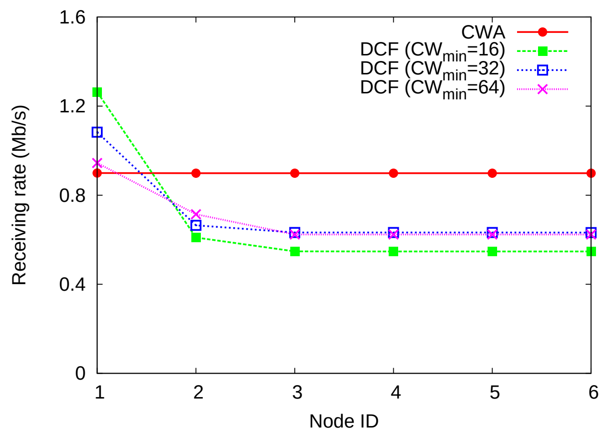
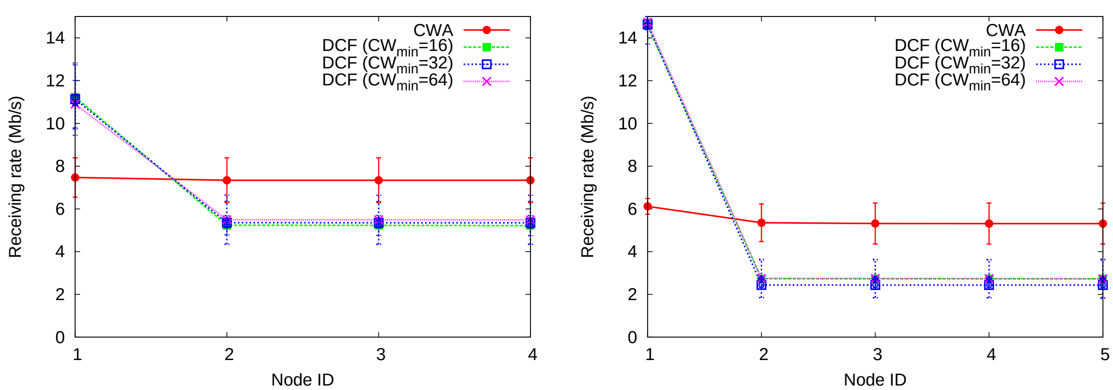


Fig. 2. Receiving traffic rate at each relay node on a 6-hop wireless path for a fixed, single $\mathrm{CW}_{\min}$ and an adaptively selected $\mathrm{CW}_{\min}$. (The reiving rate at the last node is the end-to-end throughput of the multihop wireless path.)



(a) 4-hop path.

(b) 5-hop path.

Fig. 3. Experimental throughput performance for IEEE 802.11 DCF and the proposed adaptive contention mechanism (CWA).

Algorithm 1 Adaptive contention algorithm for each node

```
// InPackets: the number of all the incoming packets for T
// DstPackets: the number of outgoing packets whose destination is itself.
PureInPackets = InPackets - DstPackets

// OutPackets: the number of all the outgoing packets for T
// SrcPackets: the number of incoming packets whose source is itself.
PureOutPackets = OutPackets - SrcPackets

if PureOutPackets > PureInPackets then
    PureOutPackets ← PureInPackets
end if

CW_min ← CW_min + (γ/T) · (PureOutPackets − α · PureInPackets)

if CW_min > max_th then
    CW_min ← max_th
else if CW_min < min_th then
    CW_min ← min_th
end if
```

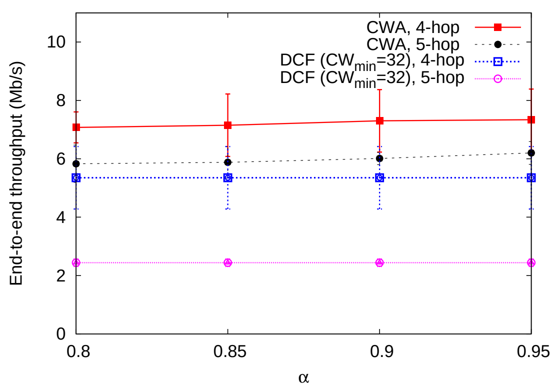
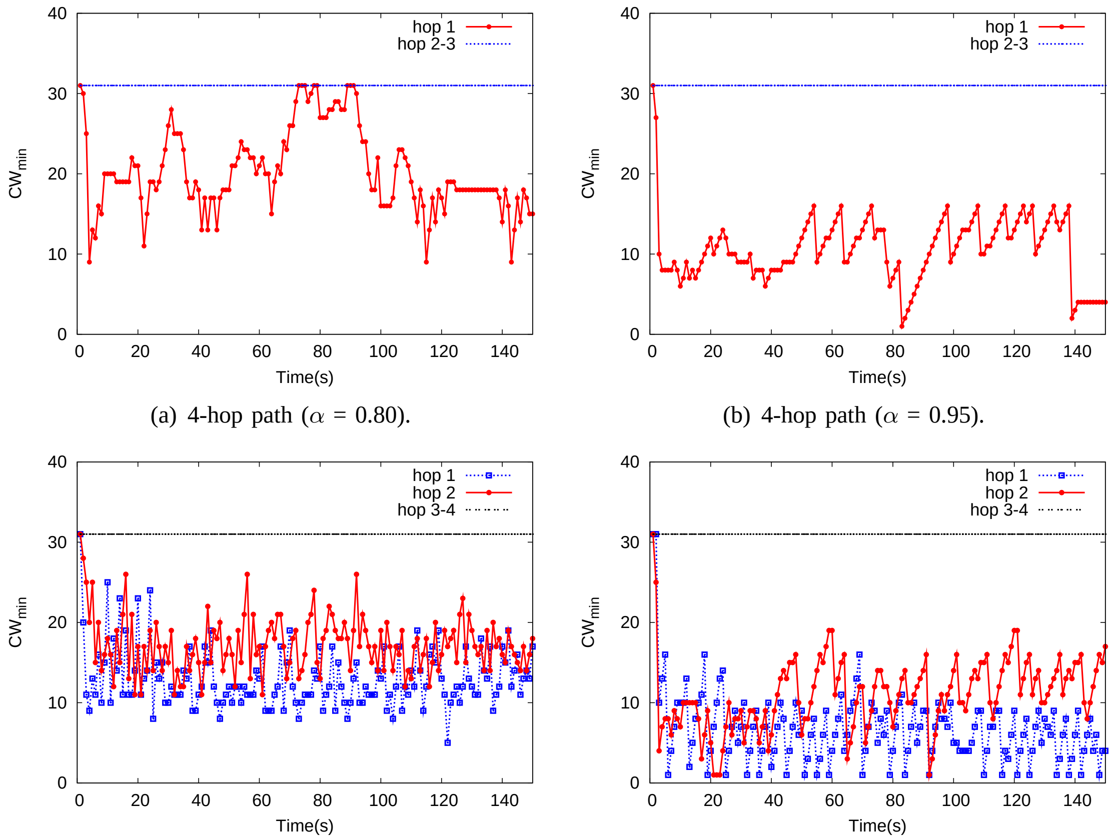


Fig. 4. Experimental throughput performance with respect to α in the 4-hop and 5-hop wireless paths.

TABLE I
END-TO-END THROUGHPUT PERFORMANCE IN 4-HOP AND 5-HOP WIRELESS PATH (MBITS/S).

Topology	Metric	IEEE 802.11 DCF			CWA
		CW_{min}=16	CW_{min}=32	CW_{min}=64	
4-hop	Avg	5.24	5.36	5.50	7.46
	Std	0.60	1.34	1.40	0.76
5-hop	Avg	2.73	2.43	2.73	5.31
	Std	0.63	0.09	0.66	0.83



(a) 4-hop path (α = 0.80).

(b) 4-hop path (α = 0.95).

(c) 5-hop path (α = 0.80).

(d) 5-hop path (α = 0.95).

Fig. 5. Variation of $\mathrm{CW}_{\min}$ with respect to time in the 4-hop and 5-hop wireless paths.

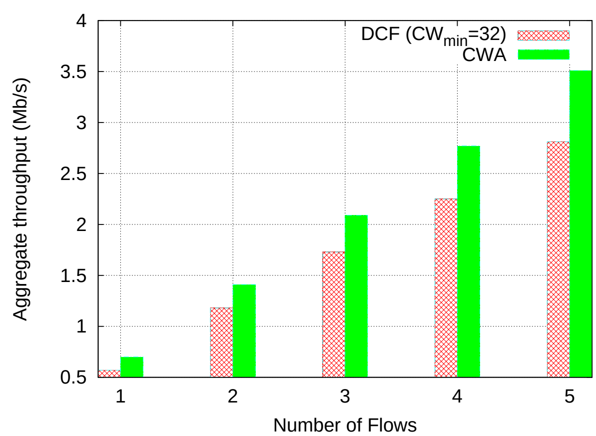


Fig. 6. Simulation result for the aggregate throughput performance with respect to the number of flows in a random topology.