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

[Invited Paper]

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ABSTRACT

In multihop wireless networks, packets of a flow originated from a source node are relayed by intermediate nodes (relay nodes) and travel towards the destination along a multihop wireless path. Since the traffic forwarding capability of each node varies according to its level of contention, a node should not transmit excessive packets to its relay node if the corresponding relay node cannot forward them. Instead, the 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 mechanism, which adjusts the channel access probability depending on the difference between the incoming traffic and the outgoing traffic at each node, in order to equate the traffic forwarding capabilities among all the nodes in the path. If the incoming rate of a node is larger/smaller than its outgoing rate, the forwarding capability of that node should be increased/decreased so as to match the outgoing rate with the incoming rate. In the proposed mechanism, a node is granted to increase/decrease its channel access probability if its traffic forwarding capability is worse/better than those of competing neighbor nodes. We give a convergence analysis of the proposed scheme as well as its steady-state performance. Through simulation, we show that the end-to-end throughput of multihop wireless path can be improved by 20–40% under variety of network topologies and traffic patterns.

Categories and Subject Descriptors

C.2.1 [**COMPUTER-COMMUNICATION NETWORKS**]: Network Architecture and Design—*Wireless communication*

General Terms

Algorithms, Performance

Keywords

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

1. INTRODUCTION

Multihop wireless networks have received considerable attention in recent years, primarily because of their wide civilian and military applications, and their capability of 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 originated from a source node are relayed by intermediate nodes (relay nodes) and travel towards the destination along a multihop wireless path. In this manner, any pairs of nodes in multihop wireless networks can exchange their packets over multihop wireless paths.

One of the critical performance metrics in multihop wireless networks is the network throughput. It highly depends on the achievable channel capacity at each individual wireless link and the level of spatial reuse. To improve the overall network capacity in multihop wireless networks, extensive studies have been carried out. (We will give a detailed summary of related work in Section 3.) 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. The transmit power and the carrier sense threshold are key parameters for exploiting spatial reuse and for improving the network capacity of wireless networks. The channel access probability is another crucial parameter that determines the level of contention among nodes in wireless networks. In particular, assigning an appropriate value for the channel access probability is an effective technique to mitigate MAC-level contention and interference and improve the throughput of multihop wireless networks.

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 IEEE 802.11 DCF is carrier sense multiple access with collision avoidance (CSMA/CA). Furthermore, to resolve contention among competing nodes, the binary exponential back-off (BEB) algorithm is adopted in IEEE 802.11 DCF. A node that intends to transmit first senses the channel and defers its transmission while the channel is sensed busy.

When the channel is sensed 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 $[0, \text{CW} - 1]$ where CW is the contention window size. CW is initially set to its minimum value $\text{CW}_{\min}$, and is doubled up to its maximum value $\text{CW}_{\max}$ after each transmission collision. The back-off timer is decreased by one if the channel is sensed idle for one physical slot time, suspended if the channel is sensed busy, and reactivated after the channel is sensed idle again for a DIFS. The node transmits its frame when the back-off timer becomes zero. After 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)*, that is less than DIFS. If an acknowledgment frame is not received, the data frame is presumed to be lost, and a retransmission is scheduled. Retransmissions for the same data frame can be made up to a pre-determined retry limit, L, times. Beyond this limit, the pending frame will be dropped. The CW value is reset to $\text{CW}_{\min}$ when a frame has been successfully transmitted. Note that it has been shown in previous studies, e.g, [5], that the channel access probability is a function of CW, i.e., $2/(CW+1)$ 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, CW_{min}, of the BEB mechanism in a distributed manner. In particular, we consider the following two major issues: (i) how does CW_{min} affect the end-to-end throughput of a multihop wireless path? (ii) if it is not sufficient for all the nodes on a multihop wireless path to use an optimal but fixed CW_{min} value, how does each node adaptively and independently adjust its CW_{min} value? To address the first issue, we first verify via simulation in Section 2 that the BEB algorithm with a fixed value of 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 $\text{CW}_{\min}$ by considering the level of traffic forwarding ratio. If the current ratio of incoming packets to outgoing packets is above/below than a pre-determined forwarding capability (which we set to between 0 and 1) in a given interval, the $\text{CW}_{\min}$ 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. Moreover, through simulation, we show that the end-to-end throughput of a multihop wireless path can be improved by 20–40% under a wide variety of network topologies and traffic patterns.

The rest of the paper is organized as follows: In Section 2 we motivate our proposed work by evaluating the throughput performance of a multihop wireless path. In Section 3, we provide a summary of related work in literature. In Section 4, we propose a contention window adaptation algorithm for maximizing the end-to-end throughput in multihop wireless networks. This is then followed by a simulation study in Section 5. Finally, we conclude the paper in Section 6.

2. MOTIVATION

To investigate how the contention among nodes affects the end-to-end throughput of a multihop wireless path, we perform simulation for a chain topology with 7 nodes operating in the IEEE 802.11 DCF mode (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. Since the number of competing neighbor nodes determines the transmission attempt rate, each node will have different forwarding capability depending on its deployment.

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 $\text{CW}_{\min}$) that gives the maximal throughput of the multihop path. Figure 2(a) shows the throughput performance when $\text{CW}_{\min}$ = 16, 32, and 64. Note that each node has a fixed value of $\text{CW}_{\min}$, which is the same for all the nodes, 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(a):

- 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 $\text{CW}_{\min} = 16$. 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 $\text{CW}_{\min}$ 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 within the same carrier sense range accesses the wireless medium aggressively, other nodes have a lesser 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 $\text{CW}_{\min} = 16$ 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 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 are 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 $\text{CW}_{\min}$ value, the node with the largest forwarding capability may grasp 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.

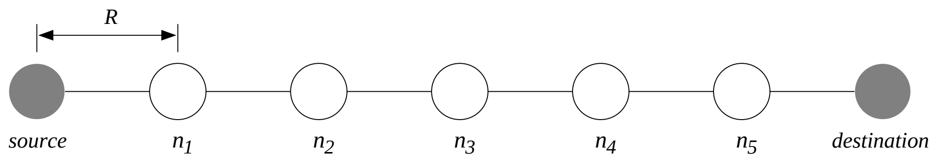
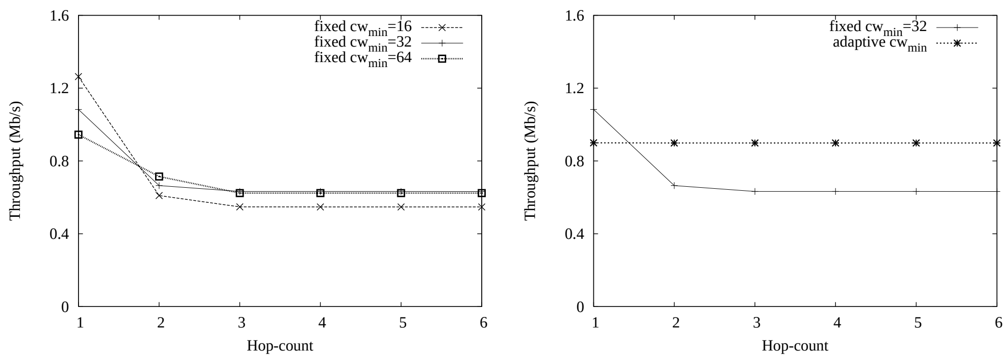


Figure 1: A multihop wireless path consisting of a source node, a destination node, and five relay nodes.



(a) A same $\mathrm{CW_{min}}$ for all the nodes.

(b) A different $\mathrm{CW_{min}}$ adaptively selected for each node.

Figure 2: Throughput performance of a 6-hop wireless path for a fixed, single $\mathrm{CW_{min}}$ and an adaptively selected $\mathrm{CW_{min}}$. (The throughput at the last hop-count is the end-to-end throughput of the multihop wireless path.)

Fig. 2(b) shows the throughput result when the $\mathrm{CW_{min}}$ value of each node is adjusted (by our proposed algorithm in Section 4). It is noticeable that the throughput achieved under the $\mathrm{CW_{min}}$ 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 comparison with the fixed $\mathrm{CW_{min}}$ case, the $\mathrm{CW_{min}}$ adaptation scheme only renders a lower throughput at the first hop. The throughput at all the other hops as well as the end-to-end throughput is higher with the use of the $\mathrm{CW_{min}}$ adaptation scheme. 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.

3. 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.

3.1 Tuning of the Back-off Parameters

In IEEE 802.11 DCF, the back-off parameters such as $\mathrm{CW_{min}}$ and $\mathrm{CW_{max}}$ are fixed, which is insufficient to guarantee a satisfactory performance under various network scenarios such as different network densities, different network topologies, and/or different network loads. To analyze the impact of the back-off parameters on network performance, Bianchi proposed a model for the back-off process by a two-dimensional Markov chain [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. Accordingly, extensive studies on improving network capacity by adapting back-off parameters have been carried out [4–6, 16]. Cali *et al*. [5] 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. Bianchi and Tinnirello [4] showed that the number of competing stations can be expressed as a function of the collision probability on the channel. Then, they proposed an extended Kalman filer with a change detection mechanism in order to estimate the number of competing stations. Kwon *et al*. [6] 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.

3.2 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, 8, 12–14]. Power control for the purpose of increasing spatial reuse and network capacity has been treated in the PCMA protocol [9], the PCDC protocol [10], and the POWMAC protocol [11]. In [9], 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 [10, 11] respectively. The PCDC protocol constructs the network topology by overhearing RTS/CTS packets, and the calculated interference margin is announced over an out-of-band channel. On the other hand, the POWMAC protocol uses a single channel for exchanging information on the interference margin.

3.3 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, 17–21]. Zhu *et al.* [21] determined an optimal carrier sense threshold value which maximizes spatial reuse for several regular topologies. Based on the SINR (signal to interference plus noise ratio) required to sustain a predetermined transmission rate, Zhu *et al.* proposed in [20] 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.* [15] 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 Vaida [18] considered several factors such as MAC overhead, transmission rate, and network density in selecting optimal carrier sense threshold that maximizes the aggregate throughput. More recently, Yang *et al.* [19] proposed a joint control algorithm for allowing each node to determine the transmit powers and the carrier sense thresholds in a distributed manner, with the objective of maximizing the network capacity. Note that the control algorithm adjusts the carrier sense threshold of each node (to eliminate hidden nodes) in a static manner.

4. 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, consecutive packets in a single flow may be spread over the route to their destination and may interfere with one another. 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 neighbor node without packet loss, then α_i is equal to 1. 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 1. 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 neighbor 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. To maximize the throughput, α^* should be close to 1. 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.

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 $\leftarrow$ PureInPackets
end if

$\mathrm{CW}_{\min} \leftarrow \mathrm{CW}_{\min} + \frac{\gamma}{T} \cdot$ (PureOutPackets – $\alpha \cdot$ PureInPackets)

if $\mathrm{CW}_{\min} > max_{th}$ **then**
    $\mathbf{CW}_{\min} \leftarrow max_{th}$
else if $\mathrm{CW}_{\min} < min_{th}$ **then**
    $\mathbf{CW}_{\min} \leftarrow min_{th}$
end if

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:

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

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 capacity α^*. Note that in a steady state, α_i becomes α^*. [1] In what follows, we will first explain the detailed algorithm, and then show the convergence analysis of the proposed algorithm.

4.1 Adaptive Contention Algorithm

We devise a fully distributed algorithm for each node to independently and adaptively determine the minimum contention window size CW_{min}. The proposed adaptation rule in Eq. (1) needs neither the status information of neighbor nodes nor the topology information of the multihop path such as the 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. The updated $\mathrm{CW}_{\min}$ affects only new packet transmissions 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

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

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, 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 Eq. (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 Eq. (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.

4.2 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 [19], 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. However, our analysis can be straightforwardly extended to a general network 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 given that a transmission attempt is made. Then, q_i can be expressed as

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

where C_i denote the set of nodes whose simultaneous transmission will collide with node i. Further, the average virtual time slot seen by node i, denoted by v_i, is

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

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. Now, we can obtain the saturation throughput of node i, denoted by $g_i(\mathbf{p})$ where $\mathbf{p} = (p_1, \cdots, p_N)$, as follows.

$$g_i(\mathbf{p}) = \frac{l p_i \left(1 - q_i(\mathbf{p}_{-i})\right)}{v_i(\mathbf{p})}, \qquad (2)$$

where $\mathbf{p}_{-i} = (p_1, \cdots, p_{i-1}, p_{i+1}, \cdots, p_N)$ and l is the payload size.

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

$$h_i^{\mathrm{out}} = \begin{cases} g_i, & \text{if } h_i^{\mathrm{in}} + h_i^{\mathrm{gen}} \geq g_i; \\ h_i^{\mathrm{in}} + h_i^{\mathrm{gen}}, & \text{otherwise.} \end{cases}$$

and

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

Also,

$$h_i^{\mathrm{in}} = \sum_{j \in S_i} \beta_{ji} h_j^{\mathrm{out}}, \qquad (3)$$

where S_i and β_{ji} denote a set of nodes sending traffic to node i and the fraction of h_j^{out} sending to node i, respectively.

At each time instance, we update the channel access probability p_i according to the following iterative algorithm.

$$p_i(t+1) = p_i(t) - \gamma \left\{ h_i^{\mathrm{rel}}(\mathbf{p}(t)) - \alpha h_i^{\mathrm{in}}(\mathbf{p}(t)) \right\}, \qquad (4)$$

where the step size $\gamma > 0$ and $0 < \alpha < 1$.

The rationale for introducing α (< 1) in Eq. (4) is as follows. Consider the case of $\alpha = 1$. Then, once $h_i^{\mathrm{in}}(\mathbf{p}) + h_i^{\mathrm{gen}}$ becomes smaller than $g_i(\mathbf{p})$, $h_i^{\mathrm{rel}}(\mathbf{p}) - \alpha h_i^{\mathrm{in}}(\mathbf{p}) = 0$ in Eq. (4) and p_i will be unchanged 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. The condition of $h_i^{\mathrm{in}}(\mathbf{p}) + h_i^{\mathrm{gen}} < g_i(\mathbf{p})$ corresponds to the unsaturated condition of node i. Hence, we hereafter assume that every node operates under the saturation condition, i.e., $h_i^{\mathrm{in}}(\mathbf{p}) + h_i^{\mathrm{gen}} \geq g_i(\mathbf{p})$ is satisfied, by a proper choice of $\alpha < 1$.[2] Then, Eq. (4) becomes

$$p_i(t+1) = p_i(t) - \gamma f_i(\mathbf{p}(t)), \qquad (5)$$

where $f_i(\mathbf{p}(\mathbf{t})) = g_i(\mathbf{p}(\mathbf{t})) h_i^{\mathrm{in}}(\mathbf{p}(\mathbf{t})) / (h_i^{\mathrm{in}}(\mathbf{p}(\mathbf{t})) + h_i^{\mathrm{gen}}) - \alpha h_i^{\mathrm{in}}(\mathbf{p}(\mathbf{t}))$. Now, we give the convergence result of Eq. (5) as follows.

Theorem 1 *The update algorithm (Eq. (5)) converges to a unique equilibrium of* $\mathbf{p}^*$ *if*

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

and

$$\sum_{k \neq i} \frac{\partial}{\partial p_k} \left(\left| \frac{g_i \sum_{j \in S_i} \beta_{ji} g_j}{\sum_{j \in S_i} \beta_{ji} g_j + h_i^{\mathrm{gen}}} \right| + \alpha \left| \sum_{j \in S_i} \beta_{ji} g_j \right| \right) < \frac{\partial f_i}{\partial p_i},$$

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

PROOF. By Eq. (5), together with Eq. (3) and $h_i^{\mathrm{in}} + h_i^{\mathrm{gen}} \geq g_i$,

$$\begin{aligned} \left| \frac{\partial f_i}{\partial p_i} \right| &= \left| \frac{h_i^{\mathrm{in}} \frac{\partial g_i}{\partial p_i} + g_i \frac{\partial h_i^{\mathrm{in}}}{\partial p_i}}{h_i^{\mathrm{in}} + h_i^{\mathrm{gen}}} - \frac{g_i h_i^{\mathrm{in}} \frac{\partial h_i^{\mathrm{in}}}{\partial p_i}}{(h_i^{\mathrm{in}} + h_i^{\mathrm{gen}})^2} - \alpha \frac{\partial h_i^{\mathrm{in}}}{\partial p_i} \right| \\ &\leq \left| \frac{\partial g_i}{\partial p_i} \right| + (\alpha + 2) \sum_{j \in S_i} \beta_{ji} \left| \frac{\partial g_j}{\partial p_i} \right| \\ &\leq \left| \frac{\partial g_i}{\partial p_i} \right| + (\alpha + 2) S_{\max} \left| \frac{\partial g_j}{\partial p_i} \right|, \qquad (6) \end{aligned}$$

[2] In fact, our simulation studies show that a value of α which is slightly smaller than 1 is sufficient to make every node operate under the saturation condition.

Table 1: Default parameters used in ns-2 simulation.

Propagation	Two-ray	Antenna height	1.5 m
Tx power	8.58 dBm	SNR thresh	10 dB
Rx thresh	-64.37 dBm	CS thresh	-78.07 dBm
Fixed CW_{max}	1023	RTS/CTS	Enabled
DCF $\mathrm{CW}_{\min}$	31	Data rate	5 Mb/s
max_{th}	31	Target capability α	0.99
min_{th}	1	Step size γ	0.09
Routing	AODV/Static	Sampling interval T	1 s

where $S_{\max} = \max_{i \in \mathcal{N}} S_i$. Meanwhile, by Eq. (2),

$$\frac{\partial g_i}{\partial p_i} = \frac{l(1-q_i)(p_i\sigma + (1-p_i)T_b)}{v_i^2}, \tag{7}$$

and

$$\left|\frac{\partial g_j}{\partial p_i}\right| \leq \left|\frac{lp_j}{v_j^2}(p_jT_c + (1-p_j)T_b) \prod_{k \in C_j \setminus i}(1-p_k)\right|. \tag{8}$$

Hence, by Eqs. (7) and (8), Eq. (6) can be expressed as

$$\left|\frac{\partial f_i}{\partial p_i}\right| \leq \frac{l\{1+(\alpha+2)S_{\max}\}\max(T_b, T_c)}{v_{\min}^2}, \tag{9}$$

where $v_{\min} = \min_{\mathbf{p},i} v_i$. Consequently, from [2, Proposition 1.1 and 1.11 in Chap. 3], $\mathbf{p}(t)$ generated by Eq. (5) converges to a unique equilibrium, denoted by $\mathbf{p}^*$, if

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

and $\sum_{k \neq i} |\partial f_i / \partial p_k| < \partial f_i / \partial p_i$, which becomes, by Eq. (5),

$$\sum_{k \neq i} \frac{\partial}{\partial p_k}\left(\left|\frac{g_i \sum_{j \in S_i} \beta_{ji} g_j}{\sum_{j \in S_i} \beta_{ji} g_j + h_i^{\text{gen}}}\right| + \alpha\left|\sum_{j \in S_i} \beta_{ji} g_j\right|\right) < \frac{\partial f_i}{\partial p_i},$$

for $\forall \mathbf{p}, \forall i$. □

Remark 1 (Stability-throughput tradeoff) *In general, there exists a tradeoff between the performance and the convergence of (5): As α decreases/increases, the convergence region will expand/contract while the end-to-end throughput will decrease/increase. Nevertheless, the conditions for convergence in Theorem 1 is not necessary but sufficient. In practice, for the convergence of (5), α only needs to be slightly smaller than 1. We will further look into the effect of α through extensive simulations in the next section.*

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. However, as previous studies have indicated [5], the relationship between the contention window size CW_i and the attempt probability p_i can be expressed as $p_i = 2/(CW_i + 1)$ in an average sense. Thus, all the results in Theorem 1 can be re-derived for CW_i in a straightforward manner, by simply using $\partial f / \partial CW_i = (\partial f / \partial p_i)(dp_i / dCW_i) = [-2/(CW_i + 1)^2](\partial f / \partial p_i)$.*

5. SIMULATION RESULTS

To evaluate the performance of our proposed algorithm and compare it against IEEE 802.11 DCF, we have carried extensive simulations using ns-2 in a variety of network scenarios. We have implemented the proposed adaptive contention algorithm in ns-2 (version 2.30), and for more accurate simulation have modified ns-2 such that i) the interference perceived at a receiver is the collective aggregate interference from all the concurrent transmissions; and ii) each node uses physical carrier sense to determine if the medium is free.

The parameter values used in the simulation are given in Table 1. With the parameter setting, the transmission range is approximately 100 m and the carrier sense range is 220 m. The distance of adjacent nodes is set to 90 m for all the simulations. Our simulations are conducted in the following topologies:

- Chain topology: The nodes are placed in a row, and the first node and the last node on the chain are the source node and the destination node, respectively, as shown in Fig. 1. The number of nodes varies from 2 to 9 to evaluate the throughput performance with respect to the number of hops.
- Cross topology: A cross topology consists of two 6-hop chain topologies, which cross at the center node. Nodes near the center node are affected by the interference from the flows belonging to the other multihop path.
- Grid topology: A total of 49 nodes are configured in a 7x7 grid topology. Every node in the network has four neighboring nodes. Packets may be forwarded toward the destination along a detour path as well as the shortest path depending on the routing algorithms.

Both AODV and static routing are used in the cross and grid topologies. We do not consider mobility or node failures in the simulation study. Note that the performance under AODV may not be accurate because it is affected by the route discovery time, route failure, and route re-discovery time in the AODV protocol. Therefore, we also carry out simulation under static routing [1], in order to exclude the effect of routing algorithms on the throughput performance in the cross and grid topologies. We vary the offered traffic load by changing the sending rates of CBR connections from 0.5 Mb/s to 2 Mb/s in the chain, cross, and grid topologies. Each simulation runs for 1000 seconds.

We will first evaluate how the parameters in the contention window adaptation algorithm such as the step size (γ), the traffic forwarding capability (α), the maximum threshold of $\mathrm{CW}_{\min}$ (max_{th}), and the sampling time (T) affect the throughput performance in the chain topology. Then we will compare the performances of the proposed contention algorithm and IEEE 802.11 DCF in a wide variety of multihop network scenarios.

5.1 Performance evaluation in the chain topology

5.1.1 *The variation of* $\mathrm{CW}_{\min}$ *w.r.t.* α *and* γ

First we carry out simulation in the chain topology. As shown in (1), there are two tunable parameters of α and γ, of which the former is the target traffic forwarding capability and the latter is the step size for the adaptive rule.

Fig. 3(a) depicts $\mathrm{CW}_{\min}$ for the default parameters setting in Table 1. $\mathrm{CW}_{\min}$ is initially set to 31. Starting from the initial value at t = 0, $\mathrm{CW}_{\min}$ gradually converges in less than tens of seconds and then fluctuates constantly. The converged value of $\mathrm{CW}_{\min}$ for each hop is dependent on the interference level it experiences. The first relay node n_1 (at the first hop in Figure 1) has the smallest $\mathrm{CW}_{\min}$ because it receives too many packets but cannot forward them due to the severe intra-flow interference from the source node. The second and third relay node have the second and third smallest $\mathrm{CW}_{\min}$, respectively, while the remaining nodes have the maximum value max_{th}. The reason is that from the 4th hop, the contention among nodes is not severe because they are far from the source node and the rate of relayed traffic is not high. Figure 3(b) depicts $\mathrm{CW}_{\min}$ for a larger value of γ. Because γ affects the convergence rate, $\mathrm{CW}_{\min}$ converges faster but fluctuates more dramatically. Fig. 3(c) $\mathrm{CW}_{\min}$ for a smaller value of α, which is the target traffic forwarding capability. If a node has smaller α, it is expected to have lower throughput and the corresponding $\mathrm{CW}_{\min}$ is higher as shown in Fig. 3(c). In other words, α affects the converged value of $\mathrm{CW}_{\min}$ in a steady state and the rate at which it can forward.

5.1.2 End-to-end throughput w.r.t. α, max_{th}, and T

In these sets of experiments, we show that the tunable parameters affect the end-to-end throughput in a multihop wireless network. As stated above, α is the target forwarding capability and dominantly affects the end-to-end throughput. In Fig. 4(a), the end-to-end throughput increases linearly for $0.9 \leq \alpha \leq 0.99$, and in the exceptional case of α = 1, the throughput goes up to 0.94 Mb/s. Note that each data point reported in the figure is an average of 10 simulation runs. In the all cases, the throughput is much higher than that of IEEE 802.11 DCF.

For a larger max_{th}, the end-to-end throughput decreases as shown in Fig. 4(b), because in the case of light traffic $\mathrm{CW}_{\min}$ converges to max_{th}, which may incur a larger delay before the first transmit attempt. The value of T determines how frequently the value of $\mathrm{CW}_{\min}$ is updated. Therefore, if T is smaller, it is possible to achieve a fine granularity control of $\mathrm{CW}_{\min}$ in a variety of dynamic traffic and interference scenarios. However, as a tradeoff, it incurs higher computational overhead because $\mathrm{CW}_{\min}$ is periodically computed at every T seconds.

5.1.3 End-to-end throughput in various scenarios

The traffic forwarding capability of a node can be affected by various factors such as the network topology, the characteristics of physical RF devices, and traffic patterns. First, Fig. 5(a) gives the end-to-end throughput with respect to the carrier sense range. With a smaller carrier sense range, the level of spatial reuse (and the number of concurrent transmissions) is increased. As shown in Fig. 5(a), in the entire range the contention window adaptation algorithm outperforms IEEE 802.11 DCF by 23–51 % in terms of the end-to-end throughput. We vary the offered traffic load from 0.5 Mb/s to 2 Mb/s. Fig. 5(b) gives the end-to-end throughput with respect to the offered load. Under lightly offered loads, the performance does not differ dramatically between the two protocols. However, the throughput improvement is quite significant when the offered load exceeds 0.8Mb/s. The end-to-end throughput is improved by 11–32% when the offered load is larger than 0.8 Mb/s. We also vary the number of hops in the chain topology from 3 to 8 hops. As shown in Fig. 5(c), as the number of hops increases beyond 4 hops, our algorithm significantly outperforms IEEE 802.11 DCF. When the number of hops is less than or equal to 4 (i.e., short multihop paths), all the nodes are within the carrier sense range of the first two nodes, and thus the improvement is not significant. This issue is expected to be resolved by adjusting the carrier sense range for better spatial reuse.

5.2 Performance evaluation in the cross and grid topologies

Fig. 6 gives the end-to-end throughput versus the offered load in the cross and grid topologies. Similar to Fig. 5(b) for the chain topology, Fig. 6 shows a similar performance trend. Under light traffic loads, the obtained throughput is the same between the proposed adaptation algorithm and IEEE 802.11 DCF. However, as the offered load increases, the improvement becomes more notable under all the cases.

Fig. 6(a) shows the end-to-end throughput for the cross topology. When static routing is used, the throughput achieved under the contention window adaptation algorithm is increased by 20–31 % under the heavy offered load. When AODV is used, the improvement is approximately 24–35 %. The performance difference between the two routing protocols lies in the inefficiency of AODV in stationary networks. Similarly, in the grid topology we observe that the contention window adaptation algorithm outperforms IEEE 802.11 DCF by 11–26 % under static routing and 15–40 % under AODV.

6. 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 scheme for tuning the minimum contention window size, 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, and carried out ns-2 simulation. The simulation results have shown that the proposed scheme efficiently controls the contention among nodes and gives a 20–35 % performance improvement with respect to the end-to-end throughput than conventional IEEE 802.11 DCF.

We have identified several avenues for future research. First, we are implementing the proposed scheme on an IEEE 802.11 based testbed with MadWifi drivers laying on top of Atheros chipsets, in order to empirically evaluate the performance. We will also extend the convergence analysis in a more general network scenario, where nodes may use different values of the transmit power and the carrier sense threshold, nodes may be mobile, and hidden nodes may exist.

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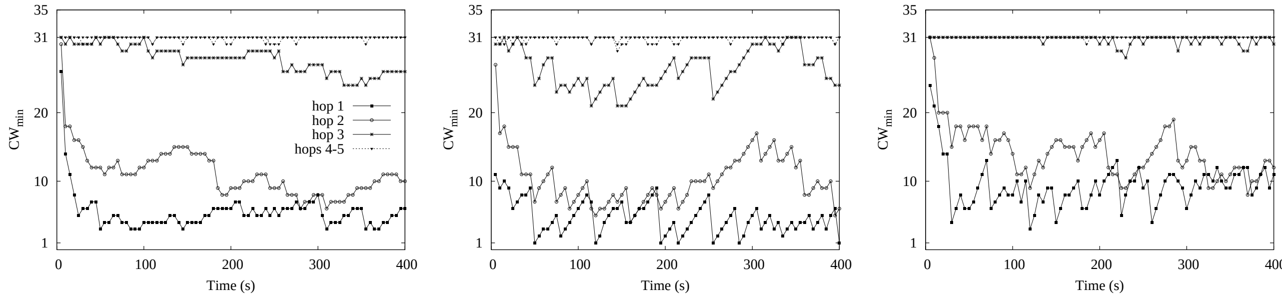
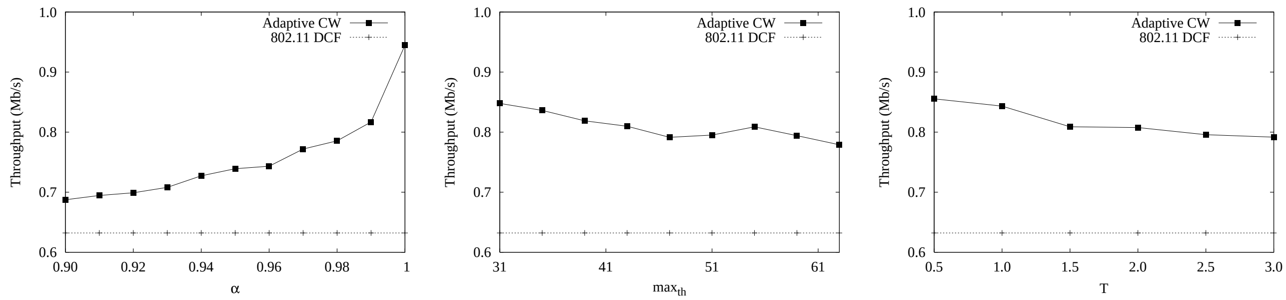


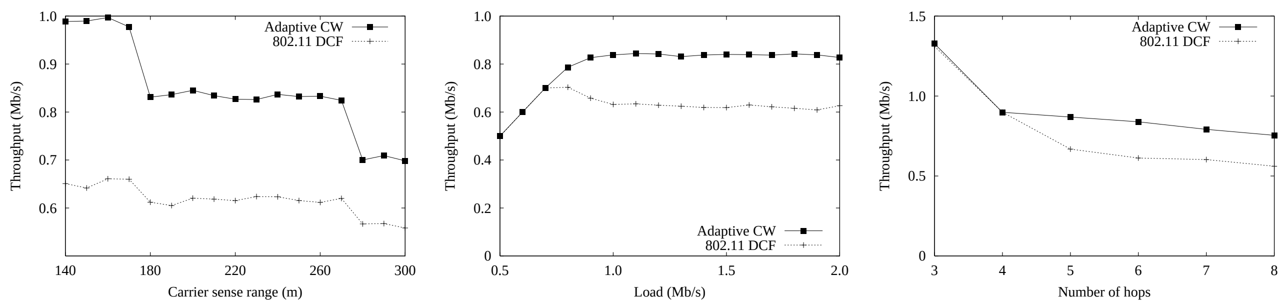
(a) Default parameters (α = 0.99, γ = 0.09). (b) α = 0.99, γ = 0.20. (c) α = 0.95, γ = 0.09.

Figure 3: The variation of CW$_{\min}$ with respect to time for the sets of α and γ in the chain topology.



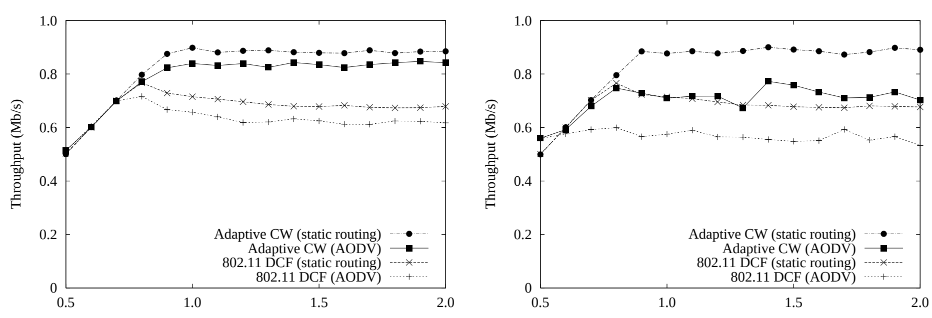
(a) Traffic forwarding capability α. (b) Max threshold max_{th}. (c) Sampling time T.

Figure 4: Throughput results with respect to the parameters (α, max_{th}, and T) in the chain topology.



(a) Carrier sense range. (b) Traffic load. (c) Number of hops.

Figure 5: End-to-end throughput results with respect to the carrier sense range, the offered load, and the number of hops in the chain topology.



(a) Cross topology. (b) Grid topology.

Figure 6: The aggregate throughput results with respect to the offered load in the cross and grid topologies.

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