Computer Communications 32 (2009) 1263–1270

Contents lists available at ScienceDirect

Computer Communications

journal homepage: www.elsevier.com/locate/comcom

Improving throughput by tuning carrier sensing in 802.11 wireless networks

Qiang Shen [a,*], Xuming Fang [a], Rongsheng Huang [b], Pan Li [b], Yuguang Fang [b]

[a] Provincial Key Lab of Information Coding and Transmission, Southwest Jiaotong University, Chengdu, Sichuan 610031, PR China
[b] Department of ECE, University of Florida, Gainesville, FL 32611, USA

ARTICLE INFO

Article history:
Available online 13 February 2009

Keywords:
Medium access control (MAC)
Spatial reuse
Carrier sensing
Interference

ABSTRACT

In this paper, we study the impacts of physical carrier sensing and channel rate on the throughput of 802.11 wireless networks with chain topology. Firstly, we show that by adopting different carrier sensing thresholds for the RTS and CTS transmissions, the blocking problem caused by exposed terminals can be greatly alleviated. In 802.11 wireless networks with this modification, the spatial reuse ratio under certain channel rates can be increased to $\frac{1}{3}$, which is the highest value to our best knowledge. Secondly, in multi-rate networks, we demonstrate that $\frac{1}{3}$ is still the best value of spatial reuse ratio in terms of maximizing the achievable data rate under certain conditions. Thirdly, this paper proposes a new method to address the intra-flow contention by decreasing the carrier sensing threshold of the source node. This method requires less response time than that of the traditional method which adjusts the backoff window size. Finally, extensive simulations are implemented in NS2 and the results show that our scheme significantly improves the throughput of 802.11 wireless networks with chain topology.

1. Introduction

Wireless mesh networks (WMNs) have been widely adopted in many scenarios, such as campus networking, community networking and so on. As a special case, wireless mesh networks with chain topology have their own interests. For example, they are usually used to provide Internet access along highways or railways. Besides, in WMNs with chain topology, the protocols should be designed differently from those for random topologies in order to work more efficiently.

Fig. 1 is one of the most common solutions to provide Internet access for the subscribers in vehicles [1]. It is a typical application of wireless networks with chain topology. Meanwhile, wireless mesh networks with chain topology are also suitable for many other applications. Generally, in those scenarios, gateways are several hops away from one another.

With the emergence of a variety of bandwidth demanding applications, the issue of how to increase the network throughput has attracted a great deal of attention. The network throughput depends on the achievable data rate at each individual wireless link determined by the Signal-to-Interference-and-Noise-Ratio (SINR) at the receiver, and the spatial reuse related to the total number of concurrent transmissions accommodated in the network as well. In 802.11 media access control (MAC) protocol, whenever a wireless node intends to transmit, it senses the channel and defers the transmission if the channel is busy. We can increase the spatial reuse either by reducing the transmission power or by increasing the carrier sensing threshold [2]. In this paper, we discuss how to increase the network throughput by adjusting spatial reuse in 802.11 wireless mesh networks with chain topology.

The rest of the paper is organized as follows. Section 2 presents the related work in wireless multi-hop networks. Section 3 introduces the wireless network models used in this paper. Then, Section 4 proposes a feasible scheme to address the blocking problem caused by exposed terminals. Section 5 extends our proposed scheme to a multi-rate environment and derives the best concurrent transmission distance which can be used to maximize the achievable data rate. After that, we illustrate in Section 6 that by decreasing the sensing threshold, the intra-flow contention can be alleviated. Finally, Section 7 provides the performance evaluation and Section 8 concludes our work.

2. Related work

Many researches have already discussed the impacts of carrier sensing and spatial reuse on the network performance in multi-hop wireless networks. Zhai and Fang [3] investigate the impacts of SINR, topology, hidden/exposed terminal problems and bidirectional handshakes on the throughput of multi-rate and multi-hop wireless ad hoc networks. Kim et al. [2] show that the spatial reuse depends on the ratio of the transmission power to the carrier sensing threshold. Based on this result, they propose a decentralized power and rate control algorithm to enable each node to adjust

* Corresponding author. Tel.: +86 28 8760 1757.
E-mail addresses: q.shen@ufl.edu, q.shen@hotmail.com (Q. Shen), xmfang@swjtu.edu.cn (X. Fang), rshuang@ufl.edu (R. Huang), lipanleo@ufl.edu (P. Li), fang@ece.ufl.edu (Y. Fang).

0140-3664/$ - see front matter © 2009 Elsevier B.V. All rights reserved.
doi:10.1016/j.comcom.2009.02.003

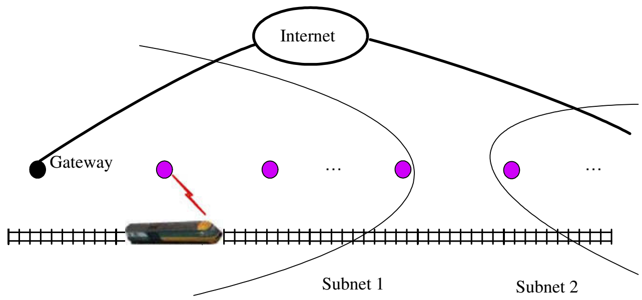

Fig. 1. Typical application of wireless networks with chain topology.

its transmission power and channel rate. Then, Lin and Hou [4] consider the issue of tuning PHY parameters (transmission power and channel rate) and MAC parameters (backoff window size) jointly in unified framework in order to optimize the overall network throughput. However, all previous works use the Honey-grid model [5], which is obviously not suitable for WMNs with chain topology as studied in this paper.

Some works have focused on the chain topology. Guo et al. [6] derive the minimum separation distance between simultaneous co-channel transmitters while maintaining a desirable SINR at receivers. However, they only consider the directional transmissions and an ideal MAC protocol is required to maintain the optimal separation distance between transmitters while minimizing the interference [7]. In [8], Li et al. claim that an ideal MAC protocol could achieve a spatial reuse ratio as high as $\frac{1}{3}$ in chain topology. However, they do not provide any practical protocols to achieve this. The motivation of this paper is to work out a feasible solution to achieve such a high spatial reuse ratio by analyzing the SINR and the environment in 802.11 wireless networks with chain topology.

In addition, intra-flow contention is another crucial problem in chain topology. Zhai and Fang [9] introduce the intra-flow contention in details and conclude that by using different backoff window sizes for the source and other nodes, this problem can be addressed. Instead of adjusting the backoff window size, we address the intra-flow contention problem by adjusting the carrier sensing threshold in this paper.

3. Wireless network models

As we know, a transmitter contributes interference to other receivers, consequently affecting their receptions. Hence, we need to quantify the impact of the accumulated interference. To analyze the maximum accumulated interference with various spatial reuse, wireless network models are discussed in this section. In addition, our analysis is based on the assumption that all the nodes use the same transmission power and it only considers the traditional 802.11 MAC distributed coordination function (DCF) with RTS/CTS.

3.1. Physical layer model

In real environments, the signal can be attenuated due to several factors, including pathloss, multipath fading and shadowing [10]. Pathloss model [11,12] is commonly used to describe the radio propagation property in wireless networks. In this paper, we only consider the signal attenuation caused by pathloss, and use pathloss model as the physical layer model. Specifically, the received power, $P_{rx}(d_t)$, at any distance $d_t > d_0$ (d_0, usually 1 meter), can be approximately expressed in terms of the received power (P_0) at d_0:

$$P_{rx}(d_t) = P_0\left(\frac{d_0}{d_t}\right)^{\gamma} \tag{1}$$

The value of P_0 can be measured in the radio environment by taking the average received power at any point located at a close-in radial distance d_0 from a transmitter (Tx). γ is the pathloss exponent that characterizes how quickly a signal fades in a particular network environment, and it usually ranges between 2 and 4 ($\gamma = 2$ for a free-space line-of-sight model and $\gamma = 4$ for the two-ray model). Specifically, since the wireless networks with chain topology (Fig. 1) are usually deployed in an outdoor or rural environment and the typical value of γ in [10] is not larger than 4.

The received power of a receiver (Rx) consists of three parts: intended signal from Tx, aggregate interference (from other concurrent transmitters, denoted by P_I) and background noise (P_N). A successful reception must satisfy the following rules:

$$P_{rx}(d_t) \geqslant P_R \tag{2}$$

$$\mathrm{SINR} = \frac{P_{rx}(d_t)}{P_I + P_N} = \frac{P_{rx}(d_t)}{\sum_i P_{rx}(d_i) + P_N} \geqslant S_0 \tag{3}$$

where P_R is the receiver sensitivity, and S_0 is the threshold of SINR for a correct reception, which is associated with the channel rate in 802.11 wireless networks. Usually, a higher channel rate requires a higher S_0. The values of S_0 for different channel rates (r_c) are provided in Table 1 [14].

3.2. Interference model

Considering 802.11 MAC, the minimal distance between the two transmission pairs is called separation distance as illustrated in Fig. 2. The definition of concurrent transmission distance (k in hops) in this paper is one hop more than the separation distance. Hence, $\frac{1}{k}$ indicates the corresponding spatial reuse ratio. In Fig. 2, d denotes the maximum transmission distance between two nodes. In fact, d is associated with r_c. Namely, different r_c corresponds to various d. If all nodes use different power to communicate with each other, it will be too complicated to accurately calculate SINR. As an alternative, we focus on the saturated status and assume that all nodes use the same power and r_c to communicate with each other. Hence, it is reasonable to use a single d to denote the maximum transmission distance of nodes in a specific environment. In this subsection, we consider the chain topology shown in Fig. 3.

In unidirectional transmission networks, in order to guarantee that all the concurrent transmissions can be conducted successfully, the aggregate interference at a receiver from all other concurrent transmissions should satisfy the restriction given by (3). In Fig. 3, the worst case of P_I can be written as:

$$\begin{aligned} P_I &= \sum_{i=1}^{+\infty} P_0\left[\frac{d_0}{(ik-1)d}\right]^{\gamma} + \sum_{i=1}^{+\infty} P_0\left[\frac{d_0}{(ik+1)d}\right]^{\gamma} \\ &= P_0\left(\frac{d_0}{d}\right)^{\gamma} \sum_{i=1}^{+\infty}\left[\frac{1}{(ik-1)^{\gamma}} + \frac{1}{(ik+1)^{\gamma}}\right] \end{aligned} \tag{4}$$

Table 1
Signal-To-Noise-Ratio and Receiver Sensitivity.

Rates (r_c, Mbps)	S_0 (dB)	Receiver sensitivity (dBm)
54	24.56	−65
48	24.05	−66
36	18.80	−70
24	17.04	−74
18	10.79	−77
12	9.03	−79
9	7.78	−81
6	6.02	−82

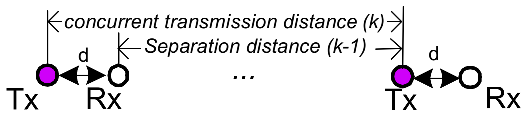

Fig. 2. Definition of concurrent transmission distance in 802.11 wireless networks.

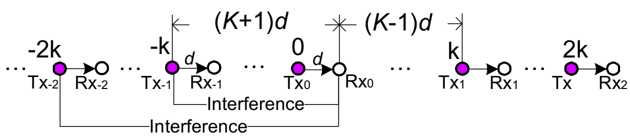

Fig. 3. Interference model.

But, if we consider the 802.11 MAC, the interference on the left side may come from $R_{X-1}, R_{X-2}, \ldots$. Hence, (4) should be formulated as:

$$P_I = P_0\left(\frac{d_0}{d}\right)^{\gamma}\sum_{i=1}^{+\infty}\left[\frac{1}{(ik-1)^{\gamma}}+\frac{1}{(ik)^{\gamma}}\right] \tag{5}$$

Similar to other related analysis [2,3], the closest interference node in each side contributes the majority of the interference. Hence, the interference to the receiver can be approximated by:

$$P_I = P_0\left(\frac{d_0}{d}\right)^{\gamma}\left[\frac{1}{(k-1)^{\gamma}}+\frac{1}{k^{\gamma}}\right] \tag{6}$$

Since P_N is much smaller than P_I and $d_t = d$, (3) can be changed as follows:

$$\mathrm{SINR} = \frac{P_{rx}(d)}{P_I} = \frac{1}{\frac{1}{k^{\gamma}}+\frac{1}{(k-1)^{\gamma}}} \geqslant S_0 \tag{7}$$

As described in Fig. 3, the interference from the left side is different from that from the right side. Since we take the 802.11 MAC into consideration, our interference model is more practical than the model described in [6]. In addition, according to (7), we can conclude that SINR and d are independent of each other when all nodes use the same power and r_c to communicate with each other.

The values of SINR with respect to γ when $k = 2, 3, 4$, respectively, are shown in Fig. 4. Since γ is determined by the environment, we intend to investigate the tendency of SINR with different k in various environments. According to Fig. 4, we can observe that k cannot be equal to 2 since the SINR is below the minimum S_0 (6.02 dB) regardless the value of γ. Intuitively, when $k = 2$, a receiver cannot distinguish the signal of one transmitter from that of another. When $k = 3$, it is feasible that nodes which are 3 hops away from each other can transmit simultaneously. Since SINR $\geqslant$ 6.02 when $\gamma \geqslant 2.45$, k can be equal to 3 which is consistent with the results of [3] and [6]. Furthermore, there are two important properties that deserve more attention (assume $k = 3$):

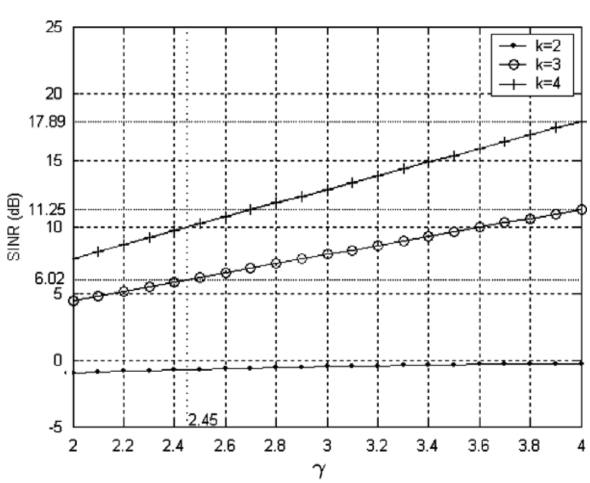

Fig. 4. SINR with different γ in terms of $k = 2, 3, 4$.

3.2.1. IEEE 802.11 MAC protocol limitation

We use the topology shown in Fig. 5 to explain this problem. The distance between every two neighbors is d. Theoretically, node 1 and 4 can transmit simultaneously when $k = 3$ according to our previous analysis. However, due to the restriction of physical carrier sensing mechanism, after receiving RTS from node 1, node 2 may not be able to reply a CTS if node 4 is transmitting. Namely, node 4's transmission blocks node 2's CTS transmission and we call it blocking problem hereafter. This problem will be addressed in Section 4.

3.2.2. Existence of optimal k

$k = 3$ is feasible only when SINR is bigger than S_0. Hence, when $S_0 = 6.02$ dB, there will be no doubt we can guarantee that $k = 3$ if $\gamma \geqslant 2.45$. However, if $\gamma = 4$ and k is equal to 3 and 4, the values of SINR should be 11.25 and 17.89 dB, respectively. According to Table 1, 18 and 24 Mbps can be supported with the constrain of the bit error rate. If we increase the value of k, the maximum channel rate that can be supported by the network will increase due to the increase of SINR. On the other hand, if we decrease the value of k, the number of concurrent transmissions can be increased. Therefore, there should be an optimal k which can maximize the achievable data rate. We will study this problem in Section 5.

4. Solution to the blocking problem

A node starts to transmit only when the level of the sensing power is below the carrier sensing threshold, which determines how much interference a communication can tolerate and decides a carrier sensing range (X). Hereafter, we will discuss X instead of the carrier sensing threshold. By analyzing the relationship between X and the interference range (I), we propose a feasible solution to alleviate the blocking problem. The following discussion in this section uses the topology illustrated in Fig. 5 and assumes $k = 3$. In addition, we only focus on the minimum channel rate (6 Mbps) in this section.

4.1. Optimum sensing range for RTS

Within the interference range decided by I, any sender can ruin the reception of the tagged receiver. I in [7] is given by:

$$I = d\left[\frac{1}{S_0} - \left(\frac{d}{d_0}\right)^{\gamma}\frac{P_N}{P_0}\right]^{-\frac{1}{\gamma}} \tag{8}$$

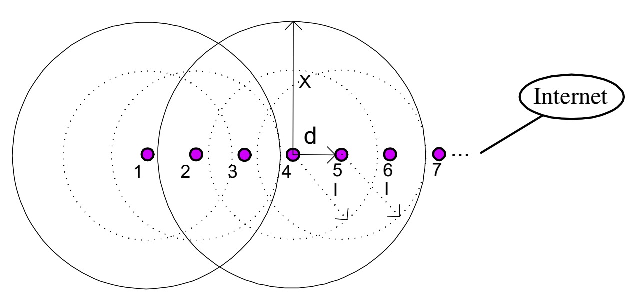

Fig. 5. Typical chain topology.

With negligible P_N, (8) becomes:

$$I = dS_0^{\frac{1}{\gamma}} \tag{9}$$

Considering the transmission from node 4 to node 5 as an example, to keep the nodes in node 5's interference range silence, the sensing range of node 4 must cover the entire interference range of node 5. Hence,

$$X \geqslant d + I \tag{10}$$

X cannot be too large since it is related to the spatial reuse and the number of concurrent transmissions. So, we have the following limitation:

$$X < kd \tag{11}$$

When $k = 3$, I must be larger than d since a receiver cannot distinguish the signal from the transmitter and that from the interfering node. Finally, we can obtain the optimal carrier sensing range for the RTS transmission:

$$2d \leqslant X < 3d \tag{12}$$

There will be no difference between $2d$ and $3d$, if the distance between two neighbors is equal to d. Generally, the X for RTS transmission can be expressed as follows:

$$(k-1)d \leqslant X < kd \tag{13}$$

4.2. Optimum sensing range for CTS

According to the analysis in Section 3.2, if the RTS sensing range is set as that in (13), node 5 in Fig. 5 can receive RTS from node 4 successfully since SINR $\geqslant S_0$ when $\gamma \geqslant 2.45$.

After receiving RTS, if the CTS sensing range of node 5 is given the same as the RTS sensing range of node 4, node 5 fails to transmit CTS when node 7 is transmitting. This phenomena is also observed in [8]. However, according to our analysis in Section 3.2, node 5's transmission will not interfere with other ongoing transmissions if $\gamma \geqslant 2.45$ and S_0 = 6.08 dB. Furthermore, after the transmission of RTS, nodes in node 4's interference range will not initiate a new transmission in the duration of *DIFS*. Hence, while node 5 is transmitting CTS, node 3 and 6 will not transmit. Consequently, node 4 receives CTS successfully. Namely, node 4 receives CTS successfully since its SINR at this time is still higher than S_0 even when node 2 and 7 are transmitting concurrently.

Obviously, when node 5 is sending CTS, the CTS sensing range does not need to be the same as the RTS sensing range. In chain topology, since (7) is satisfied, the optimal sensing range for the receiver, when it sends CTS, is given by:

$$d \leqslant X = I < 2d \tag{14}$$

For the same reason as the RTS sensing range, there will be no difference if X chooses different value between d and $2d$. Generally, the optimal X for CTS transmission should be:

$$(k-2)d \leqslant X < (k-1)d \tag{15}$$

By adopting different carrier sensing ranges for transmissions of RTS and CTS, node 4's transmission will not block node 2's CTS transmission anymore. Hence, the blocking problem can be alleviated. In this way, k can be guaranteed to be 3 and the spatial reuse ratio can reach the highest value in 802.11 wireless networks, namely, $\frac{1}{3}$, which is the highest spatial reuse to our best knowledge.

5. Maximization of the achievable data rate

In a multi-rate environment, a smaller SINR leads to a lower channel rate. In this section, we study the relationship between the spatial reuse and the maximal achievable data rate (r_d).

Table 2
System parameters in IEEE 802.11.

Base rate (r_b)	1 Mbps
SIFS (T_{sifs})	10 µs
DIFS (T_{difs})	50 µs
Backoff slot time	20 µs
Phy header (L_{phy})	192 bits
MAC header (L_{mac})	256 bits
Route header (L_{rt})	160 bits
Payload (L_{pl})	8000 bits
Data packet	$L_{pl} + L_{rt} + L_{mac} + L_{phy}$
RTS (L_{rts})	160 bits + L_{phy}
CTS/ACK ($L_{cts/ack}$)	112 bits + L_{phy}

5.1. Definition of the achievable data rate

Given channel rate r_c, the corresponding r_d can be obtained as described in [3]:

$$r_d = \frac{1}{k}\frac{L_{pl}}{T_b + T_p + \frac{L_H + L_{pl}}{r_c} + T_c} \tag{16}$$

where T_p is the transmission time for the preamble of a packet, T_b and T_c are the average backoff time and the average collision time, respectively. L_H is protocol overhead from different protocol layers such as routing layer and MAC layer, and L_{pl} is the size of the payload. If we adopt the minimum backoff window size (namely, 8 slots) and do not change it, T_b will be equal to 4 slots. By addressing the blocking problem, T_c will be very small. Hence, we do not consider T_c in this paper. Specifically, if the system parameters are given as described in Table 2, r_d can also be shown as:

$$r_d = \frac{1}{k}\frac{L_{pl}}{T_b + \frac{L_{rts}+L_{cts}+L_{ack}+L_{phy}}{r_b} + 3T_{sifs} + T_{difs} + \frac{L_{rt}+L_{mac}+L_{pl}}{r_c}}$$

5.2. Relationship between the spatial reuse and the achievable data rate

In this subsection, we intend to obtain the optimal value of k and r_c to maximize r_d. Based on (16), r_d can be obtained from r_c. Hence, we can get the relationship between r_d and r_c in case of different k, as illustrated in Fig. 6 and Table 3.

Based on Fig. 6, we can conclude that when $\gamma = 4$ and r_c is 6, 9, 12 or 18 Mbps, $k = 3$ is the best choice since a system with $k = 3$ can provide the highest r_d in chain topology. However, a system with $k = 3$ cannot support any higher r_c because the requirement of SINR is so high and when SINR is below this value the bit error rate is not acceptable. If we want to use r_c which is equal to 24, 36, 48 and 54 Mbps as the channel rate, the best choice of k is 4, 5, 6 and 6, accordingly.

As shown in Table 3, to achieve the highest r_d (1.5 Mbps), $k = 3$ and $r_c = 18$ Mbps are the best settings when $\gamma = 4$. According to our numerical analysis, under the same constraint of γ, a system with $k = 3$ can obtain higher r_d than those with other values of k. Hence, in this paper, we demonstrate that $k = 3$ is the best concurrent transmission distance to maximize r_d when $\gamma \geqslant 2.45$. In wireless networks with chain topology, $\gamma \geqslant 2.45$ can be satisfied easily since they are deployed in an outdoor or rural environment.

6. Alleviation of the intra-flow contention

In this section, we address the intra-flow contention by adjusting the transmission probability of each node. We will introduce two methods of balancing transmission probabilities of different nodes: one is to differentiate various nodes by adopting different

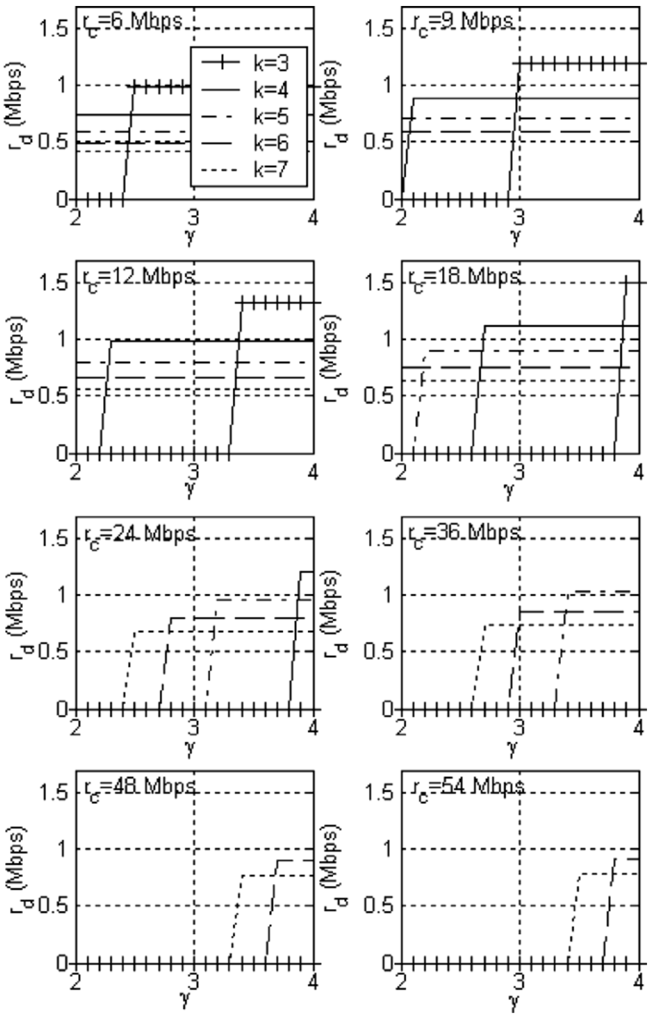

Fig. 6. comparison of r_d in the chain topology in terms of different r_c and k.

Table 3
Relationship between the spatial reuse and the achievable data rate.

r_c (Mbps)	k (hops)	r_d (Mbps)	γ Constrain
6	3	1.01	⩾2.45
9	3	1.23	⩾2.95
12	3	1.38	⩾3.35
18	3	1.5	⩾3.85
24	4	1.29	⩾3.85
36	5	1.09	⩾3.35
48	6	0.9	⩾3.65
54	6	0.96	⩾3.75

backoff window sizes and the other is to increase the carrier sensing range of the source node.

6.1. Adjusting the backoff window size

Adjusting the backoff window size is a traditional way to address the contention in wireless ad hoc networks. According to [9,13], the size of the backoff window is very crucial to achieve the maximum throughput. The basic idea of this approach is to adjust the backoff window size to guarantee that all the nodes have the same probability to use channel resource.

When a node detects congestion, it notifies the upstream node to increase its backoff window size. When an upstream node receives the message, it uses different steps to increase or decrease its backoff window size. For example, increasing step is twice as long as the decreasing step. In this way, if congestion occurs, it can be alleviated immediately. When the wireless resource becomes abundant, the backoff window size is decreased with a smaller step. By adjusting backoff window sizes, all the nodes in chain topology tend to have the same transmission probability. Hence, the intra-flow contention can be alleviated. Consequently, this method shortens the transmission delay and improves the efficiency of the resource usage. However, the response time of this method could be very long.

6.2. Increasing the sensing range

As described in Fig. 5, if all nodes in the network use the same carrier sensing range when $k = 3$, five nodes are in node 4's RTS sensing range and only three nodes in node 1's RTS sensing range. Since the number of nodes in the sensing range affects the transmission probability, node 1's transmission probability is much higher than that of node 4. Therefore, we try to change the transmission probability of the source node by adjusting its carrier sensing range in this subsection.

When there is a flow from node 1 to the gateway, we should prevent node 1 from injecting more data packets to the network than what can be delivered immediately by the downstream nodes. To achieve this goal, the transmission probability of node 1 should be the same as that of node 3 or 4. We try to find out the most suitable RTS sensing range for node 1 to alleviate the intra-flow contention by experiments. The CTS sensing range here is still one hop less than the RTS sensing range. According to Fig. 7, we observe that when the RTS sensing range is bigger than 3 but smaller than 4 hops (denoted by 3.5 in Fig. 7), the best performance can be achieved.

We should notice that, using a larger sensing range for the source node does not mean that it can be allowed to transmit at a higher rate r_c. Instead, it still uses r_c determined by the normal RTS sensing range as discussed in Section 5. The shortcoming of this idea is that we cannot adjust it very precisely. Nevertheless, this method can address the intra-flow contention in chain topology when $k = 3$. In addition, if we consider multi-flows in our scenario, nodes should use different sensing ranges for packets which are forwarded various times to guarantee that each flow has a fair probability to share the resource. However, this is beyond the

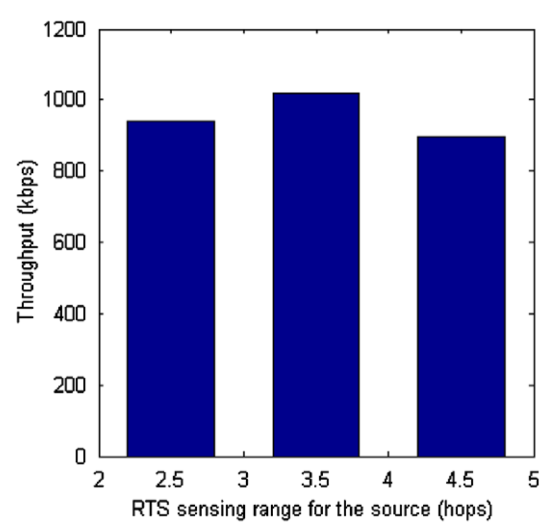

Fig. 7. The maximum throughput with different RTS sensing ranges.

scope of this paper, and we will discuss the fairness problem in our future work.

Adjusting the backoff window size to achieve the optimal throughput takes long time since the optimal backoff window size is determined by the traffic tensity [13]. In contrast, increasing the sensing range takes much shorter time. Consequently, increasing the sensing range is better than adjusting the backoff window size in terms of the response time. The further comparison of the two methods will be discussed in the following section.

7. Performance evaluation

In this paper, a series of simulations are conducted to demonstrate the important role of spatial reuse and carrier sensing range in improving network performance in chain topology. All simulations are implemented in NS2 and we do not use any special routing protocol. When a node receives a packet, it forwards the packet to the predetermined next hop. In addition, all parameters are given by Table 2.

7.1. Alleviating the blocking problem

We use the simple four nodes topology where $k = 3$ and $r_c = 6$ Mbps. Node 1 and 2 are in each other's transmission range, so are node 3 and 4. However, node 3 is two hops away from node 2. Namely, node 3 and 2 are in each other's RTS sensing range but not CTS range.

One flow is from node 1 to node 2 (flow 1) and another is from node 4 to node 3 (flow 2). The throughput in Fig. 8 shows that two flows do not interfere with each other because of adopting different RTS/CTS sensing ranges.

However, by changing the direction of flow 2, the scenario becomes different. If two flows can transmit simultaneously, they will not interfere with each other. In this paper, we do not assume two flows are synchronized. Hence, node 3 cannot transmit RTS while node 2 is transmitting CTS since node 2 is in node 3's RTS sensing range. Consequently, flow 2 will be interfered by flow 1. In contrast, node 2 can transmit CTS while node 3 is transmitting RTS or DATA. Therefore, flow 1 will not be interfered by flow 2. According to the performance shown in Fig. 9, our scheme can alleviate the blocking problem.

7.2. Achieving the maximum channel rate

We demonstrate the maximal r_d with different values of k, for example, 3, 4, 5 and 6. Table 3 is the numerical result. In this sub-

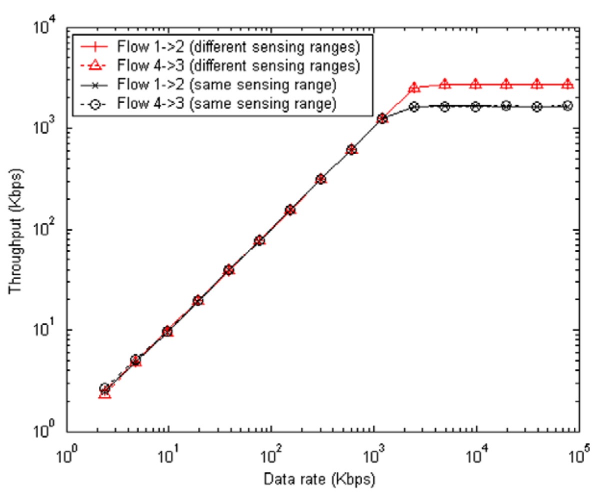

Fig. 8. Solution to the blocking problem: throughput of node 1–2 and 4–3.

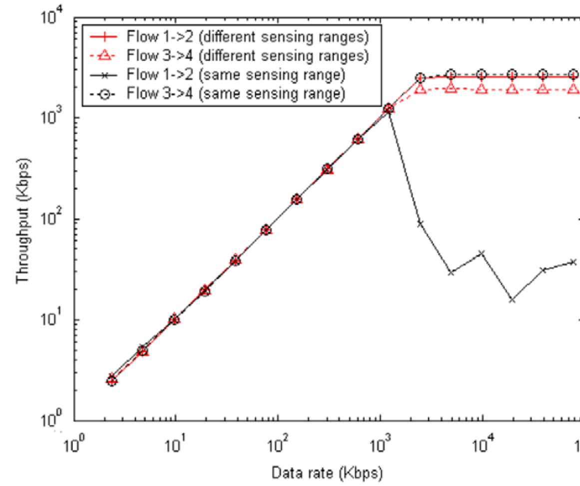

Fig. 9. Solution to the blocking problem: throughput of Node 1–2 and 3–4.

section, we try to verify it by NS2 simulations. According to our previous analysis, we set the basic channel rates to 18, 24, 36 and 54 Mbps for $k = 3$, 4, 5 and 6, respectively. The sensing ranges for RTS and CTS are set according to (13) and (15), respectively.

Fig. 10 illustrates the maximal achievable data rates when k has different values. We can conclude that when $k = 3$ the highest achievable data rate can be achieved, which is the same as the result obtained in Section 5. The maximal achievable data rate obtained in NS2 simulation is smaller than that in our previous theoretical results since we did not consider the collisions in our theoretical analysis.

7.3. Alleviating the intra-flow contention

The simulations of this subsection are conducted in chain topology with 7 nodes. When we alleviate intra-flow contention by increasing the RTS sensing range of the source node (IRSR), the minimal backoff window size is used by all the nodes in the network.

The fixed window size method which is the same as the one described in [9] is used to compare with our scheme. 32 is set to be the backoff window size for the source node and 8 for the other nodes, and all of them are fixed. To compare our scheme, we imple-

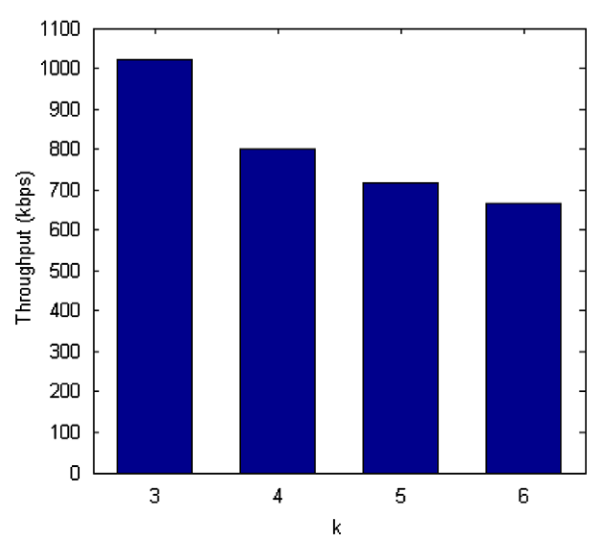

Fig. 10. End-to-end throughput with different values of k.

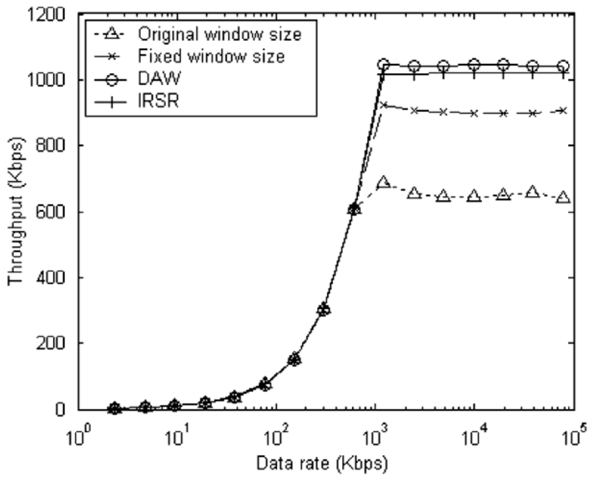

Fig. 11. Average End-to-end throughput comparison of different methods.

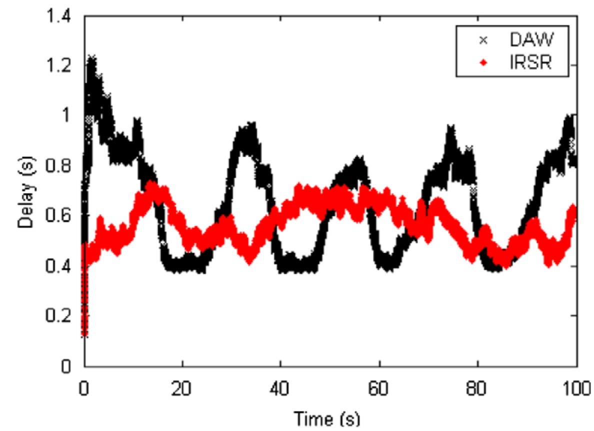

Fig. 13. Delay comparison of IRSR and DAW.

ment a simple method to adjust the backoff window size dynamically based on the fixed window size method, namely, dynamically adjusting window size (DAW). Each node checks the length of its queue periodically. If it is larger than half of the total length, DAW will increase the backoff window size of the upstream node. In contrast, if it is smaller than the threshold (we use 4 packets in our simulation) and the backoff window size is larger than 8 slots, backoff window size of upstream node will be decreased. In addition, we set the length of transmitting queue, increasing step and decreasing step as 50, 8 and 4 slots, respectively. Based on those methods, we can get those results shown in Fig. 11.

From Fig. 11, we can observe that both DAW and IRSR can alleviate the intra-flow contention problem significantly. Due to the benefit of addressing the intra-flow contention, the average end-to-end throughput is absolutely higher than those without addressing this problem. Meanwhile, both of them are more efficient than the fixed window size method and the original backoff method in 802.11 MAC.

The performance of each hop is shown in Fig. 12 when a fixed channel rate is used from the source to the destination. The performance results show that IRSR can outperform DAW by achieving higher and more stable throughput.

The delays of DAW and IRSR are compared in Fig. 13. We find that the average delay of DAW is 1.15 times as much as that of IRSR.

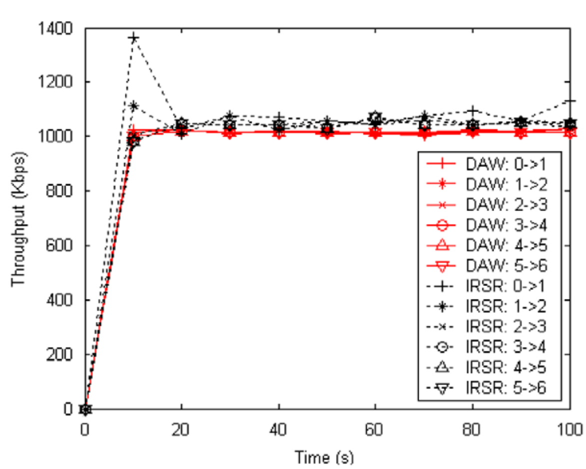

Fig. 12. Throughput comparison of IRSR and DAW.

Although those two methods address the intra-flow contention properly, we can observe that IRSR achieves better performance than DAW in terms of delay and throughput.

8. Conclusions

Increasing the throughput of 802.11 wireless networks is always a big challenge. In this paper, we study the impacts of physical carrier sensing and channel rate on the throughput of the 802.11 wireless networks with chain topology. Extensive simulations show that, under certain channel rates, adopting different carrier sensing thresholds for the transmissions of RTS and CTS can achieve the spatial reuse ratio as high as $\frac{1}{3}$. Furthermore, by increasing the sensing range of the source node, our scheme alleviates greatly the intra-flow contention problem and improves the throughput performance significantly.

Acknowledgements

The work of Qiang Shen and Xuming Fang was partially supported by the Ph.D. innovation Fund of SWJTU, NSFC under Grant 60772085 and the Open Research Fund of National Key Laboratory of Integrated Services Networks, Xidian University under Grant ISN8-01. The work of Yuguang Fang was partially supported by Chunghwa Telecom M-Taiwan Program M-Taoyuan Project and the National Science Council (NSC), Taiwan, under the NSC Visiting Professorship with contract number NSC-96-2811-E-002-010 while he was a visiting professor in the Department of Computer Science and Information Engineering at National Taiwan University.

References

[1] M. Xie, X. Fang, Q. Shen, A cross-layer fast handoff protocol for vehicle communication system, in: IET CCWMSN, Shang Hai, China, 2007.
[2] T. Kim, H. Lim, J. Hou, Improving spatial reuse through tuning transmit power, carrier sense threshold, and data rate in multihop wireless networks, in: ACM MOBICOM, Los Angeles, USA, 2006.
[3] H. Zhai, Y. Fang, Physical carrier sensing and spatial reuse in multi-rate and multihop wireless ad hoc networks, in: IEEE Infocom, Barcelona, Spain, 2006, pp. 1–12.
[4] T. Lin, J. Hou, Interplay of spatial reuse and SINR-determined data rates in CSMA/CA-based, multi-hop, multi-rate wireless networks, in: IEEE INFOCOM, Anchorage, USA, 2007, pp. 803–811.
[5] R. Hekmat, P.V. Mieghem, Interference in wireless multi-hop ad-hoc networks and its effect on network capacity, Wireless Networks 10 (4) (2004) 389–399.
[6] X. Guo, S. Roy, W.S. Conner, Spatial reuse in wireless ad-hoc networks, in: IEEE VTC,3, Orlando, USA, 2003, pp. 1437–1442.
[7] J. Zhu, X. Guo, L.L. Yang, W.S. Conner, Leveraging spatial reuse in 802.11 mesh networks with enhanced physical carrier sensing, in: IEEE ICC,7, Paris, France, 2004, pp. 4004–4011.
[8] J. Li, C. Blake, D.S.J. De Couto, H.I. Lee, R. Morris, Capacity of ad hoc wireless networks, in: ACM MOBICOM, Rome, Italy, July 2001.

[9] H. Zhai, Y. Fang, Distributed flow control and medium access in multihop ad hoc networks, IEEE Transactions on Mobile Computing 5 (11) (2006) 1503–1514.
[10] T.S. Rappaport, Wireless Communications: Principles and Practice, second ed., Upper Saddles River Prentice-Hall, 2002.
[11] P. Gupata, P.R. Kumar, The capacity of wireless networks, IEEE Transactions on Information Theory 46 (2) (2000) 388–404.
[12] T.J. Shepard, A channel access scheme for large dense packet radio networks, in: ACM SIGCOMM, California, USA, 1996, pp. 219–230.
[13] F. Cali, M. Conti, E. Gregori, Dynamic tuning of the IEEE 802.11 protocol to achieve a theoretical throughput limit, IEEE Transactions on Networking 8 (6) (2000) 785–799.
[14] J. Yee, H. Pezeshki-Esfahani, Understanding wireless lan performance trade-offs, CommsDesign.Com, 2002.