This full text paper was peer reviewed at the direction of IEEE Communications Society subject matter experts for publication in the WCNC 2007 proceedings.

Effectiveness of Physical and Virtual Carrier Sensing in IEEE 802.11 Wireless Ad Hoc Networks

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Abstract – IEEE 802.11 defines physical and virtual carrier sensing mechanisms to avoid interference in wireless local area networks for the kind of interference originating from within the receiving range of a receiver. However, in wireless ad hoc networks most interference comes from outside of this range. So, the effectiveness of IEEE 802.11 carrier sensing mechanism in ad hoc networks has attracted many studies. Prior research has attempted to evaluate effectiveness from a spatial viewpoint only, using an analytical model to estimate the size of the interference area of an ongoing communication based on the transmitter-receiver distance. Unlike this, the temporal effectiveness of the carrier sensing mechanism has been ignored. In this paper we propose an analysis combining spatial and temporal viewpoint to study the effect of interference on the performance of IEEE 802.11 protocol in ad hoc networks. We also compare the effectiveness of physical and virtual carrier sensing mechanisms, known as RTS/CTS mechanism, in wireless ad hoc networks.

I. INTRODUCTION

IEEE 802.11 MAC protocol [1] is the most popular standard used in wireless ad hoc networks. Its contention-based distributed coordination function (DCF) can support peer-to-peer communication for wireless ad hoc networks without centralized control of the channel access. In order to resolve the hidden station problem, request-to-send/clear-to-send (RTS/CTS) handshake is defined in DCF to reserve and announce the right of channel access, to avoid interference from hidden stations. However, RTS/CTS mechanism is designed mainly to support wireless local area networks (LANs) and not multihop wireless ad hoc networks [7]. The basic assumption of this mechanism is that all hidden stations are within the receiving range of a receiver, but this may not work when the transmitter-receiver distance grows so that some stations are outside this range [2]. Hence, RTS/CTS cannot work well in the latter scenario. Unfortunately, this scenario is common in wireless ad hoc networks because of wide distribution of mobile stations. Prior research attempted to evaluate the effectiveness of IEEE 802.11 MAC and physical protocol in wireless ad hoc networks through the spatial analytical model. In [2], the authors present a spatial model to describe the relation between transmission, carrier sensing, and interference range. They show that the effectiveness of RTS/CTS mechanism decreases gradually as the transmitter-receiver distance exceeds a threshold distance. In [3], a quantitative measure, the spatial reuse index, is introduced to evaluate the efficiency of the channel reservation by RTS/CTS method. Ref. [4] presents an analytic model to investigate the co-channel spatial reuse in dense wireless ad hoc networks based on RF propagation models for some common network topology. Ref. [5] demonstrates that physical carrier sensing, enhanced with tunable sensing, is effective in avoiding interference in 802.11-based mesh networks without requiring the use of virtual carrier sensing.

In addition to the spatial analysis, we also evaluate the interference from a temporal viewpoint. This shows that the network performance depends not only on the size of the area containing the hidden and exposed stations but also the vulnerable period relative to the hidden stations and the period of blocking the exposed stations. If the stations are uniformly distributed, the larger hidden-stations area, the more hidden stations could interfere with the ongoing transmission. On the other hand, the longer the vulnerable period due to a hidden station, the higher the probability of collision with an ongoing transmission [10]. Secondly, we compare the performance of the virtual and physical carrier sensing mechanisms in ad hoc networks. The former is relatively ineffective in this environment especially under the multiple transmission rate mechanism. The latter could improve the performance of the network if an optimum carrier sensing range or threshold can be found. This paper determines the upper and lower bounds on the carrier sensing optimum range.

The rest of this paper is organized as follows. In section II, we present the propagation- and interference analytical models and discuss the 802.11 multiple transmission rate mechanism. In section III, we evaluate the spatial and temporal effectiveness of virtual and physical carrier sensing mechanisms. In section IV, we show the simulation results. Finally, conclusions are presented in section V.

II. INTERFERENCE MODEL

The basic radio propagation model used in this paper is the two-ray ground reflection model [8], given by:

$$P_r = P_t \frac{G_t G_r h_t^2 h_r^2}{d^4 L} \tag{1}$$

where P_r is the received power, P_t is the transmitted power, G_t and G_r are the antenna gains of the transmitter and receiver, h_t and h_r are the antenna heights of the transmitter and receiver, d is the transmitter-receiver distance and L is the system loss. Based on this model and 802.11 protocol, we can have two ranges: transmission range (R_t) and carrier sensing range (R_c), defined as follows.

Transmission Range (R_t) is the range within which frames can be reliably transmitted between transmitter and receiver if there is no interference. The reliable transmission means RTS, CTS, DATA and ACK frames can be correctly identified and frame error ratio (FER) must be lower than a specified value.

Carrier sensing range (R_c) is the range within which the other stations can sense transmitted power. A station reports the channel state as busy, if its 802.11 clear channel assessment (CCA) mechanism senses the energy above the threshold that is determined by antenna sensitivity.

In wireless network environment, when there is interference on the same channel, a reliable transmission requires that the signal-interference-noise-ratio (SINR) is higher than a threshold (S_0):

$$\frac{P_r}{\sum_k P_i(k) + N} \geq S_0 \qquad (2)$$

where $P_i(k)$ is the signal power of interference source k and N is the power of the ambient noise. The noise level can be ignored when compared to the interference power level. Based on this model and considering the effect of a single interfering station, we can determine the interference range as follows.

Interference Range (R_i) is the range within which any other transmission can interfere with the frame receiving on the receiver and cause the FER be higher than the requirement. This range is not fixed and depends on the transmitter-receiver distance. Let X_i denote the ratio of the interference range to the transmission range. Then from the equation (1) it follows:

$$X_i = \frac{R_i}{d} = 10^{\left(\frac{SINR}{40}\right)} \qquad (3)$$

In this paper, we use the following assumptions:

(a) All antennas are omni-directional, so the above three ranges are circular; (b) All the stations within the transmission range can identify the transmitted frame; (c) All the stations within the carrier sensing range can sense the transmitted frame. (d) All the station within the interference range can corrupt the currently transmitted frame.

III. MULTI-RATE MECHANISM

IEEE 802.11 standard defines multiple transmission rates to support reliable transmission on channels of different quality. In general, the higher transmission rate requires higher receiver sensitivity and higher SINR to keep the same bit-error-rate (BER) as a lower transmission rate. Based on the propagation model (1), the received signal power decays by the power of four of the transmitter-receiver distance. This indicates that the higher transmission rate is limited to a shorter transmission range because of requiring higher receiver sensitivity. In order to maximize the throughput, the multi-rate mechanism will use the highest rate among the available rates based on the channel quality between the transmitter and receiver. This means that each rate will be used near its transmission limit except for the highest rate. For example, according to Table I [9], if the received signal is –80dBm, then the 9 and 6 Mbps rates are available and the 9 Mbps will be selected as the transmission rate. According to this mechanism, the 9 Mbps is used only when the received signal power is between –79 to –81 dBm or the transmitter-receiver distance is between 103 to 116 meters.

TABLE I
SINR AND RECEIVER SENSITIVITY
FOR STANDARD DATA RATES OF IEEE 802.11g [9]

Rates (Mbps)	Receiver Sensitivity (dBm)	SINR (dB)	Transmission Range R_t
54	–65	24.56	46
48	–66	24.05	49
36	–70	18.80	61
24	–74	17.04	77
18	–77	10.79	92
12	–79	9.03	103
9	–81	7.78	116
6	–82	6.02	123

* R_t is calculated based on eq. (1) and the ns-2 default values.

IV. SPATIAL-TEMPORAL ANALYSIS

A. Virtual Carrier Sensing Mechanism

IEEE 802.11 MAC protocol defines the RTS/CTS methods to alleviate the hidden station problem through the four-way-handshaking procedure. We evaluate and compare the effectiveness of this method with the basic method from both spatial and temporal viewpoints.

According to the 802.11 protocols, a station resumes its suspended transmission procedure after channel is idle and waits a DCF Inter Frame Space (DIFS). To simplify the analysis, we neglect this DIFS period in the figures of the temporal analysis. This only slightly increases the vulnerable period, about few microseconds.

Based on the transmitter-receiver distance, we classify all scenarios into three categories.

Case 1: $d < R_t / (1 + X_i)$

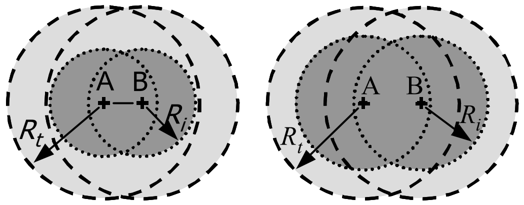
The whole interference area is within the transmission range of the sender (Figure 1a). There is no hidden station area in this situation. The area outside the interference range but inside the transmission range is the exposed station area. The RTS/CTS method covers more of the exposed station area but covers the same interference area as the basic method. So, the RTS/CTS method is redundant in this case.

Case 2: $R_t / (1 + X_i) < d < R_t / X_i$

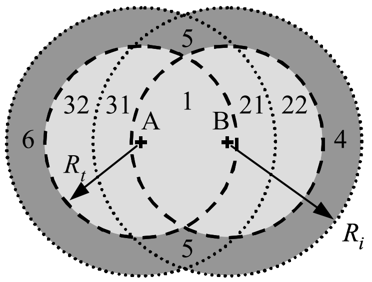
The sender's transmission range only covers part of the interference area, but the receiver's transmission range still covers the whole interference area (Figure 1b). The hidden station area is getting larger in the basic access method as the transmitter-receiver distance grows. Conversely, the RTS/CTS method provides the complete coverage of the interference area through broadcasting of the RTS frame, but it covers slightly larger exposed-station area than the basic method.

Case 3: $d > R_t / X_i$

Both the transmission ranges of the sender and receiver cover part of the interference area (Figure 1c). The RTS/CTS method covers more interference area, zone 21 and 22, than the basic method, covering zones 1 and 31. It is more spatially effective than the basic method, though both methods provide low spatial coverage of the interference area. Unfortunately, based on the multi-rate mechanism, this is the most common

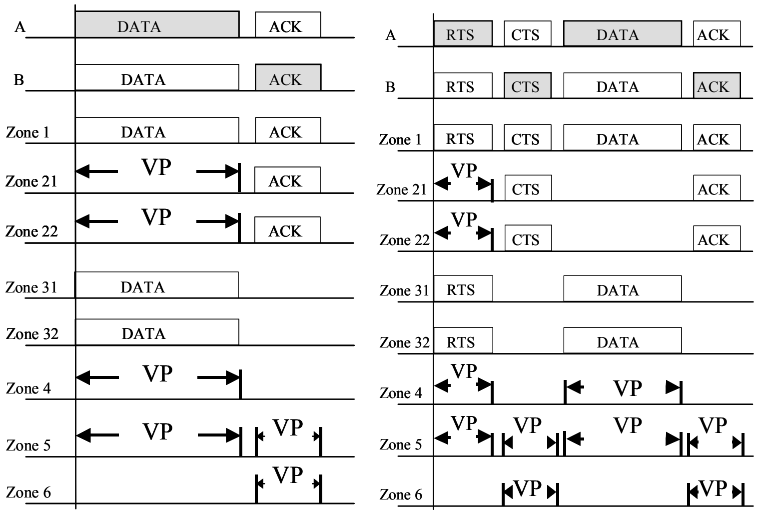


(a) Case 1 (b) Case 2



(c) Case 3

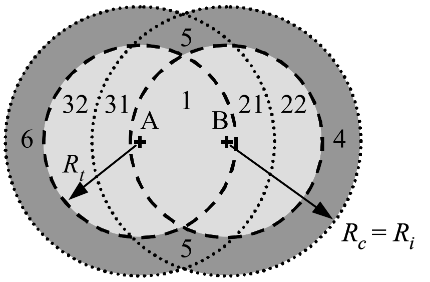
Figure 1. Spatial analysis for basic and RTS/CTS methods



VP = Vulnerable Period
(a) Basic access method

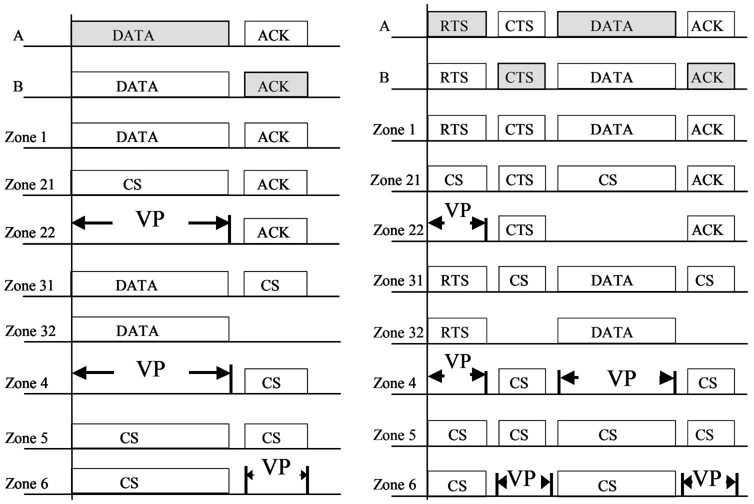
VP = Vulnerable Period
(b) RTS/CTS access method

Figure 2. Temporal analysis for the case 3



Case 6

Figure 3. Spatial analysis for basic and RTS/CTS methods



CS = Carrier Sensed only
(b) Basic access method

CS = Carrier Sensed only
(c) RTS/CTS access method

Figure 4. Temporal analysis for the case 6

situation in wireless networks. So, we study the case 3 from a temporal viewpoint. Compared with the basic method, the RTS/CTS method reduces the vulnerable period (VP) of zones 21 and 22 from the length of a DATA frame to an RTS frame. At the same time, it increases the VP of zone 4 from a DATA frame by an additional RTS frame. In zones 5 and 6, the situation is similar. As for the exposed station zone 32, the RTS/CTS method increases the blocking period from a DATA frame by an additional RTS frame. The RTS/CTS method improves the temporal effectiveness only in the transmission range of the receiver and degrades the temporal effectiveness in all other interference areas.

B. Physical Carrier Sensing Mechanism

The physical carrier sensing mechanism is used to detect the presence of any coded signal on the channel. A station performs CCA to report a busy channel if it senses any energy above the energy detection (ED) threshold. We assume that ED threshold is adjustable and can be much lower than the receiver sensitivity (Table I). The ratio *C* of the carrier sensing threshold to the receiver sensitivity is defined as:

$$C = (CS\_Threshold) - (RX\_Sensitivity) \quad (dB) \qquad (4)$$

The maximum value of *C* is 0 dB because an identifiable signal must be sensed. This means

$$C \le 0 \qquad (5)$$

$$R_c \ge R_t \qquad (6)$$

On the other hand, what is the reasonable minimum value of T_c or the maximum value of R_c? When the transmitter-receiver distance is d, the corresponding interference range is R_i. The maximum distance of the interference area from the sender is $d + R_i$. If $R_c = d + R_i$, then the carrier sensing range covers the entire interference area. However, if the carrier sensing range is larger than this, $R_c > d + R_i$, then it does not cover more interference area but does cover more exposed station area. So the reasonable upper bound on the carrier sensing range is

$$R_c \le d + R_i \tag{7}$$

The maximum value of d is R_t and the maximum value of R_i is R_{i_max}. Substituting these two values into (7), we obtain

$$R_{c\_\max} = R_t + R_{i\_\max} \tag{8}$$

Based on (3), the maximum R_i can be represented as

$$R_{i\_\max} = 10^{\left(\frac{SINR}{40}\right)} \cdot R_t = X_i \cdot R_t \tag{9}$$

Substituting (9) into (8), we have

$$R_{c\_\max} = R_t \cdot (1 + X_i) \tag{10}$$

So, the reasonable adaptive range of R_c is

$$R_t \le R_c \le R_t \cdot (1 + X_i) \tag{11}$$

This means the reasonable adaptive range of the ratio C is

$$-10 \cdot \log(1 + X_i)^4 \le C \le 0 \quad (dB) \tag{12}$$

In general, the optimum carrier sensing threshold that maximizes the aggregate network throughput should be inside this range, for a uniformly distributed network topology. However, the maximum carrier sensing range or minimum threshold does not indicate optimum throughput because of a trade-off between the hidden-station and exposed-station areas.

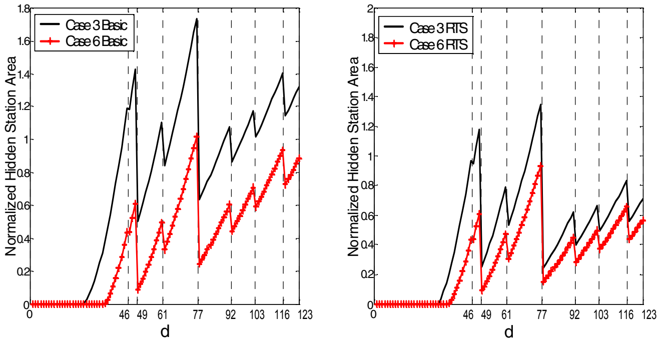
C. Combining the Virtual and Physical Carrier Sensing Mechanisms

The RTS/CTS method does not work effectively because of insufficient coverage of interference outside the transmission range of the RTS frame. We are interested whether, by combining the virtual carrier sensing mechanism with the physical one, we can improve the performance of the RTS/CTS method. Based on the transmitter-receiver distance, we also classify all possible scenarios into three categories:

Case 4: Case 1 with physical carrier sensing mechanism.

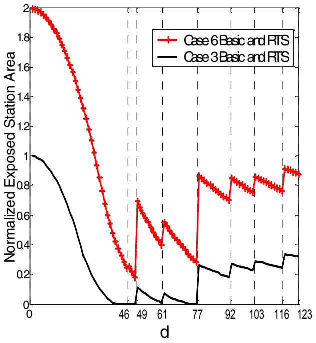
Case 5: Case 2 with physical carrier sensing mechanism.

Case 6: Case 3 with physical carrier sensing mechanism.



(a) Basic access method

(b) RTS/CTS access method



(c) Normalized Exposed station area

Figure 5. Hidden and Exposed station area in multi-rate mechanism

Table II VULNERABLE PERIOD FOR HIDDEN STATION

Zone #	Case 3 Basic	Case 3 RTS	Case 6 Basic	Case 6 RTS
21	D	R	D	R
22	D	R		
4	D	R+D	D	R+D
5	D+A	R+C+D+A		
6	A	C+A	A	C+A

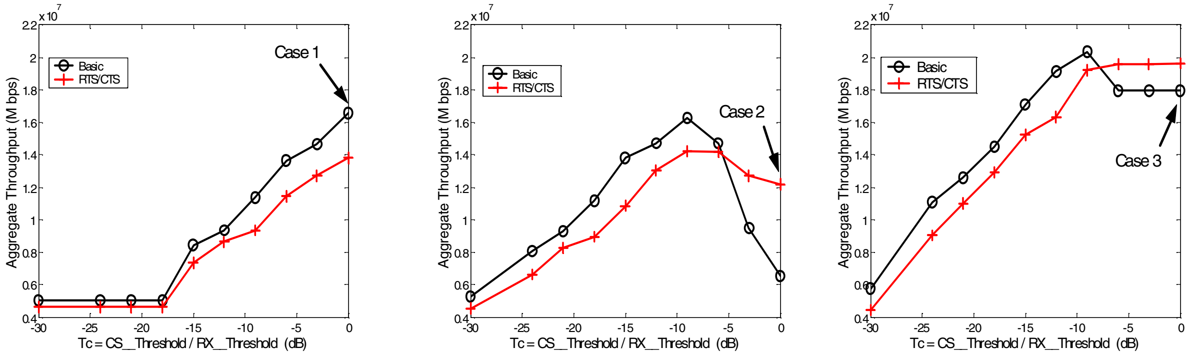
Note: R = RTS, C = CTS, D = DATA and A = ACK

Table III BLOCKING PERIOD FOR EXPOSED STATION

Zone #	Case 3 Basic	Case 3 RTS	Case 6 Basic	Case 6 RTS
22	A	C+A	A	C+A
32	D	R+D	D	R+D
4			A	C+A
6			D	R+D

Note: R = RTS, C = CTS, D = DATA and A = ACK

We only show the analysis of Case 6 (Figures 3 and 4) because the analysis of Cases 4 and 5 is same as for Case 6. In Figure 3, we study the scenario where the carrier sensing range is exactly the same as the interference range. From the spatial viewpoint, the carrier sensing range of RTS and CTS frames covers the entire interference area. Intuitively, there is no hidden station in this situation because every potential interfering station can sense the carrier signal of RTS or CTS frames. However, we get a very different result from the temporal view (Figure 4). Here, the CS box represents the case when the station senses the carrier signal only but cannot identify the frame. In the RTS/CTS method, even the carrier sensing range of the CTS frame covers zone 4; it is still an interference area to the receiver B during the transmission period of the DATA frame (Figure 4b), because any station in zone 4 just senses the carrier signal of the CTS frame but cannot identify it. This means that any backlogged station in this zone will resume its deferred transmission procedure after the CTS frame instead of setting its Network Allocation Vector (NAV) to defer its transmission after the ACK frame. This is the fundamental difference between these two carrier sensing mechanisms. The RTS/CTS method requires that the potential interfering station can not only sense but also identify the RTS or CTS frame to defer its transmission for the NAV period defined in the RTS and CTS frame. However, the physical carrier sensing mechanism just requires that the



(a) Case 4

(b) Case 5

(c) Case 6

Figure 6. Aggregate throughput of the basic vs. RTS/CTS access methods. Cases 1, 2, and 3 are special cases of Cases 4, 5, and 6, respectively, for $T_c = 0$, as indicated by arrows in the figures.

potentional interfering station can sense the signal to distinguish the channel state as idle or busy to defer it transmission based on the sensed state. So, increasing the carrier sensing range in the RTS/CTS method does not imply increasing the effective range of the RTS and CTS frame. The physical carrier sensing mechanism improves the spatial effectiveness of the sender-initiated channel-access method, such as the basic method, but it does not help the receiver-initiated channel-access mechanism, such as the RTS/CTS method.

Based on the above study, we compare the area of the hidden and exposed station under the multi-rate mechanism in Figure 5. The results are piecewise continuous because the multi-rate mechanism switches transmission rate in every interrupted point. We normalize the hidden and exposed areas by the transmission area of the 6 Mbps rate, which has the largest range of all the 802.11g rates. When carrier sensing threshold decreases from receiver sensitivity (case 3) to the same value as the SINR (Case 6), the basic method (Figure 5a) reduces the hidden station area more then the RTS/CTS method (Figure 5b), though the area in the basic method is still larger than that in the RTS/CTS method. Besides the hidden station area, both methods cover the same area of exposed station (Figure 5c). From the temporal viewpoint (Tables II and III), the RTS/CTS introduces greater vulnerable and deferred periods than basic method.

V. SIMULATION EVALUATION

The simulation is performed using the ns-2 simulator. The physical layer parameters follow the 802.11g specifications. The required SINR and receiver sensitivity is listed in Table I. The simulation topology is a ring with 20 evenly distributed stations. Each station sends frame to its right neighbor. The traffic is set to be saturated so that each station is always backlogged. We also use an extension in ns-2 to calculate SINR, which compares received signal with the aggregate interference rather individual interference.

Comparing the basic and RTS/CTS method in Figure 6, reducing the physical carrier sensing threshold increases the aggregate network throughput in some situations for the basic method but does not improve it for the RTS/CTS method. The basic method outperforms the RTS/CTS method with the same physical carrier sensing threshold in most situations in an ad hoc wireless network.

VI. CONCLUSION

The main contribution of this paper is in combining the spatial and temporal viewpoints to analyze the characteristics of the 802.11 virtual and physical carrier sensing mechanisms in ad hoc networks. Our analysis shows that the RTS/CTS method has low effectiveness in this environment, especially when using the multi-rate mechaism that operates every rate near its transmission limit, which makes it vulnerable to a large interference area. Secondly, combining the virtual and a physical carrier sensing mechanism does not improve the effectiveness of the RTS/CTS method greatly because this method requires more information then what the physcial carrier sensing mechanism can provide. Finally, an adaptive physical carrier sensing will improve the performance of the basic method, if we can find the optimum value that depends on the topology-, traffic-, and channel conditions in wireless ad hoc networks. The development of such a mechanism is part of our continuing work.

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