Tuning the Carrier Sensing Range of IEEE 802.11 MAC

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***Abstract*— We investigate the effects of the carrier sensing range of the IEEE 802.11 Multiple Access Control (MAC) scheme in this paper. Contrary to a simple and inaccurate cut-off circular collision model that is commonly used, we employ a more accurate collision model to realistically simulate MAC schemes in ad hoc networks. We argue that the carrier sensing range is a tunable parameter that can significantly affect the MAC performance in multihop ad hoc networks. An optimal carrier sensing range should balance the trade-off between the amount of spatial frequency reuse and the possibility of packet collisions. A reward formulation for the optimization of the carrier sensing range is presented. Extensive simulation results are provided to substantiate our study.**

I. Introduction

Ah hoc networks provide information accessing services to mobile users without pre-existing infrastructure. This is accomplished through multi-hop and peer-to-peer coordinated wireless packet exchange. Traditionally, the existing Wireless Local Area Network (WLAN) specifications are tapped to provide shared medium access and radio signaling support for ad hoc networks.

The IEEE 802.11 WLAN MAC/PHY specification [1] is one of the recommended international standards for WLANs, describing technological details for the Medium Access Control layer (MAC) and the Physical layer (PHY) of the communication protocol stack. Two coordination functions are defined in the IEEE 802.11 MAC/PHY standard: Point Coordination Function (PCF) and Distributed Coordination Function (DCF). The PCF mechanism employs a polling technique through the access points, which is not suitable for multi-hop networking. In the DCF medium access mode, active nodes compete for the use of the channel in a distributed manner. Hence, the DCF is commonly proposed to be used in ad hoc networks.

The DCF utilizes a Carrier Sensing Multiple Access with Collision Avoidance (CSMA/CA) scheme, which uses physical carrier sensing and, optionally, virtual carrier sensing with the Request-To-Send/Clear-To-Send (RTS/CTS) dialogue. The RTS/CTS dialogue is designed to mitigate the so-called hidden terminal and exposed terminal problems for WLANs, which are usually formed in a multihop fashion [2].

Most of the current networking research on WLANs, and in particular ad hoc networks, assume a simplified radio transceiver model. In this model, a circular transmission range centered at the transmitter is defined, based on the transmission power and ambient noise level, such that any node inside the range can receive (successfully decode) any packet from the transmitter. When a receiver is within the transmission range of two transmitters that are transmitting simultaneously, the packets are assumed to interfere with each other, leading to a collision at the receiver, so that no packet is received successfully.

Carrier sensing can reduce the number of packet collisions. However, the IEEE 802.11 specification does not give a well-defined carrier sensing range. One commonly assumed carrier sensing range is equal to the transmission range. This clearly contributes to the hidden terminal problem [2]–[4]. In the NS2 simulator [5], a default carrier sensing range of 2.2 times the transmission range is used. This static value is sub-optimal in many network scenarios.

In fact, the carrier sensing range is a tunable parameter that can significantly affect the MAC performance in multi-hop ad hoc networks. It balances the trade-off between the amount of spatial frequency reuse and the likelihood of packet collision. Therefore, it should be carefully chosen, based on network parameters such as network topology, traffic pattern, and transceiver power.

In this paper, we consider the optimal tuning of the carrier sensing range in an ad hoc network, in order to maximize a reward function that encourages network throughput and discourages excessive packet transmission. We demonstrate the effect of the carrier sensing range on network throughput and the rate of successful packet transmission. We investigate the performance of both the basic access scheme and the RTS/CTS-based access scheme in the IEEE 802.11 MAC specification. Furthermore, a more accurate packet collision model is used, taking into account the packet capture effect and interference from multiple packets.

The rest of this paper is organized as follows. In Section II, we summarize the related work. In Section III, we explain the effect of the carrier sensing range on network performance and present a reward formulation for the optimization of the carrier sensing range. Section IV presents extensive simulation results with modifications to the NS2 simulator. Concluding remarks are given in Section V.

II. Related Work

Reference [6] showed that the power needed to interrupt a packet reception is much lower than that is needed to transmit a packet. This asymmetry property may result in ineffectiveness of the RTS/CTS dialogues in IEEE 802.11. An analytical model was provided to study this problem in [6]. A Conservative CTS Reply (CCR) scheme was proposed to improve such ineffectiveness. In the CCR scheme, when an RTS packet is received successfully at the intended receiver, the receiver will return a CTS packet only when the received power of the RTS packet is higher than a certain threshold. This scheme solves the problem by conservatively accessing the channel. It is highly dependent on the accuracy of the signal power of the received packet.

In [7], the authors studied the relations between the transmission range, the interference range, and the carrier sensing range. Through simulations, it was observed that the RTS/CTS dialogue in the IEEE 802.11 may lead to unfairness and lower throughput in WLANs. A solution was then proposed to allow each terminal to count the number of *waiting for CTS timeout* events. If this counter exceeds a certain threshold, the RTS/CTS dialogue is turned off and the basic access scheme is used instead. It was reported that such a scheme improves the performance of the IEEE 802.11 MAC scheme.

It was shown in [8] that the space reserved by the IEEE 802.11 MAC scheme for a successful transmission is far from optimal and depends on the one hop distances between the sender and the receiver. The authors introduced a new quantitative measure, called the *spatial reuse index* to evaluate the efficiency of channel reservation. An improved virtual carrier sensing mechanism was proposed to increase spatial reuse and therefore network throughput.

Reference [9] presented some practical measurements of two IEEE 802.11 compliant network Access Points (APs). It was found that the use of RTS/CTS reservation dialogue does not improve the throughput or delay performance of the WLAN. However, the measurement experiments were performed with only two access points and without any hidden/exposed terminals (nodes that are in the range of the receiver/transmitter.) The paper further suggested that frame buffering and frame fragmentation were critical to the throughput of the network deployed. In [10], significant differences between emulation results and simulation results derived from NS2 simulations were reported.

III. Effect of the Carrier Sensing Range

A. Problem of Fixed Carrier Sensing Range

There are three types of ranges related to packet transmission in the IEEE 802.11 MAC scheme:

1) The transmission range (R): the range inside which nodes are able to receive or overhear the packet transmission;
2) The carrier sensing range (R_s): the range inside which nodes are able to sense the signal, even though correct packet reception may not be available; and
3) The interference range (R_i): the range inside which any new transmission may interfere with the packet reception.

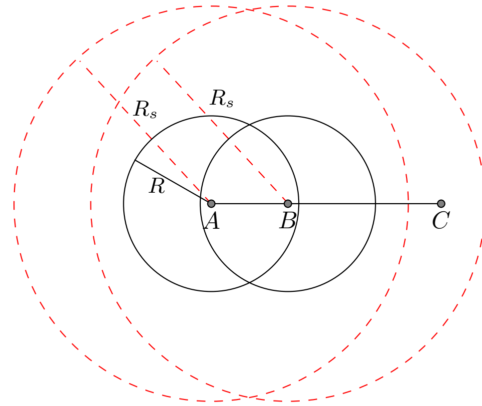

Fig. 1. Examples of Transmission and Carrier Sensing Ranges

It is generally assumed that the transmission range is smaller than the carrier sensing range and the interference range, i.e.,

$$R < R_s \qquad R < R_i \ .$$

However, the relation between the carrier sensing range and the interference range is not clear, even though reference [7] claimed that $R < R_i < R_s$. In NS2 [5], the carrier sensing range is by default set to a value of $R_s = 2.2R$. This implies $R < R_i < 2.2R$. However, R_i is actually not a fixed value due to the capture effect, as shown in the following example.

Assume node A sends a packet to node B, the transmission range of both nodes are depicted as solid-line circles in Fig. 1. The dashed-line circles represent the carrier sensing range of these nodes. For simplicity of discussions, we assume all senders use the same transmission power P_t. Based on the two-ray way-point propagation model, the signal power received by node B is

$$P_r(B) = P_t \cdot \frac{1}{|AB|^4} \ ,$$

where $|AB|$ denotes the Euclidean distance between nodes A and B.[1]

If node C happens to transmit at the same time, the signal power propagated from node C to node B becomes interference as node B intends to receive the packet from node A:

$$P_i(B) = P_t \cdot \frac{1}{|BC|^4} \ .$$

In order for node B to receive the packet from node A successfully, the signal to noise/interference ratio should be larger than the capture threshold (T_{cp}) [11]:

$$\frac{P_r(B)}{P_i(B)} > T_{cp} \ ,$$

[1] We assume $|AB|$ is larger than the threshold of attenuation in the two-ray way-point propagation model.

i.e.,

$$|BC| > (T_{cp})^{\frac{1}{4}}|AB| = \gamma|AB| \ , \tag{1}$$

where γ is defined as $(T_{cp})^{\frac{1}{4}}$.

Assuming a capture threshold of 10 dB, (1) becomes $|BC| > 1.778|AB|$. When the location of node B is close to the border of the circle covered by node A's transmission, the interference range of is about $1.778R$. It will be smaller as $|AB|$ decreases, as was also discussed in [8].

Unfortunately, in the RTS/CTS-based access scheme of the IEEE 802.11 MAC standard, only those nodes sensing the transmission from the data packet sender or overhearing the CTS packet in the transmission range of the intended receiver (node B in our example) are required to defer any transmission. When the basic access scheme is used, only nodes sensing the data packet transmissions from the sender (node A in our example) will defer from transmission. Therefore, node C in Fig. 1 is free to start any new transmission when node B is receiving. However, its transmission destroys the data packet reception at node B. Note that node C is not a hidden terminal [2], because it is not in the range of the receiver. We term the situation when a distant node, node C, transmits to corrupt node B's reception as *Distant Terminal Problem*.

B. Carrier Sensing Range Optimization

The transmission range R and capture threshold R_i of a transceiver are usually pre-determined by hardware specification and radio signal design. On the contrary, the sensing range R_s is a tunable design parameter that can significantly affect the performance of a system at the MAC layer. In this section we study the optimization of R_s.

Clearly, the larger R_s is, the more conservative a node behaves. We expect the packet collision rate to decrease, and hence the packet success rate to increase, as R_s increases. The actual channel throughput, however, does not necessary increase with R_s, since a larger R_s also leads to a lower level of spatial frequency reuse. Similarly, a smaller R_s increases spatial frequency reuses but decreases the packet success rate.

More importantly, the channel throughput is not the sole performance metric at the MAC layer of a system. Each time a node attempts to transmit a packet, whether or not the packet is successfully received, energy is consumed, and computation power is taken away from other protocols and applications. Furthermore, repeated retransmissions at the MAC layer increase the amount of delay experience by upper-layer protocols. To represent such intrinsic penalties to a packet transmission, we define a cost function, $g(t)$, that is related to the transmission time of DATA packets. This cost can represent energy consumption, transmission and queuing delay, computation power, or an aggregation of multiple factors.

The exact formulation for this cost function depends on factors that are outside of the scope of this paper. However, it is obvious that the cost functions of interest must be a non-decreasing function of t, the time of a transmission. Since the transmission time of a data packet is much longer than that of a control packet, a simple but effective cost function can be defined as

$$g(t) = \begin{cases} c, & \text{for a data packet transmission} \\ 0, & \text{for all control packet transmissions} \end{cases} . \tag{2}$$

Thus, we define the total reward of a MAC scheme as

$$\eta = N_s - cN_d \ , \tag{3}$$

where N_s represents the channel throughput, and N_d represents the total amount of transmitted data, both in bits per second. This performance metric encourages channel throughput while discouraging unnecessary packet transmission, and the parameter c now represents the *relative* cost of transmitting one bit compared with the benefit of successfully receiving one bit. Then, for different values of c, the sensing range of a node can be optimally tuned to maximize the total reward η.

IV. Performance Evaluation

Extensive simulations have been performed to analyze the throughput of the original IEEE 802.11 MAC scheme and our tuned carrier sensing range. Our simulations were performed on an extension of the popular NS2 simulator. In our simulations, we include a more complicated and more accurate packet collision model, as discussed in the following.

In the standard NS2 simulator, only packet transmissions in the carrier sensing range of a receiver are considered as potential sources of packet collisions. When more than two packets arrive to the receiver, only two packets are considered and the rest of them are simply ignored. However, the other packets should be considered as interferences as well. In our collision model, all transmissions, including those that are outside the carrier sensing range of a receiver, are considered as interferences to the receiver. When the ratio of the receiving packet power to the sum of the interferences is higher than a certain threshold (the capture threshold), the packet is considered collided. The capture threshold (CPThreshold) is assumed to be 10 dB in our simulations. The transmission range is 250 m. The data packet length is 2000 Bytes. The simulation time is 4 seconds each. Every data point represents an average of 10 simulation runs.

A. Effect of Carrier Sensing Range

Our first set of simulation results were obtained through a one-dimensional chained network, where $N + 1$ nodes are fixed at evenly distributed grid locations. The distance between two neighboring nodes is d. In our simulations, d is set to $2560/N \ m$. The variable distance was introduced to show the throughput performance of a network with fixed area but different nodal density. In the simulations, every node except the right most node has data traffic to send to its immediate neighbor to the right. Therefore, node 1 sends to node 2, node 2 sends node 3, and so on. These N one-hop traffic flows saturate the network.

Figure 2 shows the probability of successful data packet transmission in the chain network for different N and two different accessing schemes in IEEE 802.11 DCF [1]. The

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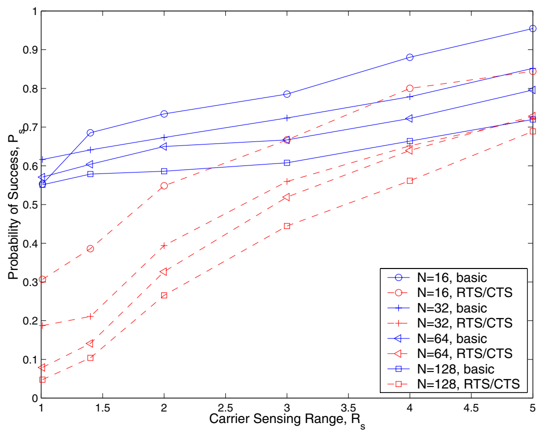

Fig. 2. Probability of Success in a Chain Network

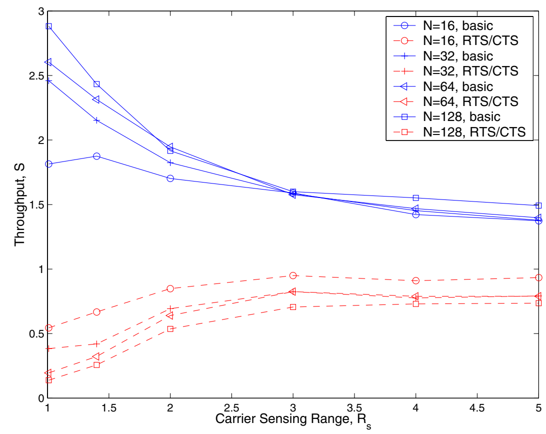

Fig. 3. Throughput of Chain Network

basic scheme is similar to slotted Carrier Sense Multiple Access (CSMA) since a ready node sends its data packet out unless either it senses the carrier on the channel or it is in the backoff state due to previous collisions. The RTS/CTS scheme is the so-called CSMA/Collision Avoidance (CA) protocol. RTS/CTS dialogues lead the transmission of data packets, followed by acknowledgment (ACK) packets. The probability of successful data packet transmission, P_s, is defined as the number of ACK packets received at the sender divided by the number of data packets transmitted.

In Fig. 2, we can see that P_s is higher as carrier sensing range R_s increases. As R_s increases, more nodes sense the carrier of one node's data transmission and go to a defer state. Therefore, it is less likely that other nodes may start transmissions to ruin the data packet reception. Note that P_s is not 1 even R_s is 5 times of the transmission range R. This is due to collisions caused by nodes starting their transmissions in the beginning of the same time slot.

It can also be observed from Fig. 2 that P_s of the basic scheme is generally higher than that of the RTS/CTS scheme. The explanation is that the RTS/CTS scheme does not sense the carrier again after the RTS/CTS dialogue has been exchanged. Some nodes, which are outside of the carrier sensing range of the sender but have not overheard the CTS packet successfully, may start a transmission, destroying the data packet reception at the receivers. Furthermore, as shown in Fig. 2, the P_s values of networks with larger N are lower, due to more competing nodes.

In Fig. 3, we show the throughput of these networks. The throughput was calculated as the number of data transmitted per second normalized by the data rate of the channel (11 Mbps). We can see from this figure that the basic scheme out-performs the RTS/CTS scheme. Similar results were reported by other researchers [9] [7]. This can be explained by the much lower P_s of the RTS/CTS access scheme, as shown in Fig. 2. The difference of throughput is higher when R_s is smaller, with more nodes being potentially interfering packet senders. The throughput of the basic scheme decreases with the increase of R_s in Fig. 3. This is because, when R_s is smaller, more spatial reuses are possible. The larger amount of possible spatial re-use also explains why the throughput of a network with larger N is higher.

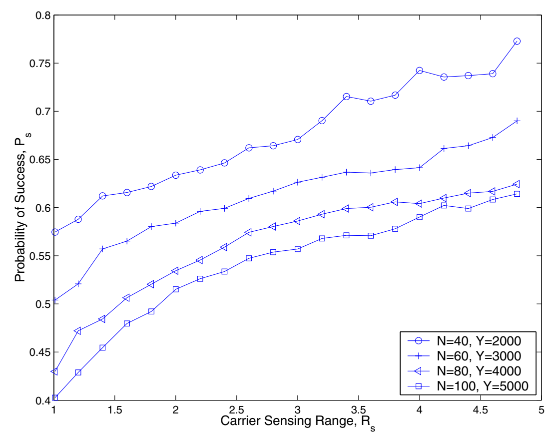

Fig. 4. Probability of Success in Random Networks

B. Carrier Sensing Range Optimization

Next, we investigate the optimization of R_s to maximize the reward function. Clearly, for the RTS/CTS scheme, a maximum R_s value should be used. Therefore, we only study the basic scheme.

In these experiments, N nodes are uniformly distributed in a $1 \times Y\ m^2$ network. The value of Y is set to $50N$. All traffic are sent to a randomly selected immediate neighbor.

Fig. 4 shows P_s for different networks that we have simulated. P_s increases with R_s, similar to Fig. 2. Interestingly, P_s is also lower for networks with smaller N, even though their nodal densities are the same.

We present the throughput of the simulated networks in Fig. 5. Once again, as R_s increases, the overall throughput decreases. The networks with larger N but larger network area (Y) result in higher throughput, due to more concurrent transmissions. However, the increase of S is not linear to Y.

Plots of the total reward are presented in Fig. 6, where we show η as given by (3) for different values of the relative

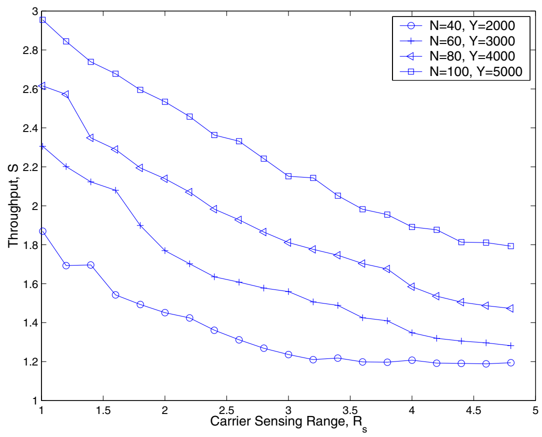

Fig. 5. Throughput of Random Network

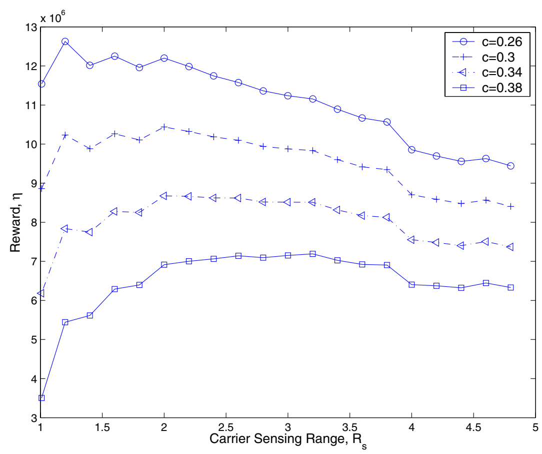

Fig. 6. Reward Function for Different c

cost, c. For each value of c, there is an optimum R_s which maximizes the total reward. The optimum R_s is clearly drifting from small to large as c increases. Fig. 6 shows that, when the relative cost of transmitting one bit is 30% of the benefit of receiving one bit (i.e., $c = 0.3$), the optimal carrier sensing range of $2R$ can improve the total reward by about 15% over the case where a carrier sensing range of R is used.

In Fig. 7, we show the optimum carrier sensing range R_s^* as a function of the relative cost c for the simulated network scenarios. Clearly, R_s^* increases with c. Furthermore, for different network scenarios, the exact values of R_s^* can differ significantly. For example, for $c = 0.31$, R_s^* is about 1 for a network with 40 nodes and $Y = 2000\ m$. It is 1.4 for a network with 60 nodes and $Y = 3000$. The stepping effect shown in the figure is due to the steps of R_s in our simulations.

V. Conclusions

We have investigated the effects of the carrier sensing range on MAC layer performance in ad hoc networks. A more accurate collision model for the popular NS2 simulator has been developed to realistically simulate the MAC layer. Using

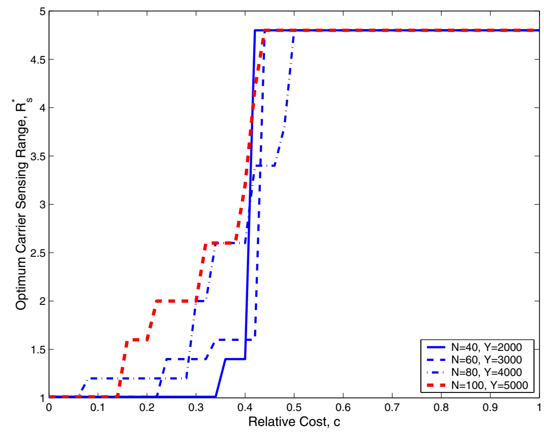

Fig. 7. Optimum Carrier Sensing Range in Random Networks

this model, we can determine the optimal carrier sensing range of CSMA for any ad hoc network.

We conclude that the fixed carrier sensing range in the IEEE 802.11 specifications should be optimized to improve the network throughput performance and overall efficiency. In particular, there is a mismatch among the transmission range, interference model, and carrier sensing range in the RTS/CTS design, which severely degrades its performance. Our study shows that an optimally chosen carrier sensing range can significantly increase the network throughput and decrease the number of data packet collisions.

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