Improving Spatial Reuse of IEEE 802.11 Based Ad Hoc Networks

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Abstract— **In this paper, we evaluate and suggest methods to improve the performance of IEEE 802.11 based ad hoc networks from the perspective of *spatial reuse*. Since 802.11 employs *virtual carrier sensing* to reserve the medium prior to a packet transmission, the relative size of the spatial region it reserves for the impending traffic significantly affects the overall network performance. We show that the space reserved by 802.11 for a successful transmission is far from optimal and depending on the one hop distances between the sender and the receiver, we can have three scenarios with very different spatial reuse characteristics. We also introduce a new quantitative measure, the *spatial reuse index*, to evaluate the efficiency of the medium reservation accomplished by 802.11 virtual carrier sensing. We also propose an improved virtual carrier sensing mechanism for wireless LAN scenarios and using analysis and simulation results, show that it can significantly increase the spatial reuse and network throughput.**

I. INTRODUCTION

In IEEE 802.11 based ad hoc networks, concurrent transmissions and channel contentions are managed by the *distributed coordination function* (DCF) [1]. DCF employs *Virtual Carrier Sensing* (VCS) to determine channel access rights and reduce collisions among the stations competing for the shared medium. While using physical carrier sensing and backoff mechanisms to distributedly determine channel access, 802.11 also uses the exchange of RTS and CTS messages to avoid the well known hidden terminal problem [1]. To avoid interfering with the ongoing transmission, all nodes which hear the RTS or CTS message defer their transmission till the ongoing transmission is over. Consequently, the geographical area over which the RTS/CTS handshake can be heard determines the overall throughput achievable in the network. To evaluate the effectiveness and efficiency of the medium reservation accomplished by the RTS/CTS mechanism and consequently the VCS, *spatial reuse* can serve as an important benchmark. We note that there is a tradeoff between higher spatial reuse and increased chances of collisions. Due to its tight connection with the network throughput and latency, spatial reuse serves as one of the key factors in wireless network capacity analysis. This paper analyzes the spatial reuse characteristics of 802.11 and proposes a protocol to significantly improve the reuse characteristics.

Recently, extensive research efforts have been devoted to the performance evaluation of ad hoc networks, most of which focus on the capacity analysis [3][4][5]. To the best of our knowledge, the influence of interference range on the network performance was first explored in [6] which examines the interaction of the 802.11 MAC and ad hoc forwarding from the perspective of spatial reuse. It is shown that for the total capacity to scale with network size, the average distance between source and destination nodes must remain small as the network grows. In [7], spatial reuse characteristics are used to examine the performance of IEEE 802.11 MAC in multihop networks. The paper presents several serious problems encountered in IEEE 802.11 multihop networks and their underlying causes and concludes that current wireless LAN protocols do not function well in multihop ad hoc networks. In [8], the 802.11 RTS/CTS handshake is analyzed and it is shown that this mechanism is not always effective due to the fact that the power needed for interrupting a packet reception is much lower than that for delivering a packet successfully. Thus the virtual carrier sensing implemented by RTS/CTS handshake cannot prevent all interferences as expected in theory.

Although some of the previous work evaluates the capacity and effectiveness of virtual carrier sensing, none of them has studied the spatial reuse characteristics thoroughly. In this paper, we evaluate the performance of IEEE 802.11 based ad hoc networks in terms of the spatial reuse and provide a quantitative measure of spatial reuse which reflects the effectiveness of medium reservation conducted by virtual carrier sensing. Our analysis shows that there are three different cases with respect to the effectiveness of medium reservation, which we describe as *underactive*, *moderate* and *overactive*, respectively. We also show that the the space reserved by 802.11 for a successful transmission does not always match the space in which interference may occur.

The paper further examines the overactive scenario and proposes an improved virtual carrier sensing scheme to enhance spatial reuse. We focus our analysis and simulations on Wireless LANs, where nodes hardly move during packet transmission and have relatively small one-hop distance between them. Experimental and analytic results show that our proposed scheme achieves significantly higher throughput over the virtual carrier sensing mechanism used in 802.11.

The rest of the paper is organized as follows. In Section II we analyze the three scenarios with respect to the effectiveness of spatial reuse and introduce the spatial reuse measure. An improved scheme is proposed and evaluated in Section III. Section IV summarizes our conclusions.

II. 802.11 SPATIAL REUSE ANALYSIS

As described in the previous section, spatial reuse is a key parameter that determines the performance of wireless networks. In this section, we present a thorough analysis of the spatial reuse in 802.11 virtual carrier sensing. We also introduce a metric to evaluate the spatial reuse.

A. The Signal to Interference Ratio Model

Successful reception of a packet at the physical layer depends on the signal to noise ratio at the receiver. The basic radio propagation model that we assume in this paper is the *two-ray ground reflection model* [2]. According to this model, the received power at distance d is given by

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

where P_t is the transmitted power, h_t and h_r are the heights of the transmitter and receiver antennas respectively, G_t and G_r are the antenna gains and L is the system loss. As will be seen shortly, it is not difficult to extend our analysis to the *free space model* [2].

Now we describe the three ranges that we use heavily in this paper, following the definitions of [8]. Since we use *ns-2* [9], [10] as our simulator, whose PHY layer is modeled on the 914MHz Lucent WaveLAN DSSS radio interface, the relevant data in *ns-2* and the WaveLAN card are also provided.

- **Transmission Range (R_t)**: The range within which a MAC frame can be successfully delivered and its type/subtype (RTS, CTS, Data, etc.) field can be correctly identified, assuming there is no interference from other radios. According to Eqn. (1) and for WaveLAN and *ns-2*, the transmission range in is equal to 250 meters.
- **Carrier Sense Range (R_s)**: The range within which the power from the transmitter can be sensed, indicating the busy state of the medium. Using Eqn. (1) and the carrier sensing power threshold of WaveLAN, we have 550 meters as the common carrier sense range.
- **Interference Range (R_i)**: The range within which stations in receive mode will be interfered with by other transmitters and thus suffer a loss. As will be shown later, it does not take a fixed value.

To obtain the value of R_i, we need to introduce the model of signal to interference ratio (SIR), which directly follows the *Physical Model* in Gupta and Kumar's work [3]. Suppose that node B is receiving packets from node A, which is at an one-hop distance of d_s meters, and concurrently another node C, d_i meters away from B, is sending packets to a fourth node D. We also assume all nodes transmit at the same power P_t and have the same radio parameters. To determine whether there is a collision at B, we need to compare the power received at B from both A and C, denoted by P_s (signal power) and P_i (interference power), respectively. Neglecting ambient noise, from Eqn. (1), we have [8]

$$SIR = \frac{P_s}{P_i} = \left(\frac{d_i}{d_s}\right)^{\alpha} \geq CPThresh \tag{2}$$

where $CPThresh$ denotes the *Capture Threshold*, set to 10 in *ns-2*, and α is the signal attenuation coefficient, which is equal to 4 in the two-ray ground reflection model. Thus the interference range is given by

$$R_i = d_s(CPThresh)^{1/\alpha} = k_{SIR} d_s \tag{3}$$

We use k_{SIR} to denote the multiplier, which depends on the SIR model. In *ns-2*, $k_{SIR} = \sqrt[4]{10} = 1.78$. Thus there is no fixed relation between R_i and R_t; R_i is proportional to the one-hop distance d_s. Note that R_t and R_s are merely radio ranges, which implies they only apply in the PHY layer. However, R_i is involved with the SIR model and the comparison of the received power, so it must be handled at the MAC layer as well. We now show how the relative magnitudes of R_i and R_t affect the performance of virtual carrier sensing and the effectiveness of the RTS/CTS handshake. Since in Wireless LANs it is common that all nodes are within R_s meters of each other, in the following sections we focus our discussions to the other two ranges.

B. Effectiveness of Virtual Carrier Sensing

In 802.11 VCS [1], nodes defer any impending transmission by the appropriate intervals whenever an RTS or CTS is overheard. This virtual carrier sensing mechanism, together with physical carrier sensing, determines the busy/idle state of the medium. Its underlying justification can be described by the conditions below.

1) **Sufficient condition**: If a node can overhear an RTS/CTS, then it is potentially able to interfere with the upcoming transmission.
2) **Necessary condition**: If a node is capable of interfering with an ongoing transmission, then it must be able to overhear the preceding RTS or CTS.

Obviously, 802.11 VCS achieves its best performance only when both conditions are satisfied. This happens when the transmission range R_t is equal to the interference range R_i. However, as we mentioned earlier, this is not the common case as R_i is not a fixed value. To better illustrate the effectiveness of RTS/CTS mechanism, we classify all the situations into three categories with respect to $r = d/R_t$, the ratio of the one-hop distance d as compared to R_t.

1) Underactive RTS/CTS Scenario: Fig. 1 shows the scenario where the interference range R_i (dotted line circle) is larger than the transmission range R_t (solid line circle). From Eqn. (2) we have $R_i = k_{SIR} d > R_t$, so in this scenario, d is confined by $R_t/k_{SIR} < d < R_t$. In *ns-2* and WaveLAN, this range is between 141 and 250 meters. As shown in Fig. 1, every location falls into one of the four zones, marked by I, II, III and IV. Specifically, Zone I, the intersection of the two solid line circles, represents the area in which a node can overhear both RTS and CTS of the ongoing transmission. In Zone II, only RTS can be overheard, while a node in Zone III can only overhear CTS. Zone IV, however, is out of R_t and a node located in it can sense some energy in the medium but is not able to identify the signal.

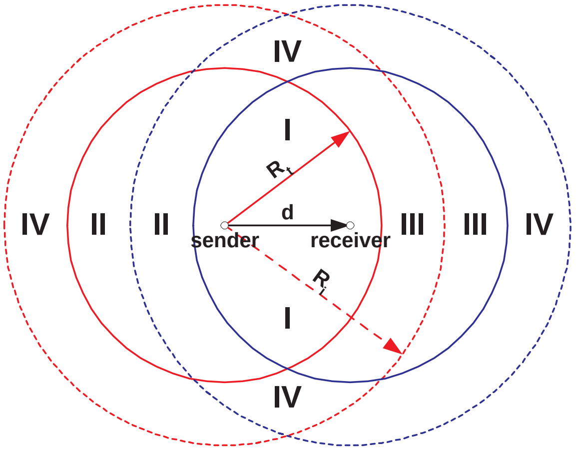

Fig. 1. Scenario I: Underactive RTS/CTS, $0.56R_t < d < R_t$

In this scenario, we can see the sufficient condition addressed previously is satisfied, as any node located in Zone I, II or III is able to interfere with the ongoing traffic. However, while a node in Zone IV can not successfully receive RTS/CTS packets, it is still able to interrupt the ongoing transmission since it is within the interference range. Note that nodes in Zone IV fail to obtain the transmission duration information from the RTS/CTS packets and thus do not defer from accessing the channel. Therefore in this scenario RTS/CTS mechanism might fail to prevent a hidden node from interfering with the transmission, and we call this the *Underactive RTS/CTS Scenario*.

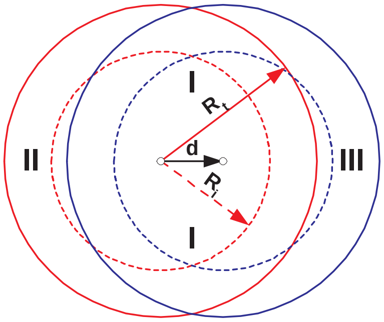

Fig. 2. Scenario II: Moderate RTS/CTS, $0.36R_t < d < 0.56R_t$

2) Moderate RTS/CTS Scenario: Fig. 2 depicts the scenario where R_i is smaller than R_t and part of the dotted line circles (interference region) lies within Zone II/III. In this scenario the range of d is $R_t/(k_{SIR}+1) < d < R_t/k_{SIR}$, which is between $0.36R_t$ and $0.56R_t$ and $90 < d < 141$ meters in Lucent's WaveLAN and *ns-2*.

In Fig. 2, observe the interference circle (dotted line) and the transmission circle (solid line). As can be seen, Zone I, II, III all intersect with the interference circle, which implies that the nodes in the three zones have a chance (equal to 100% when $R_i = R_t$) to interfere with the ongoing traffic. On the other hand, all the nodes within the interference circle are able to receive the preceding RTS/CTS, which satisfies the necessary condition. Thus the RTS/CTS handshake and consequently the VCS has reasonable performance in this case and we call it the *Moderate RTS/CTS Scenario*.

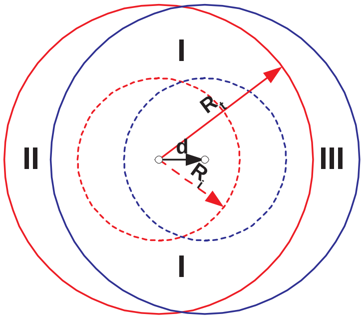

Fig. 3. Scenario III: Overactive RTS/CTS, $d < 0.36R_t$

3) Overactive RTS/CTS Scenario: In Fig. 3, R_i is small enough so that there is no intersection between the interference circle and Zone II/III and both interference circles are located within Zone I. In this case, the range of d is $d < R_t/(k_{SIR}+1)$ and for Lucent's WaveLAN and *ns-2*, d is below $0.36R_t$ (90 meters).

We call this the *Overactive RTS/CTS Scenario* since the sufficient condition is no longer satisfied while the necessary condition still holds. It is seen that, although the nodes in Zone II/III can still receive RTS/CTS, they are not capable of interrupting the ongoing transmission. In this case RTS/CTS gives false alarms that reduce the spatial reuse. It is also interesting that the power level needed for a successful packet delivery is much smaller than that of interrupting a transmission, a scenario which might not have been considered when the VCS was first proposed.

C. Evaluation of 802.11 Spatial Reuse

The effectiveness of VCS is closely related to the efficiency of spatial reuse, which in turn has a strong influence on the throughput and delay characteristics. Since the necessary and sufficient conditions mentioned above are rarely satisfied simultaneously, the spatial reuse achieved in general is far from ideal. In Fig. 3, the spatial reuse is low since nodes outside the interference circles could actually transmit/receive despite the detection of RTS/CTS. In this scenario the RTS/CTS handshake claims much more space than necessary for a successful transmission, thereby reducing the spatial reuse. On the other hand, in Fig. 1, RTS/CTS mechanism underestimates the space required for a successful transmission and thus incurs potential collisions by excessive spatial reuse, which is also undesirable.

To evaluate 802.11 spatial reuse quantitatively, we introduce the *Spatial Reuse Index (SRI)* as follows:

$$\text{SRI} = \frac{\text{area of the region where interference may occur}}{\text{area of the region reserved by RTS/CTS to avoid interference}} \tag{4}$$

In a single hop scenario, this index is equivalent to the ratio of the area of the interference region (union of the two dotted line circles) to that of the transmission region (union of the

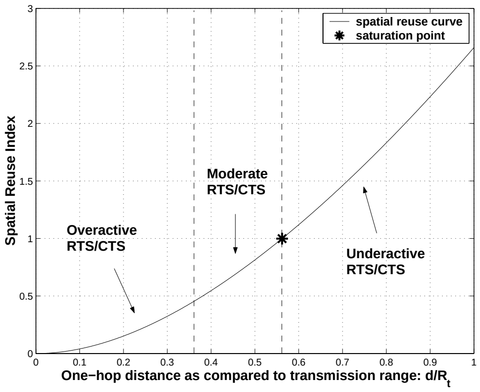

Fig. 4. Spatial Reuse Index (SRI)

two solid line circles). Assume $r = d/R_t$, the ratio of the one-hop distance d to the transmission range R_t, we can compute the one-hop SRI as

$$SRI_{one-hop} = \frac{(\pi k^2 - k^2 \cos^{-1}\frac{1}{2k} + \frac{1}{4}\sqrt{4k^2-1})r^2}{\pi - \cos^{-1}\frac{r}{2} + \frac{r}{4}\sqrt{4-r^2}} \qquad (5)$$

where $k = k_{SIR}$ as specified in (2). Using $k_{SIR} = \sqrt[4]{10} = 1.78$, we obtain the SRI curve in Fig. 4.

In Fig. 4, the reuse index achieves its optimal (saturation) value of 1 as $r = 1/k_{SIR} = 0.56$. This happens when $R_i = R_t$ and RTS/CTS handshake delivers its best performance. For SRI above 1, underactive RTS/CTS causes an excessive spatial reuse, which may introduce unforeseeable collisions. We also see that overactive RTS/CTS has a low spatial reuse with its SRI below 0.5. It can be seen that the SRI serves as a good measure for evaluating both spatial reuse and RTS/CTS handshake efficiency.

III. AN IMPROVED VCS SCHEME AND EXPERIMENTAL RESULTS

In generic Wireless LAN settings, one-hop distances less than 100 meters are one of the most common scenarios since such environments are primarily expected to span rooms in a building, a few houses or buildings. According to the WaveLAN and *ns-2* settings, these would correspond to the overactive RTS/CTS scenario. Also, while the underactive RTS/CTS scenario is not desirable due to the potential collisions incurred, an alternative CTS reply scheme to eliminate such collisions has been proposed in [8]. For these reasons, we only consider the overactive RTS/CTS scenario in our proposed scheme.

A. Aggressive Virtual Carrier Sensing (AVCS)

We see in Fig. 3 that spatial reuse is inadequate in most wireless LAN scenarios since 802.11 VCS prohibits eligible nodes in Zone II/III from sending or receiving. To enhance spatial reuse, we propose a simple new scheme named *Aggressive Virtual Carrier Sensing* (AVCS). Its basic idea is described in Table III-A, where we use an event-action table.

To illustrate the working of AVCS, consider a node in Zone II with data to send. Under 802.11 VCS, the node has to defer/hold its RTS till the end of the ongoing transmission and then use the backoff mechanism. In our proposed scheme, however, a node in Zone II would send its RTS immediately whenever it wants to send a packet, or respond instantly with a CTS if it is an intended receiver. In short, a node which overhears either a RTS or a CTS but not both would not consider the media as busy. The underlying justification for AVCS is that in the overactive RTS/CTS scenario, if a sender or receiver can hear either a RTS or a CTS but not both, it is guaranteed that such a node cannot interfere with the ongoing transmission.

		Sender's action		**Receiver's action**	
Zone	**RTS/CTS detection**	**Normal VCS**	**Aggressive VCS**	**Normal VCS**	**Aggressive VCS**
I	RTS&CTS	hold	hold	hold	hold
II	RTS only	hold	send RTS	hold	respond with CTS
III	CTS only	hold	send RTS	hold	respond with CTS

TABLE I

NORMAL VCS VS. AGGRESSIVE VCS: EVENT-ACTION TABLE

B. Evaluation of AVCS

From the discussion in the Section III-A, it is clear that AVCS increases the spatial reuse in wireless LANs by allowing nodes in Zones II and III to transmit. This improvement can be quantified if we re-evaluate the spatial reuse index of Eqn. 5. According to its definition, the VCS-reserved region (denominator in Eqn. (4)) shrinks to the intersection of the two transmission circles when we apply AVCS. Therefore we can re-derive the SRI as

$$SRI_{AVCS} = \frac{(\pi k^2 - k^2 \cos^{-1}\frac{1}{2k} + \frac{1}{4}\sqrt{4k^2-1})r^2}{\cos^{-1}\frac{r}{2} - \frac{r}{4}\sqrt{4-r^2}} \qquad (6)$$

In Fig. 5, we compare the new SRI curve with the original one, with the X-axis set as the real-world one-hop distance. We see that the spatial reuse improves significantly with AVCS in wireless LAN settings, specially as the one hop distance increases.

In fact, the spatial reuse can be further improved in the overactive RTS/CTS scenario if we extend our attention to Zone I. In Fig. 3, the nodes in Zone I which are not within the interference circles, can also send and receive packets without

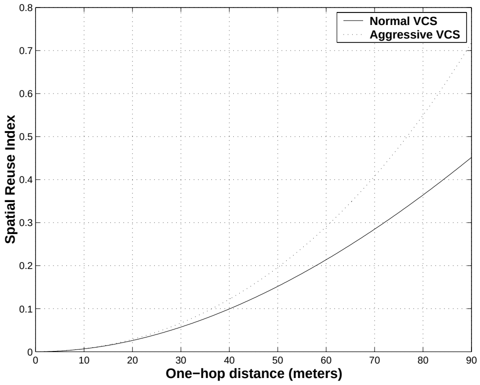

Fig. 5. Comparison of AVCS with the normal VCS in terms of SRI

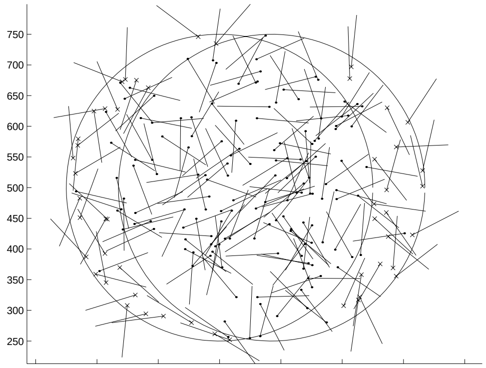

Fig. 6. Random connection patterns for one hop distance of 85 meters

interrupting the ongoing transmission. However, in order to judge whether such a node is within the interference circle, the distance information between the nodes is also required. With a more sophisticated MAC protocol that can handle distance measurements and distribution, even better spatial reuse can be achieved.

Finally, we note that there are some tradeoffs when using the AVCS. Since nodes in Zone II and III transmit while the original transmission is going on, the original source and destination nodes will not update their NAV which might lead to potential collisions. However, the probability of such collisions depends on the spatial distribution of the traffic patterns and are likely to be small.

C. Simulation Results

Using *ns-2* based simulation results, we now show that the improved SRI results in increased network throughput. The radio parameters assumed correspond to Lucent's WaveLAN. For evaluating the scheme, we use a test topology wherein we randomly generate two pairs of nodes with the same one-hop distance. Due to the assumption of wireless LAN settings, we confine this one-hop distance to less than 90 meters, the upper bound for the overactive RTS scenario. The locations of the pairs are generated randomly so that either pair has a chance to be placed in any zone of the other pair. UDP is used as the transport protocol for both the connections and each source is a CBR traffic generator with a rate of 448Kbps. The generated topology is then simulated and the per-connection throughput is measured. This experiment is then repeated 200 times with randomized placement of the two source destination pairs. From these 200 runs, the average per-connection throughput is computed for both AVCS and the normal VCS. The 200 random connections pairs generated for the case of one hop distance of 85 meters is shown in Figure 6.

Fig. 7 plot the achieved per session throughput for different one-hop distances. It can be seen from the figure that AVCS achieves about 20% greater throughput that normal VCS in the overactive RTS scenario. In Fig. 7, the throughput achieved by normal VCS stays at a constant level and has little fluctuation, while for AVCS, the throughput goes up slightly as we increase the one-hop distance. This matches our intuition that as Zone II and Zone III grow larger, AVCS gains a better chance to enhance the spatial reuse, consequently improving the overall throughput.

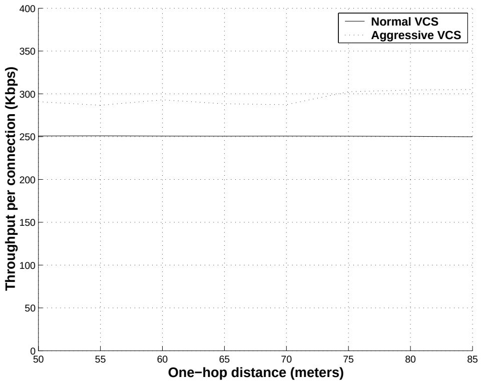

Fig. 7. Throughput in Aggressive VCS and Normal VCS

IV. CONCLUSIONS

The performance of wireless networks in general and IEEE 802.11 based ad hoc networks in particular, in terms of both the throughput and delay characteristics, depend on the spatial reuse characteristics. In this paper, we present a thorough analysis of the spatial reuse characteristics of 802.11 based ad hoc networks. We showed that depending on the one hop distances between the sender and the receiver, we can have three scenarios with different spatial reuse characteristics. We also introduced a new metric, spatial reuse index, and demonstrated its effectiveness in evaluating the spatial reuse.

The paper also proposed an improved virtual carrier sensing scheme for wireless LAN scenarios. This protocol is specifically designed to enhance the spatial reuse in the overactive RTS/CTS scenario. Through both analytic and simulation results, we show the effectiveness of our scheme in increasing the spatial reuse and also the network throughput.

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