Distance-Aware Virtual Carrier Sensing for Improved Spatial Reuse in Wireless Networks

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***Abstract*— In this paper we address the issue of improving the spatial reuse in virtual carrier sensing (VCS) mechanisms for wireless networks. The paper examines in detail the channel reservation mechanisms of IEEE 802.11 VCS and shows that its spatial reuse is sub-optimal in a number of scenarios. We also show that the area that should be reserved by the VCS depends on the distance between the transmitter and receiver. We then present a novel VCS scheme that optimizes spatial reuse by incorporating this distance information in the decision making process for the channel reservation. Unlike existing proposals for improving spatial reuse, our scheme does not rely on special hardware design such as directional antennas, power adaptable or dual-channel devices etc., and is thus easily implementable. Simulation results quantify and demonstrate the substantial performance improvements obtained by the proposed scheme.**

I. Introduction

One of the most important metrics which characterize the performance of Medium Access Control (MAC) protocols in wireless networks is their *spatial reuse* which determines the number of simultaneous connections allowed in a given region, which in turn strongly affects the throughput and delay characteristics at each node. In this paper, we analyze and show the drawbacks of the virtual carrier sensing mechanism of IEEE 802.11 based networks in terms of their spatial reuse characteristics. The RTS/CTS exchange in 802.11 VCS forces nodes in the entire region where these signals can be overheard to defer access. This paper shows that there are scenarios where the reception of RTS/CTS messages do not necessarily imply interference. IEEE 802.11 VCS fails to identify such cases thereby reducing the spatial reuse and the network's throughput. We then propose a simple and novel VCS technique that outperforms IEEE 802.11 based VCS schemes and achieves the best possible spatial reuse in a wide range of scenarios without the need for specialized hardware and the resulting improvements are verified with simulations.

Existing work on evaluating the performance of wireless networks have primarily focused on the capacity analysis [2]. In [3], [5], spatial reuse characteristics are used to examine the performance of 802.11 protocol under different scenarios. In [4], the 802.11 RTS/CTS handshake is analyzed and it is shown that this mechanism is not always effective. A sophisticated dual-channel power control MAC protocol has been proposed in [6], which focuses on increasing channel efficiency within the collision avoidance framework. Finally, directional antennas have been proposed to improve the spatial reuse of wireless networks [7].

Amongst the various approaches to improve the spatial reuse, directional antennas [7] and power control [6] are the most popular. These solutions, however, incur higher cost on the device (directional antennas, dual channel power controlled cards), and require complicated processing. In this paper, our goal is to develop a simple protocols without these requirements which can still improve the spatial reuse. To achieve this, we first examine the channel reservation mechanisms of IEEE 802.11 VCS. We show that the space reserved by 802.11 for a successful transmission is far from optimal and its effectiveness depends on the distance between the transmitter and receiver. We then present a novel VCS scheme that optimizes spatial reuse by incorporating distance information in the decision making process for the channel reservation. To facilitate the dissemination of distance information, we introduce the three-way handshake and demonstrate its multiple advantages in improving the network performance. Our analysis and experimental results show that the proposed scheme achieves substantial performance improvement in the context of real-world traffic.

The rest of the paper is organized as follows. In Section II we analyze the 802.11 VCS in terms of spatial reuse. A distance-aware carrier sensing scheme is then introduced in Section III, followed by simulation results in Section IV. Section V summarizes our conclusions.

II. Virtual Carrier Sensing and 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. We start from the *two-ray ground reflection model* [1], the basic radio propagation model assumed in this paper. According to this model, the received power at distance d is given by

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

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.

We introduce three ranges that are widely used in this paper, following the definitions in [4].

- **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 no interference from other radios.

- **Interference Range (R_i)**: The range within which stations in receive mode will be interfered with by other transmitters and thus suffer a loss. The value of R_i is the focus of our discussion. As will be shown later, it does not have a fixed value.

To obtain R_i, we introduce the model of *signal to interference ratio* (SIR), directly following the *Physical Model* in Gupta and Kumar's work [2]. Suppose that node B is receiving packets from node A, with the 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 compare the power received at B from A and C, denoted by P_s (signal power) and P_i (interference power), respectively. Neglecting ambient noise, from Eqn. (1), we derive the signal to interference ratio required for successful reception as [4]

$$\text{SIR} = P_s/P_i = (d_i/d_s)^\alpha \geq \text{CPThresh} \tag{2}$$

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

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

We use k_{SIR} to denote the multiplier, which depends on the specific SIR model. With CPThresh set to 10dB, $k_{\text{SIR}} = \sqrt[4]{10} = 1.78$. It is not at all difficult to extend to the *free space model* [1], in which we only need to modify k_{SIR} due to the change of α. We see that there is no explicit relationship between R_i and R_t; R_i is proportional to the one-hop distance d_s.

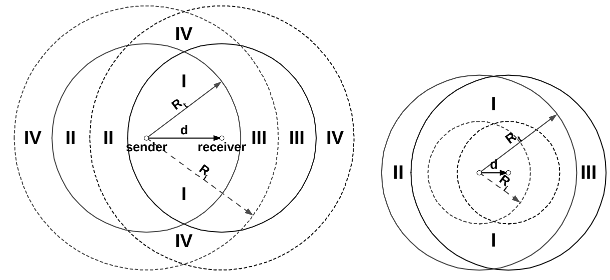
B. Effectiveness of 802.11 Virtual Carrier Sensing

In 802.11, nodes defer any impending transmission by the appropriate intervals whenever an RTS or CTS is overheard. This Virtual Carrier Sensing (VCS) mechanism, together with Physical Carrier Sensing, determines the busy/idle state of the medium. The underlying justification is summarized as in [5]:

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, this is not always true as R_i is not a fixed value. We study three scenarios with respect to $r = d/R_t$, the ratio of the one-hop distance d and R_t.

1) Underactive RTS/CTS Scenario: Fig. 1(a) shows the scenario where R_i (dotted line circle) is larger than R_t (solid line circle). From Eqn. (3) we have $R_i = k_{\text{SIR}} d > R_t$, so d is confined by $R_t/k_{\text{SIR}} < d < R_t$. As shown in Fig. 1(a), 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.



(a) Underactive scenario (b) Overactive scenario

Fig. 1. Spatial reservation scenarios with IEEE 802.11

In this scenario, the sufficient condition is satisfied as any node in Zone I, II or III is able to interfere with the ongoing traffic. However, while any 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. 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*.

2) Overactive RTS/CTS Scenario: In Fig. 1(b), R_i is small enough so that both interference circles are located within Zone I, and we have $d < R_t/(k_{\text{SIR}} + 1)$. We call this the *Overactive RTS/CTS Scenario* since 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.

3) Moderate RTS/CTS Scenario: In this scenario, the range of d is $R_t/(k_{\text{SIR}}+1) < d < R_t/k_{\text{SIR}}$. Hence the nodes in Zone I, II, III have a chance 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. Thus VCS has reasonable performance in the *Moderate RTS/CTS Scenario*.

C. Spatial Reuse Efficiency in 802.11

Since the necessary and sufficient conditions mentioned above are rarely satisfied simultaneously, in general the achieved spatial reuse of 802.11 is far from ideal. Only when $R_i = R_t$ ($d = R_t/k_{\text{SIR}}$) does the spatial reuse achieve its optimal characteristics and 802.11 VCS performs fully effectively. In the overactive case of Fig. 1(b), 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(b), RTS/CTS mechanism underestimates the space required for a successful transmission and thus incurs potential collisions by excessive spatial reuse. These observations motivate the need for a more efficient carrier sensing mechanism for wireless network and we address this issue in the next section.

III. A Distance-Aware Carrier Sensing Scheme

To address the causes which lead to inefficient spatial reuse with 802.11, this section proposes a *Distance-Aware Carrier Sensing* (DACS) scheme which employs distance information to enhance the effectiveness of medium reservation. The basic idea is, by collecting and using the distance information from other nodes, a node can accurately determine whether it can interfere with any ongoing transmission. With this additional information and the resulting accurate picture of the current state of the medium, we now develop a VCS mechanism to perform optimal medium reservation. This scheme intends to only serve as an alternative to 802.11 VCS while adopting other parts in 802.11 like its backoff mechanism. While our DACS scheme identifies the Underactive Scenario in which spatial reuse is excessive, we take no corrective measures in order to keep the protocol simple without compromising its performance. The primary objective of DACS is to optimize the spatial reuse in Moderate and Overactive Scenarios.

A. Obtaining Distance Estimates

Various techniques exist to determine the distance between nodes in wireless systems including the Signal Strength, the Angle of Arrival (AOA), the Time of Arrival (TOA) and Time Difference of Arrival (TDOA) methods [8]. Additionally, techniques to correct for normal sources of errors in such measurements have been proposed in [9], [10]. We use a technique based on the signal strength method where we assume that RTS and CTS packets carry information on the transmitter's power levels. Let the transmission range be denoted by R_t and let P_{RxTh} denote the receiving power threshold, i.e., the minimum power required to successfully retrieve the transmitted signal. Suppose a node receives a signal with power P_r. From Eqn. (1), its distance to the sender, d, satisfies $P_r d^\alpha = P_{\text{RxTh}} R_t^\alpha$ where α is the signal attenuation coefficient. Thus the distance information is calculated using

$$d = R_t \left(P_{\text{RxTh}}/P_r\right)^{\frac{1}{\alpha}} . \quad (4)$$

The above expression can be used for different types of channels by choosing the appropriate value of α, which depends on the basic radio propagation model. We use $\alpha = 4$, as per the two-ray ground reflection model.

B. The Three-way Handshake

DACS uses distance information between the nodes involved in the ongoing transmission and other nodes in their vicinity to determine the spatial region for channel reservation. To achieve this, the RTS/CTS exchange mechanisms needs to be modified and these frames now carry distance information in addition to the timing information.

To disseminate the distance information about a source destination pair to all nodes in their neighborhood, we propose a three-way handshake. Aside from RTS and CTS, DACS uses a third handshake signal, STS, namely, Start-To-Send. The mechanism is illustrated in Fig. 2. The sender initiates the reservation process by transmitting an RTS frame and the receiver uses the received signal strength to calculate its distance from the receiver. This distance information is now added to the CTS frame and transmitted. Thus all nodes in the transmission range of the receiver are now aware of the distance between the communicating nodes. However, nodes which are only in the transmission range of the sender do not have this information. To address this, the sender now transmits the third handshake frame (an STS frame) which contains the distance information obtained from the CTS packet. The data frame is transmitted immediately after the STS frame and the rest of the procedure is exactly the same as IEEE 802.11 VCS. Thus with the aid of CTS and STS frame, the one-hop distance is broadcast within the vicinity of both the sender and the receiver, effectively passing the topology information to the nodes in Zones I, II and III.

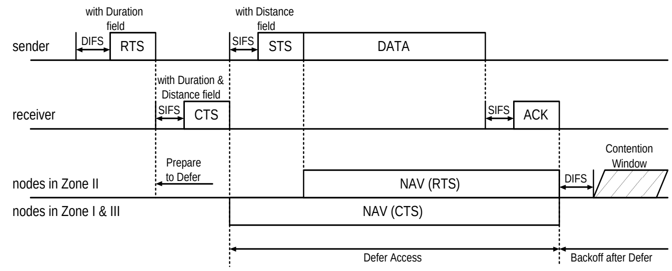


Fig. 2. The three-way handshake in DACS

In the three-way handshake, RTS frames probe for possible medium reservation, rather than directly claiming the future use of the channel as done in 802.11. The confirmation of medium reservation is done through STS frames instead. An advantage of this design is to prevent channel wastage from *unsuccessful* RTS frames, the case in which a node sends out an RTS but fails to receive the responding CTS. In 802.11, it does great harm because all the nodes overhearing the unsuccessful RTS would defer access till end of the duration, despite the fake medium reservation. However, this problem no longer exists in DACS because the nodes overhearing an RTS are required to wait for the STS instead of deferring.

Now we explain how other nodes respond to the three-way handshake. In DACS, a node maintains multiple Network Allocation Vectors (NAVs), one for each ongoing transmission in its vicinity. The content of an NAV is enriched as well and besides the duration information, it also has an identifier and records all the relevant distance information. Specifically, a node in Zone I/III that overhears a CTS would:

1) *Set a new NAV according to the Duration field in CTS frame;*
2) *Store the Distance field of the CTS frame;*
3) *Measure and store its distance to the CTS sender (when in Zone I, also measure and store its distance to the RTS sender);*
4) *Defer access till NAV counts down to zero only if distance criteria (described in the next subsection) are not met.*

Similarly, a node that overhears an RTS but not CTS would:

1) *Set a new NAV according to the Duration field in RTS frame;*
2) *Wait for the corresponding STS;*
3) *If no STS detected, reset NAV and start over; otherwise go to the next step;*
4) *Store the Distance field in the STS frame;*
5) *Measure and store its distance to the STS sender;*
6) *Defer access till NAV counts down to zero only if distance criteria (described in the next subsection) are not met.*

We now describe the conditions under which nodes are allowed to transmit simultaneously with the ongoing transmission and with multiple NAVs, we will see that a node can transmit even if some of its NAVs have not cleared to zero.

C. Optimizing Spatial Reuse by Using Distance Information

To illustrate the operation of DACS, consider a case where node S_1 wants to send a packet to R_1, forming a S_1-R_1 pair as shown in Fig. 3. In their neighborhood there are some other transmissions in progress, whose duration and distance information is maintained at the NAVs of S_1 and R_1. Assume S_2-R_2 is one of these ongoing transmission pairs, with S_2 sending a packet to R_2. Although the other transmissions in the vicinity of S_1-R_1 also influence the working of DACS, for illustrative purposes, it suffices to focus only on S_2-R_2 and it is simple to extend the discussion for multiple transmissions. Note that Fig. 3 shows a specific example in which S_2-R_2 operates in the Moderate RTS/CTS Scenario. Again, the transmission circle is in solid line, and the interference circle in dotted line. S_1, the sender of our interest, is located in Zone I (overhears RTS and CTS from S_2-R_2), while the receiver R_1 is in Zone III (overhears CTS only).

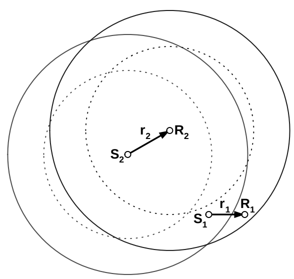


Fig. 3. An Example of Optimal Medium Reservation in DACS

The one-hop distance of S_1-R_1 and S_2-R_2 are r_1 and r_2, respectively. We use $\|\cdot\|$ to denote the Euclidean distance between two nodes. If the distance is greater than R_t, the case in which no distance measure can be conducted, we specify the distance as infinity. Now we formulate our strategy in three steps. In each step, S_1-R_1 performs distance comparison and then decides the action with the handshake signal. The decisions are made upon whether the involved pairs are in Moderate and Overactive Scenarios, and whether the transmissions of S_1-R_1 and S_2-R_2 would interfere with each other.

1) S_1 sends an RTS to R_1: The initial handshake happens if and only if the following requirements are met:

$$\begin{cases} r_2 < R_t/k_{\text{SIR}} & \text{(conditional)} \\ \|S_1S_2\| > k_{\text{SIR}} r_2 \\ \|S_1R_2\| > k_{\text{SIR}} r_2 \end{cases} \quad (5)$$

The first inequality checks whether the S_2-R_2 pair is operating in the Moderate or Overactive Scenario. The failure of this condition implies that the nodes are in the Underactive Scenario and no RTS would be sent. Note that there are certain special situations where this condition does not need to be evaluated at S_1 (hence this is marked "conditional"). The special case happens when S_1, but not R_1, is beyond the Transmission Range of either S_2 or R_2. In this case S_1 has no idea about the transmission of S_2-R_2, and the test of the first inequality is not done at S_1.

The other two inequalities in Eqn. (5) guarantee that the transmission from S_1 would not interfere with S_2 and R_2, respectively. In the example shown in Fig. 3, S_2-R_2 is in the Moderate Scenario, and S_1 lies outside the Interference Range. Therefore all the three inequalities of Eqn. (5) are satisfied and S_1 can safely send an RTS to R_1.

2) R_1 sends a CTS back to S_1: On receiving the RTS, R_1 responds with a CTS if and only if:

$$\begin{cases} r_1 < R_t/k_{\text{SIR}} & \text{(conditional)} \\ \|R_1S_2\| > k_{\text{SIR}} r_1 \\ \|R_1R_2\| > k_{\text{SIR}} r_1 \\ \|R_1S_2\| > k_{\text{SIR}} r_2 \\ \|R_1R_2\| > k_{\text{SIR}} r_2 \end{cases} \quad (6)$$

Again, the first inequality confines S_1-R_1 to the Moderate or Overactive Scenario. Note that it is a conditional test, which needs to be performed only when some ongoing transmission, like S_2-R_2, exists in the vicinity of S_1-R_1. The rest of the tests ensure that there is no interference between R_1 and the S_2-R_2 pair.

In the example shown in Fig. 3, S_1-R_1 is not in the Underactive Scenario. Additionally, R_1 is outside the interference range of S_2-R_2, and vice versa. So it is safe for R_1 to respond with a CTS. Note that in this example, $\|R_1S_2\|$ is set to infinity because R_1 is outside the Transmission Range of S_2, making a distance estimate using the technique of Eqn. (4) impossible. Hence the tests concerning $\|R_1S_2\|$ can be skipped.

3) S_1 sends an STS and Data frame: Once S_1 receives the CTS frame, in order for it to respond with the STS frame, the following conditions need to be satisfied:

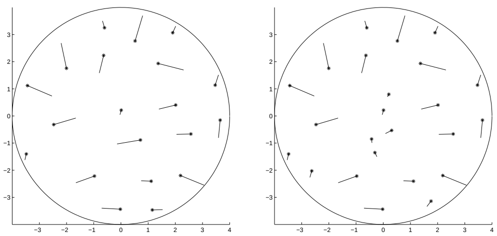
$$\begin{cases} \|S_1S_2\| > k_{\text{SIR}} r_1 \\ \|S_1R_2\| > k_{\text{SIR}} r_1 \end{cases} \quad (7)$$

These tests are performed at S_1 to make sure the transmission of S_2-R_2 would not cause interference at S_1. In the example in Fig. 3, since S_2 and R_2 are outside the interference circle of S_1 (not shown in the figure), S_1 can proceed with the transmission of the STS and Data frames. It is evident that in this example the concurrent transmissions of S_1-R_1 and S_2-R_2 are allowed, which would not be the case with IEEE 802.11 VCS. This illustrates how DACS improves the efficiency of medium reservation using carrier sensing and achieves the optimal spatial reuse in the Moderate and Overactive scenarios.

IV. Simulation Results

In this section, we report on the results of the simulations carried out to further validate the performance of the proposed scheme. In these simulations, sender-receiver pairs were randomly generated in a disk of radius $4R_t$, for various values of λ. The pairs are uniformly distributed, and for each pair the receiver is evenly located in the sender's neighborhood, with one-hop distance less than R_t. For two different selection policies, we then compare the spatial reuse of the VCS schemes by evaluating the maximum number of concurrent transmissions that are allowed by the two VCS schemes.

A. Transmissions with Random Pair Selection



(a) 802.11 VCS (20 pairs) (b) DACS (24 pairs)

Fig. 4. Concurrent transmissions with random selection ($\lambda = 10$)

With random pair selection, from the list of pairs, at each step, a pair is randomly selected and checked to see if its transmission is allowed by the VCS scheme, accounting for the transmissions of the pairs already selected. Fig. 4 shows a snapshot of the pairs selected for a simulation with $\lambda = 10$. For 802.11 VCS and DACS, the maximum number of coexisting pairs are 20 and 24 respectively, concurring with our claim that DACS can support a larger number of simultaneous transmissions by optimizing the spatial reuse.

Fig. 5 shows the maximum concurrent transmissions achieved by the two VCS schemes as a function of λ. We note that the number of coexisting connections increases as λ increases. Also, we note that DACS allows considerably more connections to coexist simultaneously, specially as the traffic load increases. This shows that DACS is considerably more effective in scenarios with high node densities and in realistic traffic scenarios.

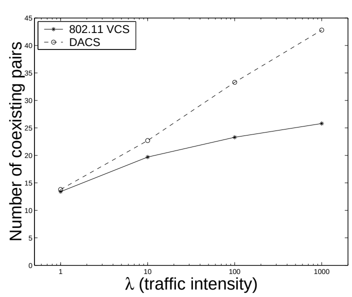
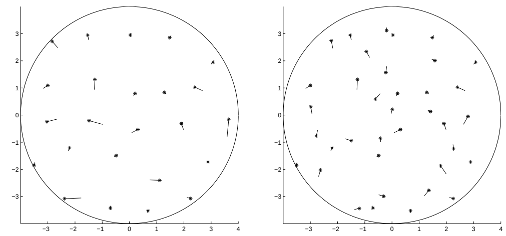


Fig. 5. Comparison of saturation throughput between 802.11 VCS and DACS with random pair selection

B. Transmissions with Greedy Selection

In the greedy pair selection policy, at each step, the node pair with the shortest distance is selected and checked to see if the VCS allows its concurrent scheduling with the existing connections. This obviously increases the likelihood of allowing more concurrent transmissions in a region of a given area. Fig. 6 shows a snapshot of the pairs selected with the greedy algorithm for a simulation with $\lambda = 10$. We note that DACS significantly enhances spatial reuse by accommodating more pairs. Additionally, Table I shows the average number of coexisting pairs with greedy pair selection



(a) 802.11 VCS (24 pairs) (b) DACS (37 pairs)

Fig. 6. Concurrent transmissions with greedy selection ($\lambda = 10$)

for various values of λ. It can be seen that DACS exhibits significant improvements over IEEE 802.11 VCS, with the improvement increasing as the node density increases.

TABLE I
NUMBER OF COEXISTING PAIRS IN GREEDY SELECTION

traffic intensity λ	1	10	100	1000
pairs in 802.11 VCS	14.4	24.4	31.4	34.3
pairs in DACS	15.3	42.0	130.7	414.5

V. CONCLUSIONS

In wireless ad hoc networks, the spatial reuse characteristics of the underlying MAC protocol's virtual carrier sensing scheme plays an important role in determining the effectiveness of medium reservation. In this paper, we investigated and proposed mechanisms to improve the spatial reuse characteristics of VCS schemes. Our study reveals that the space reserved by 802.11 for a successful transmission is far from optimal and its effectiveness depends on the one-hop distances between the sender and receiver. We also proposed a novel VCS scheme that optimizes spatial reuse with the distance information. Experimental results are used to further validate the performance improvements of the proposed scheme.

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