A Distributed Spatial Reuse (DSR) MAC Protocol for IEEE 802.11 Ad-Hoc Wireless LANs*

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Abstract

The paper proposes a distributed spatial reuse (DSR) MAC protocol for IEEE 802.11 ad-hoc wireless LANs (WLANs) to increase bandwidth utilization and reduce power consumption. Through power control, the communications that do not interfere with each other can transmit simultaneously. Therefore, the overall efficiency and effectiveness of IEEE 802.11 ad-hoc WLANs can be enhanced. DSR allows the maximum number of interference-free communication pairs to transmit in parallel without collisions. According to the experiment results, DSR is much better than traditional WLAN protocol, IEEE 802.11 DCF, and the related work. The protocol indeed can effectively enhance the overall WLANs efficiency.

1. Introduction

In ad-hoc networks, stations (STAs) in an IBSS can communicate directly with each other, without through the access point [1]. STAs use CSMA/CA and four-way handshaking (RTS/CTS/DATA/ACK) mechanisms to exchange data. In an IEEE 802.11 ad-hoc WLAN, only one communication pair (CP) is allowed to transmit in wireless medium (WM) at a time. Nevertheless, WM is a shared and very limited resource. Thus, how to effectively use WM is a very important issue for IEEE 802.11 ad-hoc WLANs. This paper pays much attention to increase the spatial reuse and to improve the network productivity for ad-hoc WLANs.

Some researchers adopt the concept of spatial reuse [2, 4, 5, 8, 11] to increase the network productivity. The main idea behind these is to let the CPs that do not interfere with each other transmit in parallel. However, in IEEE 802.11 ad-hoc WLANs, only one CP is allowed at one time. Thus, if we can design a kind of mechanism to ensure that communications not interfering with each other can be done simultaneously, the network overall effectiveness and efficiency can be enhanced accordingly.

The paper focuses on how to make use of WM resource to perform spatial reuse under the IEEE 802.11 ad-hoc WLANs. Based on the same idea that CPs not interfering with each other transmit in parallel, the paper proposes a distributed spatial reuse (DSR) MAC protocol for IEEE 802.11 ad-hoc WLANs to maximize the pairs of communications that can be done simultaneously and further increase the network effectiveness and efficiency. Through power control, STAs use the exact power to transmit. To do so can not only reduce the interference to other STAs caused by this transmission, but also increase the possibility of parallel transmissions. In addition, a greedy maximum independent set (MIS) algorithm is designed to maximize the number of CPs that do not interfere with each other. Lots of experiments are made to examine the proposed protocol. Experimental results verify that DSR is indeed beneficial to IEEE 802.11 ad-hoc WLANs in increasing spatial reuse.

The rest of the paper is organized as follows. Section 2 introduces background and related work. Section 3 describes the proposed DSR mechanism. Section 4 presents the experimental results. Section 5 concludes the paper.

2. Related Work

Distributed Coordination Function (DCF) is the ad-hoc WLANs channel access scheme specified in IEEE 802.11 Spec. [1]. Based on DCF, many researchers proposed the spatial reuse concept to relieve the constraint of one transmission at a time to enhance the network productivity. Basically, there are three ways to enhance spatial reuse: 1) through solving the exposed-terminal problem [2, 3, 10]. However, they are only suitable for multi-hop networks and

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cannot be adopted in the single-hop networks. 2) by using direction antenna [4, 11]. However, the hardware cost for using directional antennas to achieve spatial reuse is too high. and 3) via adopting power control to enhance spatial reuse. We will explain power control mechanism as follows.

Spatial reuse can also be achieved via power control to reduce the influence range such that the probability of parallel transmissions can be increased [8, 12]. In [8], the authors proposed a Distributed Cycle Stealing (DCS) mechanism to make use of power control to enhance spatial reuse in single-hop wireless networks. However, DCS mechanism has some drawbacks. The performance of DCS depends on the duration of the standard transmission and the distance between the sender and the receiver. If the duration of the standard transmission is too small or the distance between the sender and the receiver is too far, it is very possible that no spatial reuse can be made. Besides, DCS cannot completely avoid collisions between the transmissions of CPs.

Based on the similar idea of DCS, DSR proposed in the paper also uses power control to enable multiple pairs of communications to transmit simultaneously in an IEEE 802.11 ad-hoc WLAN. The major difference between DSR and DCS is that, instead of taking the first CP as the standard transmission, DSR takes the durations of the transmissions, the distances among STAs, and the interference relations among all communications into consideration. DSR chooses the maximum number of transmission pairs not to interfere with each other to transmit in parallel. As a result, DSR can achieve a better spatial reuse than DCS and prevent from the collision problem in DCS mechanism.

3. The DSR MAC Protocol

DSR (Distributed Spatial Reuse) mechanism is a MAC protocol for IEEE 802.11 ad-hoc WLANs to increase the spatial reuse. Power control is adopted in DSR mechanism to enhance the spatial reuse such that multiple CPs can transmit simultaneously. The paper reasonably assumed that a STA has the capability of inferring the distance from the sender according to the received signal strength. Readers can refer to [8, 7, 9] for further information.

3.1. Channel Access Mechanism and Operation Strategies

DSR channel access mechanism is different from that of DCF and DCS, which is illustrated in Figure 1. A *control window* is introduced in DSR. All STAs intending to send out packets adopt CSMA/CA mechanism to compete the channel access right. At the very beginning, the first STA successfully contending the channel access right transmits the RTS packet and announces the start of a control window and its duration. The destined STA then replies with

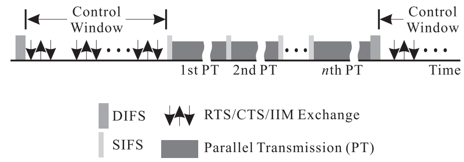

Figure 1. DSR channel model.

the CTS packet, if could. The remaining time of the control window is enclosed in the CTS packet and all the following packets transmitted in the control window. In addition, the difference of DSR from DCF and DCS is that the sender has to send out another packet named IIM (Interference Indication Message) after it received the CTS packet. The details of the IIM packet will be described in Section 3.2.

Only RTS/CTS/IIM packets are allowed to transmit in the control window. All data packets are scheduled to send out and should be waited until the end of the control window. The scheduling policy will be described in detail in Section 3.3. Thereafter, the STAs intending to send out packets also have to contend the channel access right within the control window. However, before STAs send out the RTS packets, they have to make sure whether there is enough time left in the control window to finish the RTS/CTS/IIM exchanges. As mentioned above, the remaining time of the control window will be enclosed in all the packets transmitted in the control window[1]. During control window, all STAs should monitor every RTS/CTS/IIM packets and calculate the distance from the sending STA based on signal attenuation. The distance information will be used as the decision of interference relation and the power level to transmit DATA/ACK packets later.

RTS/CTS/IIM packets use the maximum power level to transmit. It is because some important information, such as the remaining time of the control window and the interference relations with previous CPs, has to be known by all the other STAs in the ad-hoc WLAN. DATA/ACK packets use the exact power to transmit to reduce the interference and increase the spatial reuse. Since the data packet is not sent immediately followed the IIM packet, the durations in RTS/CTS/IIM packets are different from those in the IEEE 802.11. The durations in RTS/CTS/IIM packets are modified to the time to transmit the DATA, ACK packets and a short inter-frame spacing, aSIFSTime.

After control window ends and waits for an SIFS time, the parallel transmission period starts. CPs successfully exchanging RTS/CTS/IIM packets during the control window

[1]The length of a control window could be varied to meet the different service requests. If a STA needs to transmit a delay-constrained packet, it can set the remaining time of the control window to be an appropriate time period or even to be 0. If a STA sets the remaining time to 0, after its RTS/CTS/IIM packets are successfully exchanged and an SIFS time, the parallel transmission period starts.

have to perform a parallel transmission scheduling to schedule when to transmit their DATA/ACK packets. Since the scheduling algorithm designed in the paper guarantees that the resulting schedule calculated by every STA is the same, so no collision will occur. Firstly, the parallel transmission scheduling selects the maximum number of CPs not interfering with each other as the first parallel transmission set (PTSet) from all CPs that had sent out RTS/CTS/IIM successfully during the control window. Excluding the CPs in the first PTSet, the parallel transmission scheduling then selects from the remaining CPs the maximum number of CPs that can transmit simultaneously without collision as the second PTSet. Likewise, until all CPs are classified, the algorithm stops.

When the control window ends and an SIFS time is past, the parallel transmission period begins. All the CPs scheduled in the first PTSet starts to transmit. When the first parallel transmission (PT) finished and an SIFS ended, the CPs in the second PTSet starts the second PT. Similarly, until all PTSets finished the transmission, the parallel transmission period ends. As for the duration of each PT, it is set as the duration of the CP with the longest duration in the PTSet.

STAs intending to deliver data have to exchange RTS/CTS/ IIM first either within the control window or to create a new control window. A newly joined STA intending to send out packets should wait for a period of time.

3.2. Distance-Based Interference Inference and IIM

The interference relations among CPs are based on the distances from the other CPs. Suppose that S and D are the first CP, S' and D' the second CP, and S'' and D'' the third CP. S and D use the maximum power level to exchange RTS/CTS/IIM packets. Note that it is required that the receiver measures the distance from the source and includes this distance information into the CTS packet. That is, the distance between S and D is enclosed in the CTS packet which D is going to transmit to S. Therefore, not only can all the other STAs measure the distances from S and D according to the received signal strength, but obtain the distance between S and D from the CTS packet as well.

After the first CP finished the exchange of RTS/CTS/IIM, S' has the information of $\overline{S'S}$, $\overline{S'D}$, and $\overline{SD}$, where the distance between S and D is denoted as $\overline{SD}$. However, since S' has no idea about the distance from the receiver D', S' can not decide whether its transmission after power control will interfere with the transmission of S and D. Hence, the RTS packet sending from S' is just to inform D' the following DATA packet. On the contrary, D' can measure the distance from S' according to the signal strength of the received RTS packet. Accompanied with the information of $\overline{D'S}$, $\overline{D'D}$, and $\overline{SD}$, D' can infer

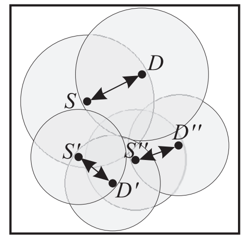

Figure 2. The distance-based interference inference mechanism.

whether the transmission with S' after power control will interfere with the transmission of S and D. This important information is recorded in a vector termed *interference vector* (IV), which is enclosed in the CTS packet.

IV is a bit-mapped vector in which the interference relation of the current STA with all previous CPs which have successfully exchanged RTS/CTS/IIM packets within the same control window is indicated. The formal definition of IV is as follow.

Definition 1 *For the STA of the p-th CP, $p > 1$, the IV of this STA is a $(p-1)$-tuple 0/1 vector, denoted as IV_p, in which the i-th entry indicates the interference relation with the i-th CP, where 0 means the STA and the i-th CP will not interfere with each other if they transmit simultaneously and 1 means otherwise, $0 < i < p$. IV_0 is a null vector.* □

In the example shown in Figure 2, the first CP will interfere with the second CP after power control. Thus, $IV_2 = (1)$. It means that the two CPs can not transmit in parallel. On the other hand, the third CP does not interfere with the first CP, but interferes with the second CP. As a result, $IV_3 = (0, 1)$.

Actually IV will be varied subject to different locations of the STAs of a CP. That is, for the two STAs of a CP, their IV may be different. For the example shown in Figure 2, for the second CP (S' and D'), the IVs of S' and D' are different. As explained above, from the viewpoint of D', no interference would be incurred. Therefore, $IV_2 = (0)$. However, from the viewpoint of S', after received the CTS packet from D', it obtains the distance information of $\overline{S'D'}$. Accompanied with the the information of $\overline{S'S}$, $\overline{S'D}$, and $\overline{SD}$, S' can infer that its transmission after power control will interfere with the first CP. Hence, the $IV_2 = (1)$, from the viewpoint of S'. As a result, although IV has been enclosed in CTS packet, IV from the sender's viewpoint is also necessary. Therefore, IV should be enclosed both in CTS and IIM packets. That is the reason why IIM packet is necessary. After control window ends, all STAs can obtain the relative positions from the IIM packets and begin the process of parallel transmission scheduling.

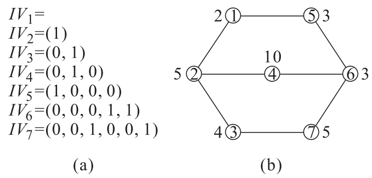

Figure 3. Interference Graph $IG(V, E)$ of 7 CPs. (a) The 7 IVs indicated from the 7 CPs' IIM packets. (b) The corresponding IG.

3.3. Parallel Transmissions Scheduling

With the information of interference relations among all CPs, the problem of finding the maximum CPs which can transmit simultaneously without interference is similar to the maximum independent set (MIS) or colorings of graph problems [6]. However, it is well-known that MIS problem is an NP-complete problem. Therefore, a greedy but polynomial-time algorithm is designed in the paper. All CPs are required to conduct the maximum independent set algorithm to find out when to transmit DATA/ACK packets. After parallel transmission is scheduled, all CPs transmit DATA/ACK according to their arranged sequence and time. After all data transmission is completed, next control window will begin when next RTS packet is sent out.

To enhance the spatial reuse of IEEE 802.11 ad-hoc WLANs, the best way is to maximize the number of parallel communications that can transmit simultaneously without interfering with each other. So it is required that the interference relations among all CPs should be known in advance before the parallel transmission schedules. The information can be acquired from IVs of IIM packets. A undirected graph, termed *interference graph*, $IG(V, E)$ is used to denote the interference relations among all CPs revealed in IVs, where V is the set of CPs successfully exchanged RTS/CTS/IIM packets in a control window and E is the set of edges indicating the interferences among the CPs.

Take Figure 3 as an example. Suppose there are 7 CPs successfully exchanged RTS/CTS/IIM packets in the control window. The IVs indicated from the 7 CPs' IIM packets are shown in Figure 3(a) and the corresponding IG is illustrated in Figure 3(b). The number in the circle indicates the CP number. The number besides the circle means the duration of DATA/ACK transmissions of that CP. As a result, $V = \{\mathrm{CP}_i, i = 1, 2, \cdots, 7\}$. Since $IV_2 = (1)$, there is one edge connecting CP1 and CP2 to indicate the two CPs can not transmit simultaneously. $IV_3 = (0, 1)$ means that there is no edge between CP3 and CP1 and there is one edge between CP3 and CP2, likewise. What's worth-noticing is that the length of an edge does not stand for the actual distance of the connected CPs. The related position of CPs do not represents the actual related position of the CPs.

The paper proposes a greedy but polynomial-time algorithm to find MIS. Figure 4 illustrates the greedy parallel transmission scheduling algorithm. The illustrations of the parallel transmission scheduling algorithm on the interference graph shown in Figure 3 are shown in Figure 5. Due to the space limitation, the detailed description is omitted.

After the end of the control window and an SIFS, the CPs in the first PTSet start to transmit. Until the duration of this PT expires and another SIFS time, the second PTSet starts, and so on. Formally, suppose there are n parallel transmission sets after parallel transmission scheduling is applied. The CPs in the PTSet(i) have to wait until the $(i-1)$-th PT expires and another SIFS time, then to transmit, as shown in Figure 1. The duration of the i-th PT is set as the CP with the longest duration in the i-th PTSet. For the previous example, there are three parallel transmission sets. The durations of the 1st , 2nd, and 3rd PTSets are 10, 4, 5, respectively. Upon the finish of the n PTs, following DCF mechanism, the first STA successfully contending the channel access right to send out the RTS packet begins a new control window.

4. Performance Evaluations

This section presents the simulation results in comparison with DCF and DCS. To adequately measure the effectiveness of DSR, a 4×4 mesh network is used as the network topology. The channel capacity is 2 Mbps. The traffic model adopts the Poisson arrival process. The packet size are randomly generated and is from 100 bytes to 2312 bytes. The transmission is confined to 1-grid, 2-grid, 3-grid, and 4-grid, where 1-grid means that the receiver is one grid away from the sender, and so on. The meaning behind the 1-grid communication is the high possibility of spatial reuse. The control window size of DSR varies from 1000 μs to 3000 μs. The contention window size of DSR is ranged from 7 to 63. Note that the contention window size of DSR is smaller than that of DCF and DCS (ranged from 31 to 1023). This is because that it is no need to wait for such a long time since the maximum control window size is 3000 μs, which is only 150 slots, supposed a slot is 20 μs [1]. Another reason is due to the low contention possibility, the benefit of the spatial reuse caused by the DSR mechanism. The total simulation time is 10 seconds. The experiment compares DSR with DCF [1] and DCS [8]. The network throughput, and mean delay time versus different traffic loads are evaluated. Among them, DSR-1000, DSR-2000, and DSR-3000 represent that the control window sizes of the DSR mechanism are 1000 μs, 2000 μs, and 3000 μs, respectively. Due to the space limitation, only the results for 1-grid and 4-grid are illustrated.

Figure 6 shows the network throughput for 1-grid and 4-

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Algorithm: Parallel Transmission Scheduling
Input: $IG(V, E)$, the *Interference Graph*, where
V, the set of CPs successfully exchanged RTS/CTS/IIM packets in a control window
E, the set of edges indicating the interferences among the CPs
Output: PTSet(), *Parallel Transmission Set*
Assumption: $deg(v)$ is the *degree* of vertex v
$dur(v)$ is the *duration* of vertex v
$ID(v)$ is the *ID* of vertex v
$|V|$ is the cardinality of the set V
Program:
PT_Scheduling($IG(V, E)$**)**
begin
$i = 0$
while $V \neq \emptyset$ **do**
$i = i + 1$
PTSet(i) = Maximum_Independent_Set($IG(V, E)$)
$V = V -$ PTSet(i)
$E = E - \{\overline{uv} \mid v \in$ PTSet$(i), u \in V, \overline{uv} \in E\}$
end while
return PTSet()
end

Maximum_Independent_Set($IG(V, E)$**)**
begin
while $E \neq \emptyset$ **do**
$V' = \{v \mid \max_{v \in V} deg(v)\}$
if $|V'| > 1$ **then**
$V' = \{v \mid \min_{v \in V'} dur(v)\}$
if $|V'| > 1$ **then**
$V' = \{v \mid \min_{v \in V'} ID(v)\}$
end if
end if
$E' = \{\overline{uv} \mid v \in V', u \in V, \overline{uv} \in E\}$
$V = V - V'$
$E = E - E'$
end while
return V
end

Figure 4. The parallel transmission scheduling algorithm.

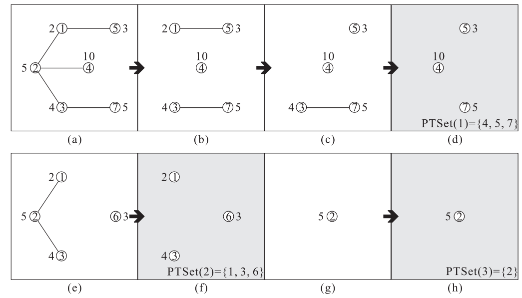


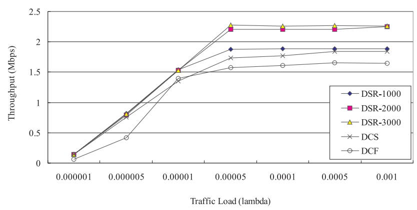
Figure 5. The illustrations of the parallel transmission scheduling algorithm from (a) to (h) to find the PTSets.

grid communications versus various traffic load. DSR outperforms over DCS and DCF in network throughput, especially in case of 1-grid due to the high potentiality of spatial reuse. Obviously, DCF performs the worst. It is because no spatial reuse is explored in DCF. In the case of 4-grid, the performance of DCS is close to that of DSR since the possibility of spatial reuse is very low. On the contrary, in the 1-grid case, in addition to the high possibility of spatial reuse, since DSR maximizes the number of parallel CPs without collisions, therefore, the performance of DSR is better than that of DCS in all cases of DSR-1000, DSR-2000, and DSR-3000. On the other hand, regarding the control window size, general speaking, the longer the length of the control window is, the more the number of CPs can transmit simultaneously. It is true in most cases. However, it is interesting that, in the 4-grid case, DSR-2000 is a slight better than DSR-3000. This is because the longer the control window, the more the overhead in throughput, when the possibility of spatial reuse is low.

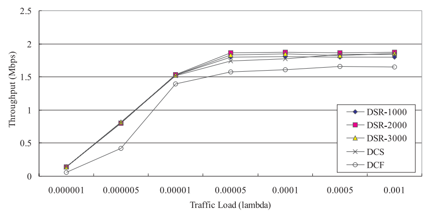
The average time needed from sending out RTS packet to receiving the ACK packet successfully is the mean delay time. Figure 7 shows the mean delay time for 1-grid and 4-grid communications versus various traffic load. In DSR, data transmissions are done after control window ends. As a result, the mean delay time is longer than that of DCF and DCS. The longer control window is, the longer the mean delay time is. The difference between the 1-grid and 4-grid cases is that the spatial reuse is least happen in the 4-grid case. Although DSR might have selected multiple parallel communication pairs, simultaneous transmission cannot be done. This will lead to an increase of mean delay time.

5. Conclusions

The paper proposed a Distributed Spatial Reuse (DSR) MAC Protocol for IEEE 802.11 ad-hoc WLANs to improve bandwidth utilization and increase network lifetime.

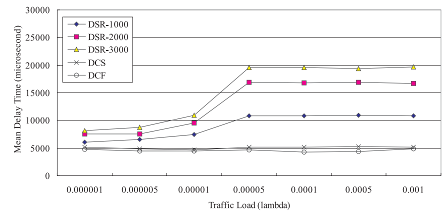


(a) 1-grid.

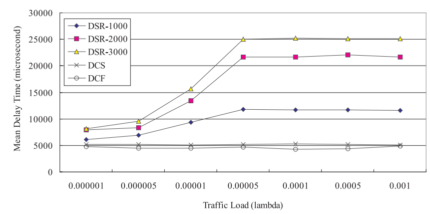


(b) 4-grid.

Figure 6. Network throughput. (a) 1-grid. (b) 4-grid.



(a) 1-grid.



(b) 4-grid.

Figure 7. Mean delay time. (a) 1-grid. (b) 4-grid.

Through power control, the communication pair uses exact power to transmit to each other. To do so not only can reduce the interference range, increase the spatial reuse, and further increase the network throughput, but also can reduce the power consumption of stations and increase the network lifetime. DSR allows the maximum number of communication pairs not interfering with each other to transmit simultaneously. A greedy but polynomial-time MIS algorithm is devised in the paper. DSR also preserves the fairness among stations due to the DCF characteristic. The experiment results show that the throughput of DSR is better than those of DCF and DCS mechanisms. DSR can indeed enhance the network throughput of IEEE 802.11 ad-hoc WLANs.

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