Admission Control for Wireless LANs with Multi-Packet Reception Capability

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Abstract

In a multi-packet reception (MPR) system, a wireless node can successfully receive multiple packets from simultaneous transmitters. The increase in the number of simultaneous transmissions leads to higher throughput as long as the transmissions can be successfully decoded by the receiver. The maximum number of simultaneous transmissions that the receiver can successfully decode should be determined and used as the criterion of admission control in order to maximize the MPR system performance. In this paper, we propose an admission control scheme that derives the maximum number of simultaneous transmissions and regulates the number of simultaneous transmissions on the basis the derived number. To evaluate the performance of our proposed scheme, we carry out extensive simulations and show that our proposed scheme significantly improves the network throughput.

I. Introduction

In traditional wireless local area networks (WLANs), an access point (AP) can only receive one packet at a time. If more than one transmission is performed, packet collision occurs. With the increase in the technological level of signal processing and multiuser detection (MUD), multiple packets can be received simultaneously at MUD receivers equipped with multiple antennas. The maximum number of simultaneous packet transmissions that can be successfully decoded is defined as the multi-packet reception (MPR) capability. This MPR capability can enhance the throughput performance as compared with traditional wireless networks with single-packet reception (SPR) capability [1], [2].

However, existing medium access control (MAC) schemes such as IEEE 802.11 DCF have been designed without any consideration of the MPR capability and are difficult to apply effectively in MPR-capable systems. Recently, several MAC schemes for MPR systems [3]–[5] have been proposed. Most of them have been devised with the assumption that the MPR capability is determined as a fixed value in advance. However, this assumption is not true for real operational wireless systems owing to the mobility of nodes and the wireless channel characteristics. In order to fully take advantage of the MPR capability, it is essential to appropriately estimate the value of the MPR capability based on the MPR channel state information.

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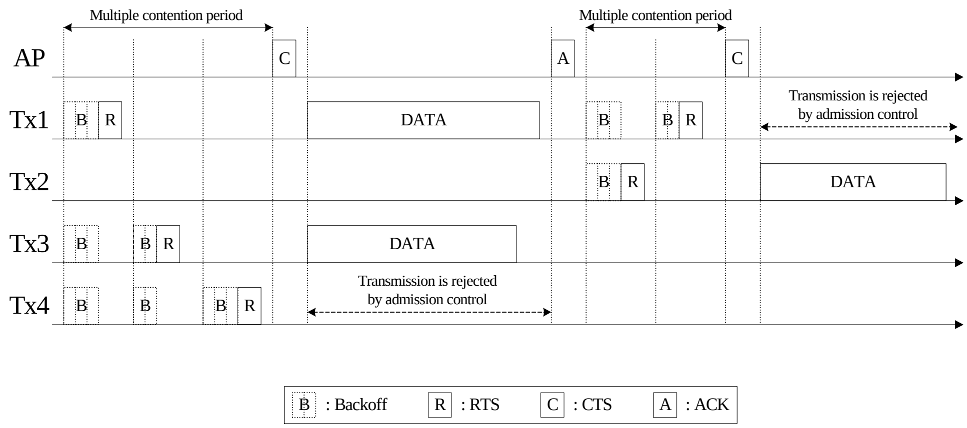

Fig. 1. Operation of a multiple-contention random-access scheme for an MPR system.

We consider a multiple-contention random-access scheme for a wireless MPR system, as shown in Figure 1. The basic access method is carrier sensing multiple access with collision avoidance (CSMA/CA), similar to IEEE 802.11 DCF. A node that intends to transmit senses the channel and defers its transmission while the channel is sensed as busy. When the channel becomes idle, a node with the smallest back-off number transmits a request-to-send (RTS) packet to the AP. In contrast to IEEE 802.11 DCF, the AP does not respond to the first RTS packet. Instead, it defers to send a clear-to-send (CTS) packet until more RTS packets from other nodes are received in order to provide the other nodes with multiple contention opportunities. Note that if too many RTS packets are simultaneously transmitted, the AP may not be able to decode the RTS packets. In such case, the corrupt RTS packets are simply discarded, and the nodes continue to contend for transmission opportunities. At a certain instant in time, the AP stops receiving RTS packets for data transmission and broadcasts a CTS packet that consists of multiple fields that indicate which transmitters are allowed to transmit a packet and how long the longest transmission will last. Then, the winning nodes begin simultaneous data transmissions, whereas all other nodes wait until the end of the ongoing transmissions.

In Figure 1, the AP received three and two RTS packets in the first and second contention periods, respectively. During the contention periods, the AP can possibly obtain the received power of the transmitters and is aware of the channel state information using the received power levels. After all the simultaneous data transmissions are completed, the AP transmits an acknowledgement (ACK) packet, which has multiple fields for notifying the successful reception, to transmitters.

In this case, an important problem is how many RTS packets the AP needs to wait for before it starts its transmissions; however, this problem has not been substantially studied in the literature. If the number of simultaneous transmissions is small, the MPR channel is under-utilized. In contrast, if a large number of simultaneous transmissions are performed, the AP fails to decode the signals of the simultaneous transmissions. Because the maximum number of simultaneous transmissions depends on the received powers that fluctuate according to the frequently changing channel state, it cannot be assumed to be a fixed value. Note that most MAC schemes for the MPR system have made the assumption that the value for the MPR capability is somehow given in advance. Therefore, we require the appropriate number of simultaneous transmissions depending on the channel state each time the transmissions are performed.

In this letter, we propose an admission control scheme for improving the network throughput in an MPR system. After receiving transmission requests during multiple contention periods, our proposed scheme finds the maximum number of simultaneous transmissions depending on the MPR channel condition and regulates the number of simultaneous transmissions.

II. Related Work

Several MAC protocols for MPR systems have been proposed in [3]–[5]. In [3], Zheng *et al.* proposed an RTS/CTS exchange-based MAC protocol for supporting the MPR capability. They assumed that it was possible for the AP to successfully decode M packets by means of an orthogonal-training-sequence-based MUD technique when the AP had M antennas. The nodes randomly transmit RTS packets to the AP. If the number of simultaneously received RTS packets is less than or equal to the MPR capability, the AP can successfully receive the RTS packets and broadcast a CTS packet. Then, the nodes that sent the RTS packet simultaneously start to transmit. In [3], they attempted to maximize the throughput performance by adjusting the transmission probability of RTS packet without direct admission control. Because it is very difficult in practice to achieve M-MPR capability despite the MUD technique, the MPR capability needs to be dynamically estimated rather than assumed to be a constant value M.

Zhao *et al.* [4] proposed a centralized approach for coordinating multiple packet transmissions. A central controller has multiple queues for maintaining the transmission requests for transmitters. The controller computes an optimal set of transmitters that can maximally utilize the MPR capability by avoiding unnecessary empty slots for light traffic and excessive collisions for heavy traffic. The channel model in [4] is a simple slotted random access channel, where the success probability of simultaneous transmissions only depends on the number of transmitted packets for a given value of MPR capability. Our work considers an SINR-based capture model that is more realistic when the characteristics of wireless channel dynamically change.

In [5], Chen *et al.* proposed a multi-reservation multiple access (MRMA) scheme for wireless multimedia networks with MPR capability. A central controller of MRMA coordinates the channel access of contending nodes by a reservation scheme for guaranteeing the quality of service (QoS) of real-time traffic. For non-real-time best-effort services, each node adopts a simple p-persistent random access scheme. In [5], the MPR capability was represented in a matrix form, and they showed how to obtain the MPR matrix for a code division multiple access (CDMA) network system. To the contrary, we do not estimate the MPR matrix. Instead, when the AP receives the transmission requests from the nodes, it decides whether or not the acceptance of each request achieves higher utilization of MPR channel depending on the received signal strengths of the received RTS packets.

III. Proposed Admission Control Scheme

A. SINR-based Capture Model

We consider an uplink synchronous single-cell system that consists of an AP with MPR capability and transmitters. The MPR capability of the AP is represented by the SINR-based capture model [6], [7], which decides whether the transmitted signal is successfully received or collided depending on the received signal strength. The power of the received signal from the i-th node is given by $Pr_i = R^2 K \cdot r_i^{-\beta} Pt_i$, where R is a Rayleigh-distributed random variable for fading, $K \cdot r_i^{-\beta}$ is the attenuation at some distance having the power loss exponent β, and Pt_i is the transmit power of the i-th node. In the SINR-based capture model, the signal received from the i-th node is successfully captured if

$$SINR_i = \frac{Pr_i}{\sum_{j=1, j \neq i}^{M} Pr_j + N} \geq \gamma, \tag{1}$$

where M is the number of transmitting nodes, N is the background noise power, and γ is the capture threshold. The capture threshold is determined by the physical system characteristics and has a range of $1 < \gamma < 10$ for general SPR narrow-band systems, whereas a wide-band MPR system such as UWB and CDMA has a range of $\gamma < 1$. The maximum number of packet transmissions that can be successfully decoded is defined as the MPR capability and has a value of $\lceil 1/\gamma \rceil$ or $1 + \lfloor 1/\gamma \rfloor$ [6], [7].

B. Admission Control

From the SINR capture model in (1), the received power for successfully decoding the signal of the i-th transmitter can be rewritten as follows:

$$Pr_i \geq \gamma\Big(\sum_{j=1, j \neq i}^{M} Pr_j + N\Big). \tag{2}$$

This inequality denotes the minimum level of the received power for each successful reception. Using this inequality, we can find the maximum number of simultaneous transmissions.

Theorem 1. *All transmitters are successfully decoded if the received power of the node with the weakest received power satisfies the following inequality:*

$$Pr_M \geq \frac{N\gamma}{1 - (M-1)\gamma}, \tag{3}$$

where M is the index for the node with the weakest received power.

Proof. By adding all the inequalities for $i = 1, \cdots, M$ in (2), we obtain

$$\sum_{i=1}^{M} Pr_i \geq \gamma \Big\{ (M-1) \cdot \sum_{i=1}^{M} Pr_i + MN \Big\},$$

and then

$$\sum_{i=1}^{M} Pr_i \geq \frac{MN\gamma}{1 - (M-1)\gamma}. \tag{4}$$

Suppose the received powers of the transmitting nodes are sorted in the descending order (i.e., $Pr_1 \geq Pr_2 \geq \cdots \geq Pr_M$). For $i = M$ in (2), the inequality for the received power is written as

$$\frac{Pr_M}{\gamma} - N \geq Pr_1 + Pr_2 + \cdots + Pr_{M-1}. \tag{5}$$

From (4) and (5), we have

$$Pr_M(1 + \frac{1}{\gamma}) - N \geq \frac{MN\gamma}{1-(M-1)\gamma}.$$

As a result, the minimum level of received power for the transmitter with the weakest received power is given by

$$Pr_M \geq \frac{N\gamma}{1-(M-1)\gamma}. \tag{6}$$

□

On the basis of Theorem 1, we can obtain the maximum number of simultaneous transmissions for a given wireless channel. Whenever the AP receives a transmission request at each contention round, it decides whether or not it should wait for another transmission request by computing the maximum number of simultaneous transmissions (M_{max}).

Algorithm 1 Finding M_{max}

procedure FindMaximumM(Pr, M, N, γ)
    $M_{max} \leftarrow 0$
    for $i = 1$ to M **do**
        if $Pr_i \geq \frac{N\gamma}{1-(M-1)\gamma}$ **then**
            $M_{max} \leftarrow i$
        else
            $break$
        end if
    end for
    return M_{max}
end procedure

Algorithm 1 shows the pseudo-code for computing M_{max} in detail. In Algorithm 1, M_{max} is obtained by checking if the condition in (3) is satisfied for the received power of each RTS packet. If the obtained M_{max} is greater than the previous value of M_{max}, the AP waits for another RTS packet. Otherwise, the AP terminates the contention periods and transmits a CTS packet that includes the list of the allowed transmitters. With this procedure, the AP can make a decision on whether it waits for another RTS packet or sends CTS packet to finish multiple contention rounds. Then, the transmitters that are permitted to transmit by the broadcast CTS packet simultaneously begin their data transmission.

Table I shows M_{max} obtained by Algorithm 1 when γ is 0.05, 0.1, and 0.2 in a wireless network in which the transmitters are uniformly distributed in a disk region. The number of transmitting nodes M varies from 3 to 20.

TABLE I

THE MAXIMUM M (M_{max})

γ	Number of transmitting nodes (M)																	
	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
0.05	3	4	5	6	7	7	8	9	10	10	11	12	12	13	13	14	14	15
0.1	2	3	4	4	5	5	6	6	-	-	-	-	-	-	-	-	-	-
0.2	2	2	3	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-

When M is small, M and M_{max} are almost the same because the interference between the transmitting nodes is not very severe. As M increases, all transmissions are not accepted, and M_{max} becomes less than M because a higher throughput can be achieved by rejecting some transmission requests. For example, when γ is 0.05 and M is 20, only 15 transmitters among the 20 transmitting nodes are allowed to transmit their data simultaneously. In addition, M_{max} also depends on γ. As γ increases, fewer transmissions can be accepted in (1). As shown in Table I, M_{max} decreases as γ increases for a specific value of M. For example, M_{max} for M = 5 values are 5, 4, and 3 when γ is 0.05, 0.1, and 0.2, respectively.

These results indicate that the number of transmitters that are not allowed by our proposed scheme increases as M and γ increase. That is, our proposed scheme can efficiently control the amount of interference between the transmitting nodes by rejecting the transmission requests. As a result, we expect our proposed scheme to achieve improved performance in MPR-capable WLANs.

C. Throughput Analysis

We derive the saturation throughput performance of our proposed scheme. Suppose that all the nodes have backlogged packets to transmit and perform a back-off mechanism such as IEEE 802.11 DCF during the multiple contention rounds.

Let P_m denote the reception probability that the number of nodes that transmit the transmission request is m in a given slot time. According to Algorithm 1, all the transmitted packets can be successfully received if the received power of the node with the lowest received power among the nodes satisfies (3). Therefore,

$$P_m = P\left\{\min_{1\leq i\leq m} Pr_i \geq \frac{N\gamma}{1-(m-1)\gamma}\right\}. \tag{7}$$

In this analysis, the received power is given by $Pr_i = R^2K \cdot r_i^{-\beta}Pt_i$, where r_i is a random variable, and the other parameters are assumed to be constant for simplicity. Assuming that all the nodes are uniformly distributed, (7) can be represented as follows:

$$P_m = P\left\{\max_{1\leq i\leq m} r_i \leq \left(\frac{1-(m-1)\gamma}{N\gamma} \cdot R^2K \cdot Pt\right)^{\frac{1}{\beta}}\right\}. \tag{8}$$

TABLE II

SYSTEM PARAMETERS FOR THROUGHPUT ANALYSIS

System Parameters	
RTS	160 bits
CTS	112 bits
Header	272 bits
Packet length	8000 bits
ACK	112 bits
SIFS	10 μs
DIFS	28 μs
Transmit power	0 dBm
Basic rate	6 Mb/s
Data rate	54 Mb/s

Let $P_{L,k}$ be the probability that the length of multiple rounds is k. Using (8), $P_{L,k}$ is given by

$$\begin{cases} P_{L,0} &= (1-P_1)^M, \\ P_{L,k} &= (P_k)^{k-1} \cdot (1-P_k) \quad \text{for } k = 1, \cdots, M, \\ P_{L,M'} &= (P_M)^M, \end{cases} \tag{9}$$

where $P_{L,0}$ is the probability that none of the nodes can transmit, $P_{L,k}$ is the probability that $(k-1)$ nodes can transmit after k rounds and thereby the number of multiple rounds is k, and $P_{L,M'}$ is the probability that all the nodes up to MPR capability can transmit.

We define throughput S_M as the ratio of the amount of successfully transmitted payload bits and the slot time spent for transmitting the payload when the MPR capability is M. First, we consider the required slot time in each case. If the length of multiple rounds is zero, it takes an empty slot time σ. If the length is k, the required slot time T_k is given by

$$\begin{aligned} T_1 &= T_{RTS} + T_{DIFS} \\ T_2 &= T_{RTS} + T_{SIFS} + T_{RTS} + T_{SIFS} + T_{CTS} + T_{SIFS} + T_{DATA} + T_{SIFS} + T_{ACK} + T_{DIFS} \\ T_k &= k \cdot T_{RTS} + (k+2) \cdot T_{SIFS} + T_{CTS} + T_{DATA} + T_{ACK} + T_{DIFS}. \end{aligned} \tag{10}$$

Then, by using (9) and (10), the derived throughput S_M is given by

$$S_M = \frac{E[\text{payload information transmitted in a slot time}]}{E[\text{length of a slot time}]} = \frac{E[P] \cdot \left(\sum_{k=1}^{M} (k-1) \cdot P_{L,k} + M \cdot P_{L,M'}\right)}{P_{L,0} \cdot \sigma + \sum_{k=1}^{M} P_{L,k} \cdot T_k + P_{L,M'} \cdot T_M}, \tag{11}$$

where $E[P]$ is the payload length in bits.

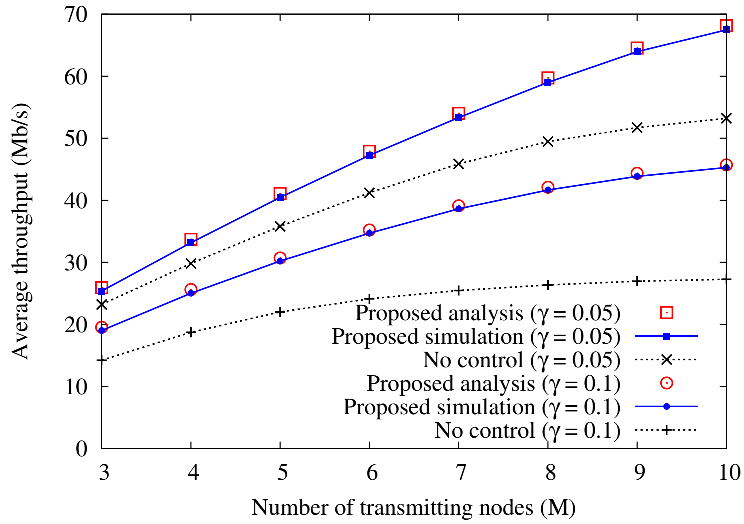

Fig. 2. Average throughput with respect to the number of transmitting nodes ($\gamma = 0.05$ and 0.1).

IV. Performance Evaluation

To evaluate the performance of our proposed admission control algorithm, extensive simulations were carried out using MATLAB. For our simulations, we considered an uplink single-cell system having an AP with MPR capability and its associated transmitters with backlogged user datagram protocol (UDP) packets. We used a disk region with a radius of 300 m, where the AP is located at the center of the region, and all transmitters are randomly distributed within the region. The transmission rates are set to 6 Mb/s for RTS/CTS/ACK control packets and 54 Mb/s for data packets. Each transmitter attempts to transmit as many UDP packets as possible. The reported values for the simulation results represented the average of 1,000 transmission sessions. We compared the performance of our proposed scheme with that of the no-control scheme, which allows all simultaneous transmissions requested by transmitters. The parameter values used in the simulations are listed in Table II.

Figure 2 shows the analytical and simulation results of the average throughput with respect to the number of transmitting nodes when γ is 0.05 and 0.1. The number of transmitting nodes on the *x*-axis increases from 3 to 10. As shown in Figure 2, we find that our proposed scheme significantly and gradually outperforms the no-control scheme as the number of transmitting nodes increases. As the number of transmitting nodes increases under the no-control scheme, their interference with each other becomes stronger, and some signals subsequently fail to be decoded. On the other hand, our proposed scheme can control the amount of interference between the transmitting nodes by rejecting transmission requests. Although the number of transmitting nodes increases, the throughput performance gradually improves with our proposed scheme.

When γ is 0.05 and M is small, there is no apparent performance improvement because M_{max} and M are almost the same owing to a low capture threshold. However, the distinction in performance between our proposed scheme and the no-control scheme gradually increases as the number of transmitting nodes increases.

To verify the maximum throughput performance of our proposed scheme, the analytical results are obtained by (11) in Section III-C and are very close to the simulation results for all cases. The results of this simulation show that our proposed scheme works properly and leads to the improvement of the network throughput performance.

V. Conclusions

The main objective of the proposed admission control scheme is to fully utilize the MPR capability by maximizing the number of simultaneous transmissions as long as their interference with each other is not very significant. With this objective in mind, we proposed an admission control scheme that derived the maximum number of simultaneous transmissions for a given wireless channel state and regulated the number of simultaneous transmissions according to the derived maximum number. As a result, our proposed algorithm could achieve an improvement in the overall network throughput.

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