MAC protocol for optimal Multipacket Reception in WLANs

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Abstract

Conventional medium access control (MAC) protocols of wireless local area networks (WLANs) have been designed based on the assumption that only a single packet can be received successfully at a time. However, the deployment of multiple antennas in WLANs makes it possible to receive multiple packets simultaneously. As a result, the design of new MAC protocol should take the multipacket reception (MPR) capability into consideration. In this paper, we propose a MAC protocol with consideration of the optimal number of simultaneous transmissions for WLANs with MPR capability. The proposed MAC protocol follows the 802.11 Distributed Coordination Function (DCF) with Request-to-Send/Clear –to-Send (RTS/CTS) exchange mode, but there is a modification in the CTS and ACK packets. We also derive the throughput equation of our proposed MAC protocol. Simulation results show that our proposed protocol outperforms convention protocols, and achieves a large throughput enhancement.

1. Introduction

Wireless local area networks (WLANs) based on IEEE 802.11 have been widely used for years since WLANs can provide wireless services of high data rate with comparably low cost. Recently, there are increasing wireless services which require higher data rate, so WLANs should be able to provide higher data rate. In an effort to increase the data rate, IEEE 802.11n standard [1] which mandates the deployment of multiple antennas at the access point (AP) has been newly introduced. The most significant advantage of multiple antennas is the multipacket reception (MPR) capability which means the multiple packets can be received successfully at the same time. This MPR capability is expected to be able to increase the data rate immensely.

The medium access control (MAC) protocols of WLANs have been designed based on the single packet reception model which assumes that only a single packet can be received successfully at a given time. However, this single packet reception model is not valid any more in WLANs with MPR capability, so the MAC protocols need to be redesigned with consideration of the MPR capability.

There has been some research of the MAC protocols which considered the MPR capability in WLANs. P.Zheng et al. [2] proposed the PHY methodology and MAC protocol which make it possible to implement MPR in WLANs for the first time. W.Huang et al. [3] developed a channel state adaptive MAC protocol for WLANs where MPR is possible due to multiple antennas. However, there is no consideration of the optimal number of simultaneous transmissions [4] which maximizes the throughput in these MAC protocols.

In this paper, we propose a MAC protocol with consideration of the optimal number of simultaneous transmissions for WLANs with MPR capability. The proposed MAC protocol follows the operation of 802.11 Distributed Coordination Function (DCF) with Request-to-Send/Clear –to-Send (RTS/CTS) exchange mode, but there is a modification in the CTS and ACK packets. We also derive the throughput equation of our proposed MAC protocol. Simulation results show that our proposed protocol outperforms convention protocols, and achieves a large throughput enhancement.

The rest of this paper is organized as follows. In section 2, we describe the system model where MPR is possible due to the multiple antennas. In section 3, we present the optimal number of simultaneous transmissions. In section 4, we propose a MAC protocol which takes into consideration of the optimal number of simultaneous transmissions. In section 5, performance analysis of the proposed MAC protocol is derived. In section 6, we show the simulation results of our proposed MAC protocol, and finally we conclude this paper in section 7.

2. System Model

In this paper, we consider the uplink transmission of a WLAN which consists of an access point (AP) and a number of stations (STAs). Assume that the number of STAs is \( M \), and each STA has only a single antenna. We also assume that the AP has N antennas, and uses zero forcing (ZF) detector to decode multiple packets from STAs. MPR is possible due to the multiple antennas at the AP, and we assume that multiple packets up to N can be decoded simultaneously.

Assume that \( k \ (k \leq M) \) STAs are transmitting simultaneously, i.e., there are \( k \) simultaneous transmissions. Then the received signals can be expressed as

\[
y = Hs + w.
\] (1)

In the above equation, \( s = (s_1, s_2, \ldots, s_k)^T \) is the transmitted signal vector where \( s_i \) is the transmitted signals.
signal from $i_{th}$ STA. $H=(h_1,h_2,...,h_k)$ is an $N \times k$ channel matrix where $h_{j,i}$ is the channel coefficient from $i_{th}$ STA to $j_{th}$ antenna at the AP. We assume that the transmitted signals experience Rayleigh flat fading, and the wireless channels from each STA to AP are independent and identically distributed (i.i.d.), so each element of $H$ is an i.i.d. complex Gaussian random variable with zero mean and unit variance, $w$ is the background noise.

The post-detection SNR of the transmission of $i_{th}$ STA at the receiver with ZF detector can be expressed as [4]

$$\gamma_i = \frac{\alpha_i}{2}.$$  \hspace{1cm} (2)

In the above equation, $\gamma$ is the average SNR at each receive antenna which is determined by the transmission power and the noise power. We assume that each STA’s transmission power is controlled by the AP using power control mechanisms, so the average SNR of transmissions of each STA is same, and the AP knows the average SNR. $\alpha_i$ is equal to $\frac{2}{[(H^H H)^{-1}_{ii}]}$, where $[(H^H H)^{-1}_{ii}]$ denotes the $(i,i)_th$ element of the matrix $(H^H H)^{-1}$, and is a Chi-Square random variable with degrees of freedom $2(N-k+1)$. Note that, at a given average SNR, $\gamma_i$ is determined by $\alpha_i$. From (2), BER can be obtained by using the approximate BER equation [5]

$$BER(\gamma_i) = C_2 \exp(-C_2 \gamma_i),$$  \hspace{1cm} (3)

where $C_1$ and $C_2$ are determined by the modulation scheme which is used for the transmission.

3. Optimal number of simultaneous transmissions

In this section, we find the optimal number of simultaneous transmissions which maximizes the throughput by using similar methods presented in [4]. Since the wireless channels for all STAs are i.i.d., and all STAs have the same average SNR, $\alpha_i$ for all STAs are i.i.d., so we can use $\alpha$ instead of $\alpha_i$.

A successful data transmission is determined by the Frame Error Rate (FER) of a data packet, and FER is determined as

$$FER(\alpha) = 1-(1-BER(\alpha))^{MAC_{hdr}+L},$$  \hspace{1cm} (4)

where $MAC_{hdr}$ is the MAC header length and $L$ is the packet payload size.

As we can see above equation, FER of a transmission depends on $\alpha$. Since $\alpha$ is the Chi-Square random variable, the expected FER of a transmission is expressed as

$$FER(\alpha) = \int_0^\infty FER(\alpha)p(\alpha;2(N-k+1))d\alpha, \hspace{1cm} (5)$$

where $p$ is the probability density function of a Chi-Square random variables with degrees of freedom $2(N-k+1)$.

Because there are $k$ simultaneous transmissions, the expected number of successfully received packets is derived as

$$C_k = k \times (1-FER(\alpha)).$$  \hspace{1cm} (6)

As we can see in (6), the expected number of successfully received packets is determined by the number of simultaneous transmissions $k$. Then the optimal number of simultaneous transmissions is expressed as

$$k_o = \arg\max_{k=1,...,N} C_k.$$  \hspace{1cm} (7)

Note that $k_o$ is the number of simultaneous transmissions which maximizes the expected number of successfully received packets. Also, the value of $k_o$ depends on the number of receive antennas and the average SNR. Fig.1 shows the expected number of successfully received packets according to each average SNR when the number of receive antennas is 4. For example, when the average SNR is 15dB, the maximum of the number of successfully received packets is 2.6, and $k_o = 3$. We can also find that the value of $k_o$ increases as the average SNR increases. For example, for the different average SNR, i.e., 5,10,15 and 20, the values of $k_o$ are 1,2,3 and 4, respectively.

![Fig. 1 $C_k$ versus the number of transmissions $k$](image)

4. MAC protocol for optimal MPR

In this section, we propose a MAC protocol which maximizes the throughput of WLANs with MPR capability. Our proposed MAC protocol follows the operation of 802.11 DCF with RTS/CTS exchange mode. However, our proposed protocol takes the value of $k_o$ into account, so the number of simultaneous transmissions is always equal to $k_o$. We assume that the AP knows the value of $k_o$ according to the average SNR and the number of receive antennas.
The proposed MAC protocol operates as shown in Fig. 2. A STA transmits an RTS packet if its backoff counter becomes zero. There can be multiple RTS packets when multiple STAs send simultaneously. We assume that the RTS packets up to N can be successfully received. If the number of simultaneous RTS packets is larger than N, there would be a collision.

After receiving the RTS packets, the AP can be aware of the number of RTS packets if there is no collision. Let $k$ denote the number of RTS packets. Even though $k$ is not equal to $k_o$, the number of simultaneous data transmissions should be $k_o$ to maximize the throughput.

The AP always grants data transmission opportunity to $k_o$ STAs, irrespective of the number of RTS packets, by sending a CTS packet with $k_o$ receiver address (RA) fields. The STA which is allowed to transmit a data packet is determined as follows:

1) $k < k_o$

The AP first grants the data transmission opportunity to $k$ STAs which transmitted the RTS packets. Then the AP randomly selects $(k_o-k)$ STAs among STAs which did not transmit the RTS packets, and grants the data transmission opportunity.

2) $k = k_o$

Since $k = k_o$, the AP grants the data transmission opportunity only to STAs which transmitted the RTS packets. In this case, the number of RTS packets and the number of data packets which will follow are same.

3) $k > k_o$

The AP randomly selects $k_o$ STAs among $k$ STAs which transmitted the RTS packets, and grants the data transmission opportunity.

Note that in all cases, the number of the data packets to be transmitted is equal to $k_o$. In case 1), the STAs which did not transmit the RTS packets also transmit the data packets if their addresses are in the CTS packet. In case 3), $k-k_o$ STAs which transmitted the RTS packets, but are not selected by the AP will increase the backoff stage by 1, and double the contention window size with the upper bound of the maximum contention window size.

The AP receives the data packets from STAs, and acknowledges the successfully received data packets by sending a ACK packet. Since there can be multiple successfully received data packets, the number of RA fields in the ACK packet is determined by the number of successfully received data packets.

The STAs which are not acknowledged by the AP increase the backoff stage and double the contention window size. In case 1), the STAs which transmitted the data packets without sending the RTS packets do not increase the backoff stage and the contention window size even though their data transmissions are failed, i.e., they just resume the previous backoff counter.

The CTS and ACK packets are shown in Fig. 3. As we mentioned before, the number of RA fields in the CTS packet is always equal to $k_o$, while the number of RA fields in the ACK packet can be changeable according to the number of successfully received data packets.

5. Performance Analysis

In this section, we derive the throughput of the proposed MAC protocol by using the similar method in [6]. We assume that the number of STAs and the number of receiver antennas at the AP are fixed. All STAs are in saturated conditions, i.e., they always have packets to transmit.

Assume that there are M STAs, and the AP has N antennas. Each STA transmits a packet with the probability $\tau$ in a slot time, and $\tau$ is expressed as

$$\tau = \frac{2(1-2p_c)}{(1-2p_c)(W+1) + p_cW(1-(2p_c)^m)},$$

where $p_c$ is the collision probability, $W$ is the minimum backoff counter size, and $m$ is the maximum backoff stage.
A transmitting STA may experience the collision which is caused by the RTS collision and data packet error. The occurrence of RTS collision depends on the number of simultaneously transmitted RTS packets. If there are less than or equal to $k_o$ of RTS packets, there would be no collision. When there are RTS packets between $k_o+1$ and $N$, the STA would succeed the RTS transmission if selected by the AP. If there are more than $N$ of RTS packets, there would be a collision. The occurrence of error in the data packet occurs with the probability of $FER$.

Let $p_r$ denote the collision probability in the RTS transmission, and is expressed as:

$$p_r = 1 - \sum_{i=0}^{k_o} \binom{M-1}{i} \tau^i (1 - \tau)^{M-1-i} + \sum_{i=k_o+1}^{N-1} \binom{M-1}{i} \tau^i (1 - \tau)^{M-1-i}$$

Since the collision consists of the RTS collision and the data packet error, the collision probability $p_c$ is expressed as

$$p_c = p_r + (1 - p_r) FER.$$  \hspace{1cm} (10)

Now, we compute the throughput by analyzing what can happen in a slot time. Let $p_{tr}$ denote the probability that there is at least one RTS transmission in the slot time. Then

$$p_{tr} = 1 - (1 - \tau)^M.$$  \hspace{1cm} (11)

Let $p_i$ denote the probability that there are $i$ simultaneous RTS transmissions. Then

$$p_i = \binom{M}{i} \tau^i (1 - \tau)^{M-i}.$$  \hspace{1cm} (12)

The probability that $j$ data transmissions out of total $i$ data transmissions are successfully received is denoted by $p_r^j$, and is expressed as

$$p_r^j = \binom{j}{i} (1 - FER)^j (FER)^{i-j}. \hspace{1cm} (13)$$

We define the throughput $S$ as the ratio of payload information bits being transmitted to the total amount of time spent to transmit the payload successfully. Then $S$ is expressed as

$$S = \frac{\sum_{i=1}^{N} p_i c_i E[L]}{1 - p_o \sigma + \sum_{i=1}^{N} p_i \sum_{j=1}^{i} T_s^j + \sum_{i=1}^{N} p_i \sum_{j=1}^{i} T_c^j + (p_o - \sum_{i=n+1}^{M} p_i) T_R}.$$  \hspace{1cm} (14)

In the above equation, $\sigma$ is the duration of an idle slot, $T_s^j$ and $T_c$ denote the average time spent for, respectively, $j$ successful data transmissions and collisions. $T_e$ denotes the average time spent for data transmissions in error, i.e., all the data packets are received in error. $E[L]$ is the average packet payload size, and we assume that all the packets have the same size, so $E[L] = L$.

In our proposed MAC protocol, $T_s^j$, $T_e$ and $T_c$ are expressed as

$$T_s^j = RTS + SIFS + \delta + CTS + SIFS + \delta + PHY_{hdr} + (MAC_{hdr} + L)/R + SIFS + \delta + ACK_j + DIFS + \delta,$$

$$T_e = RTS + DIFS + \delta,$$

$$T_c = RTS + SIFS + \delta + CTS + SIFS + \delta + PHY_{hdr} + (MAC_{hdr} + L)/R + DIFS + \delta.$$  \hspace{1cm} (15)

In the above equations, $\delta$ is the propagation delay, $PHY_{hdr}$ is the physical header length, and $R$ is the transmission rate of the data packet. RTS and CTS denote the time duration of, respectively, an RTS packet, a CTS packet. $ACK_j$ denotes the time duration of an ACK packet with $j$ RA fields.

6. Simulation Results

In this section, we show the performance of the proposed MAC protocol. We consider a WLAN which consists of an AP and 50 STAs. The AP has multiple antennas, and all STAs have a single antenna. We assume that the transmission rate of the data packet is 18Mbps using QPSK modulation scheme, the packet payload size is fixed. All the control packets such as RTS, CTS, ACK are assumed to be transmitted at 6Mbps, and the duration of the CTS and ACK packet is determined by the number of RA fields in the packet. Other simulation parameters are shown in Table 1.

We compare the performance of the proposed MAC protocol with two other protocols. One is the IEEE 802.11 protocol which only allows single packet reception. We
refer to it as no MPR protocol. Even though MPR is not possible in no MPR protocol, we still assume that there are multiple antennas at the AP. The other is the conventional MPR protocol. In this protocol, all the STAs which transmitted the RTS packets, if there is no collision, are allowed to transmit the data packets without consideration of the optimal number of simultaneous transmissions. As a result, the number of RTS packets and the number of data packets are always same.

Fig. 4 shows the throughput of the three protocols under the different average SNR when the number of receive antennas is 4. We can see that our proposed protocol outperforms other two protocols, and achieves the highest throughput. Moreover, the enhancement of throughput becomes large as the average SNR increases. This can be explained as follows. As the average SNR increases, the more packets can be successfully received, and as a result, the value of $k_o$ also increases. In our proposed protocol, when the average SNR is high, more packets are transmitted simultaneously (because there are always $k_o$ simultaneous transmissions), so there is a large throughput enhancement.

The number of antennas at the AP can significantly affect the performance of our proposed protocol, so we investigate the effect of the number of receive antennas. Fig. 5 shows the throughput of the three protocols under the different number of receive antennas when the average SNR is 15 dB. While there is a small throughput increase by no MPR protocol, our proposed protocol and conventional MPR protocol show a large throughput enhancement as the number of antennas increases. This is because the more packets can be received successfully when there are more antennas at the AP. In addition to this enhanced MPR capability by the increase of antennas, the number of simultaneous transmissions is always adjusted to $k_o$ which is determined by the number of antennas. Consequently, our proposed protocol shows larger throughput enhancement that conventional MPR protocol.

7. Conclusions

In this paper, we proposed a MAC protocol which takes into consideration of the optimal number of simultaneous transmissions. There exists the optimal number of simultaneous transmissions which is determined by the number of antennas and the average SNR. In our proposed MAC protocol, the number of simultaneous transmissions is always equal to the optimal value, so the throughput increases as a result. We also derive the throughput equation and simulation results show that our proposed MAC protocol can achieve a significant throughput enhancement compared with the conventional MAC protocols.

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8. References