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A cross-layer approach to enable multipacket transmission in MIMO-SDMA based WLAN*

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Abstract: We propose a medium access control (MAC) protocol for uplink transmissions in wireless local area networks (WLANs), where both stations and access points (APs) are equipped with multiple antennas. The protocol solves some common problems in utilizing multiple input multiple output (MIMO) under the 802.11 protocol, e.g., how to deploy preamble (training sequence) used for channel estimation and how to enable simultaneous data transmissions, and facilitates two simultaneous uplink data transmissions via a cross-layer approach. Furthermore, we develop a 3D discrete-time Markov model to analyze the performance of the proposed WLAN scheme. The analytical results are verified by simulation, and numerical results show that the system throughput can be significantly improved by our proposed scheme as compared with conventional schemes.

Key words: Multiple input multiple output (MIMO), Medium access control (MAC), Cross-layer design
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INTRODUCTION

With the rapid development of wireless local area networks (WLANs), it is of great interest to increase the data rate between stations and access points (APs). Among many solutions, multiple input multiple output (MIMO), as an important technology to enhance the physical layer (PHY) capability, can achieve this target via spatial reuse. Specifically, both stations and APs equipped with multiple antennas allow simultaneous multipacket transmissions. Recently a new standard IEEE 802.11n, where multiple antennas are deployed, has received extensive attention. However, the medium access control (MAC) protocol has not changed substantially as compared with the conventional 802.11 MAC, which has not fully exploited the benefits provided by the advanced PHY techniques. The MIMO technology thus has the potential to increase the throughput substantially.

In the conventional 802.11 protocol, once a station is transmitting data or a request-to-send (RTS) frame to an AP, all the other stations in the carrier sensing range should detect a busy channel and defer the channel access, which means that there cannot be simultaneous data transmissions. This motivates us to use the concept of multiuser detection (MUD) (Ghez *et al.*, 1988), which can be realized through multiple antennas. A scheme was proposed in (Zheng *et al.*, 2006) to facilitate MUD in WLAN. However, it did not take into consideration the bit error rate (BER), which has a great effect on the system performance. An amended policy was proposed based on the average frame error rate (FER) by Huang and Letaief (2007) and Ke *et al.*(2007), in which the transmission is controlled by the channel state information (CSI). However, they did not present how to get the CSI in the protocol. Recently a cross-layer approach, which

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combines the issues in PHY layer and MAC layer based on MIMO, has received much attention (Dimic *et al.*, 2004; Realp and Perez-Neira, 2004). Some algorithms were proposed to maximize the throughput by allowing multiple simultaneous data transmissions. However, in the literature, some questions in utilizing MIMO in WLAN are not addressed. For example, how to deploy preamble used for channel estimation and how to enable simultaneous data transmissions are still open issues.

In this paper, the primary goal of our proposed protocol is to exploit multipacket transmission in the MIMO-SDMA based WLAN. Our protocol resolves the problems in utilizing MIMO in WLAN via a cross-layer approach. A signal processing technique is adopted at the PHY layer to resolve packet collisions at the MAC layer. Specifically, the packet collision can be treated as a signal-mixing problem, which can be resolved using MUD techniques. CSI has been taken into account in the simulation. In (Bianchi, 2000) a Markov chain model was used to analyze the performance of WLAN; in this paper, we further develop a 3D discrete-time Markov model to verify the performance of our scheme.

The rest of this paper is organized as follows. We first provide the MIMO system model and our protocol for uplink MAC in Section 2. Then we present the 3D Markov model to evaluate the performance of WLAN in Section 3. Section 4 contains numerical results and Section 5 finally concludes the paper.

SYSTEM MODEL

MIMO system model

We consider the uplink transmission of a MIMO based WLAN system, where stations are equipped with K antennas, and AP is equipped with N antennas.

The following is a model for M simultaneous data transmitted in the system,

$$\boldsymbol{y}=\sum_{i=1}^{M}\boldsymbol{H}^{(i)}\boldsymbol{x}^{(i)}+\boldsymbol{w}. \tag{1}$$

In Eq.(1), $\boldsymbol{x}^{(i)}=[x_1^{(i)},x_2^{(i)},\cdots,x_K^{(i)}]^{\mathrm{T}}$ (i=1, 2, …, M) denotes the transmitted symbol vector of station i, where $x_m^{(i)}$ represents the transmitted symbol of the mth antenna. $\boldsymbol{H}^{(i)}=[\boldsymbol{H}_1^{(i)},\boldsymbol{H}_2^{(i)},\cdots,\boldsymbol{H}_K^{(i)}]$ is the flat-fading channel matrix, where $\boldsymbol{H}_K^{(i)}$ (i=1, 2, …, M) denotes an N-element column vector representing the channel gain from station i to the set of receive antennas of AP. Supposing that both the transmit antennas and the receive antennas are spaced sufficiently far apart, the entries in $\boldsymbol{H}^{(i)}$ can be assumed to be independent and identically distributed (i.i.d.). The vector $\boldsymbol{w}$ is a complex-valued background Gaussian noise with zero mean and variance σ^2.

Eq.(1) can be rewritten when the channel matrix $\boldsymbol{H}^{(i)}$ is decomposed through singular value decomposition (SVD) as

$$\begin{aligned}\boldsymbol{y}&=\boldsymbol{H}^{(1)}\boldsymbol{x}^{(1)}+\cdots+\boldsymbol{H}^{(M)}\boldsymbol{x}^{(M)}+\boldsymbol{w}\\&=\boldsymbol{u}^{(1)}s^{(1)}\boldsymbol{v}^{(1)}\boldsymbol{x}^{(1)}+\cdots+\boldsymbol{u}^{(M)}s^{(M)}\boldsymbol{v}^{(M)}\boldsymbol{x}^{(M)}+\boldsymbol{w},\end{aligned} \tag{2}$$

where $\boldsymbol{u}^{(i)}$ and $\boldsymbol{v}^{(i)}$ (i=1, 2, …, M) are the left and right singular vectors, respectively, corresponding to the maximum singular value $s^{(i)}$ of $\boldsymbol{H}^{(i)}$ for the ith user.

By pre-filtering input $\overline{\boldsymbol{x}}^{(i)}=\boldsymbol{v}^{(i)}\boldsymbol{x}^{(i)}$ at the transmitter and matching output $\overline{\boldsymbol{y}}^{(i)}=(\boldsymbol{u}^{(i)})^{\mathrm{T}}\boldsymbol{y}$ at the receiver with vector $\boldsymbol{u}^{(i)}$, Eq.(2) can be rewritten as

$$\overline{\boldsymbol{y}}^{(i)}=s^{(i)}\overline{\boldsymbol{x}}^{(i)}+\sum_{k=1,\,k\neq i}^{M}(\boldsymbol{u}^{(i)})^{\mathrm{T}}\boldsymbol{u}^{(k)}s^{(k)}\overline{\boldsymbol{x}}^{(k)}+(\boldsymbol{u}^{(i)})^{\mathrm{T}}\boldsymbol{w},\quad i=1,\,2,\,\ldots,\,M.$$

Defining $\overline{\boldsymbol{w}}^{(i)}=(\boldsymbol{u}^{(i)})^{\mathrm{T}}\boldsymbol{w}$ and correlation components $\rho^{(ij)}=(\boldsymbol{u}^{(i)})^{\mathrm{T}}\boldsymbol{u}^{(j)}$, we have

$$\overline{\boldsymbol{Y}}=\boldsymbol{RS}\overline{\boldsymbol{X}}+\overline{\boldsymbol{W}}, \tag{3}$$

where

$$\overline{\boldsymbol{Y}}=[\overline{\boldsymbol{y}}^{(1)},\overline{\boldsymbol{y}}^{(2)},\cdots,\overline{\boldsymbol{y}}^{(M)}],\quad \overline{\boldsymbol{X}}=[\overline{\boldsymbol{x}}^{(1)},\overline{\boldsymbol{x}}^{(2)},\cdots,\overline{\boldsymbol{x}}^{(M)}],$$
$$\overline{\boldsymbol{W}}=[\overline{\boldsymbol{w}}^{(1)},\overline{\boldsymbol{w}}^{(2)},\cdots,\overline{\boldsymbol{w}}^{(M)}],\quad \boldsymbol{S}=\mathrm{diag}\{s^{(1)},s^{(2)},\cdots,s^{(M)}\},$$
$$\boldsymbol{R}=\begin{pmatrix}1&\rho_{12}&\cdots\\\rho_{21}&1&\cdots\\\vdots&\vdots&\ddots\end{pmatrix}.$$

A zero forcing (ZF) detector is adopted at the receiver terminal (Kim and Cioffi, 2000) and we can decode the input signal by

$$\boldsymbol{S}^{-1}\boldsymbol{R}^{-1}\overline{\boldsymbol{Y}}=\overline{\boldsymbol{X}}+\boldsymbol{S}^{-1}\boldsymbol{R}^{-1}\overline{\boldsymbol{W}}. \tag{4}$$

Proposed MAC protocol

In the conventional 802.11 protocol, if both STA1 and STA2 have data to transmit, the one who loses the contention for channel has to wait until the winner finishes the transmission.

In our proposed MAC protocol, the normal carrier sense multiple access (CSMA) objective of isolating a single active station is not desirable. Instead, we would like to solve the problem of simultaneous transmissions. We modify the protocol as follows (Fig.1):

Step 1: All stations will contend for channel, and then the winner, e.g., STA1, will send an RTS frame to AP. Note that, the RTS is no longer the original RTS, but preambles are added behind it instead.

Step 2: After a SIFS, AP will reply a CTS with a feedback containing channel information to acknowledge the RTS, as the period of SIFS is long enough to calculate the channel gain. Thus, it is entirely possible for both transmitter terminal and receiver terminal to be aware of channel information. After this successful handshake, STA1 will enter a waiting state rather than send data immediately.

Step 3: After another SIFS, all stations except STA1 will continue contention for the channel until someone (e.g., STA2) wins out. Then STA2 will send the RTS frame including preamble to AP, which in consequence responds to CTS with feedback after SIFS.

Step 4: After Steps 1~3, there are already two successful RTS/CTS handshakes in the system. Since STA1, STA2 and AP are all aware of the channel information, STA1 and STA2 can send data frames to AP simultaneously. Based on the discussion in subsection “MIMO system model”, we can infer that the data from different stations can be distinguished via signal processing if the channel matrices of the two stations are not seriously overlapped. At last, AP will reply with an ACK to confirm data.

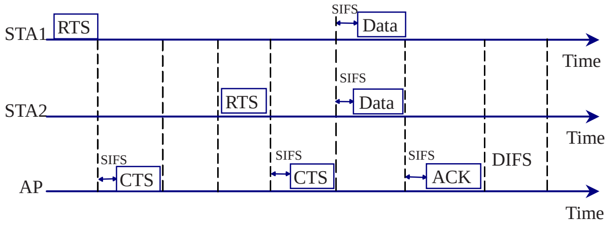

Fig.1 Operation of the proposed protocol

Step 5: If a station remains in the waiting state more than λ ms, during which the CSI is considered constant, the waiting station will send the data solely.

Step 6: If there is only one station in the system, the original protocol should be adopted instead.

Discussion

From the protocol described above, we notice that two simultaneous data transmissions are allowed. Nevertheless, the preambles for the channel estimation cannot overlap. Otherwise, the channel matrix cannot be calculated out exactly.

Attention should be paid when the stations have similar channel matrices. In such cases, the signal to interference plus noise ratio (SINR) of the detector output is very low and the data from the different stations cannot be correctly decoded. Also, AP will give up the packet. However, this is a rare situation—the simulation results in Section 4 will show that the average SINR increases when multiple antennas are adopted and the BER decreases as a result. Besides, the Markov model cannot reflect the timeout in the protocol. The simulation result of the distribution of wait slots will show that it is a reasonable approximation.

Our scheme can be easily extended for more simultaneous data transmissions by simply adding another contention after the two successful RTS/CTS handshakes.

PERFORMANCE ANALYSIS

Revised Markov chain

Considering the situation in our protocol, a 3D discrete-time Markov chain can be represented as Fig.2. In this model, the three dimensions $\{\alpha(t), \beta(t), \gamma(t)\}$ are system state, backoff stage, and slot counter, respectively. $\alpha(t)$ denotes the number of successful RTS handshakes in one successful data frame transmission at time t, and its value is either 0 or 1 according to the discussion above. $\beta(t)$ is the stochastic process on behalf of the backoff stage $(0, 1, \ldots, m)$, while $\gamma(t)$ represents the backoff time counter for a given station at time t. The backoff time counter of each station decreases at the beginning of each slot. Besides the common states, there is a special state—waiting.

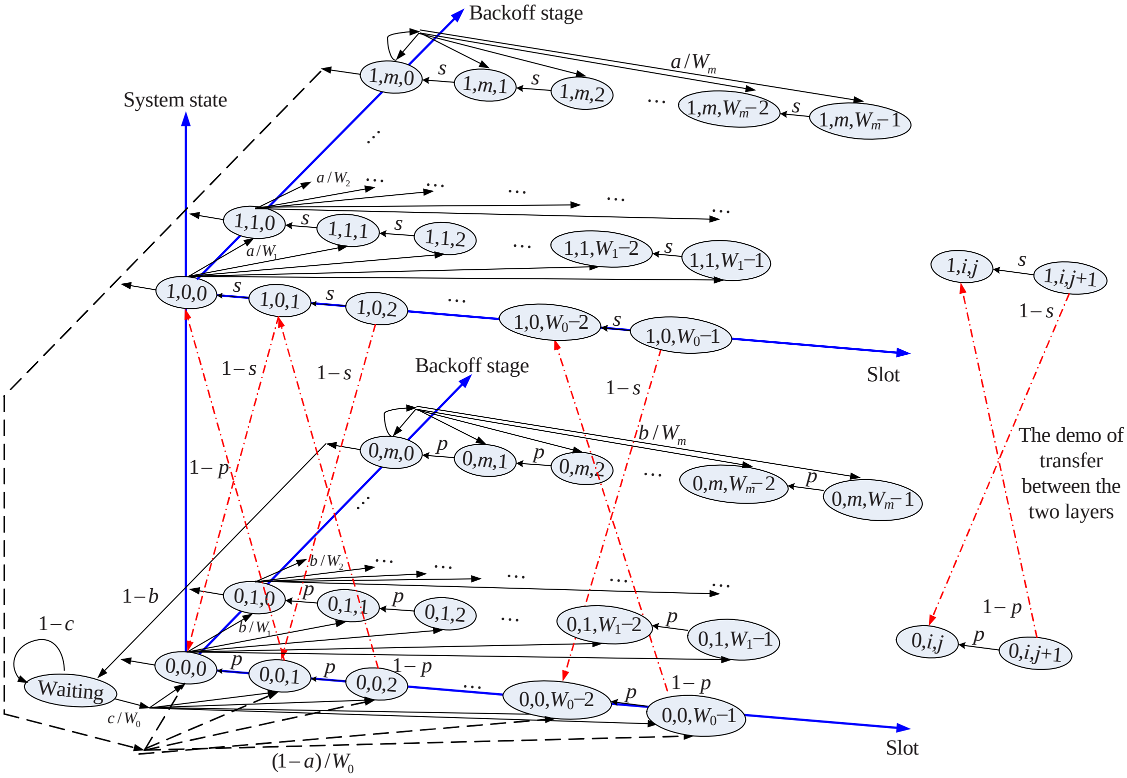

Fig.2 Three-dimensional discrete-time Markov model

This 3D Markov chain can be viewed as two layers of a 2D Markov chain, called layer 0 (when $\alpha(t)$=0) and layer 1 (when $\alpha(t)$=1). As depicted in Fig.2, the non-null one-step transition probabilities can be represented as

$$P\{0,i,k|0,i,k+1\}=p,\ \ k=0, 1, \ldots, W_i-2;\ i=0, 1, \ldots, m, \quad (5a)$$

$$P\{1,i,k|0,i,k+1\}=1-p,\ k=0, 1, \ldots, W_i-2;\ i=0, 1, \ldots, m, \quad (5b)$$

$$P\{\text{waiting}|0,i,0\}=1-b,\ \ \ i=0, 1, \ldots, m, \quad (5c)$$

$$P\{0,i,k|0,i-1,0\}=b/W_i,\ k=0, 1, \ldots, W_i-1;\ i=1, 2, \ldots, m, \quad (5d)$$

$$P\{0,m,k|0,m,0\}=b/W_m,\ \ \ k=0, 1, \ldots, W_m-1, \quad (5e)$$

$$P\{0,0,k|\text{waiting}\}=c/W_0,\ \ \ k=0, 1, \ldots, W_0-1, \quad (5f)$$

$$P\{\text{waiting}|\text{waiting}\}=1-c, \quad (5g)$$

$$P\{1,i,k|1,i,k+1\}=s,\ \ k=0, 1, \ldots, W_i-2;\ i=0, 1, \ldots, m, \quad (5h)$$

$$P\{0,i,k|1,i,k+1\}=1-s,\ k=0, 1, \ldots, W_i-2;\ i=0, 1, \ldots, m, \quad (5i)$$

$$P\{1,i,k|1,i-1,0\}=a/W_i,\ k=0, 1, \ldots, W_i-1;\ i=1, 2, \ldots, m, \quad (5j)$$

$$P\{1,m,k|1,m,0\}=a/W_m,\ \ k=0, 1, \ldots, W_m-1, \quad (5k)$$

$$P\{0,0,k|1,i,0\}=(1-a)/W_0,\ k=0, 1, \ldots, W_0-1;\ i=0, 1, \ldots, m, \quad (5l)$$

where a, b, c, p, s are the parameters of the transfer probability in the Markov chain.

Eq.(5a) accounts for the fact that at the beginning of each time slot, the backoff time counter decreases with the probability of p. The other cases model the system after a successful RTS transmission; in particular, as considered in Eq.(5b), when a successful RTS transmission occurs at slot $j-1$, the state of all stations, except the one that sends the RTS, will transfer from layer 0 to layer 1 while keeping decreasing the time slot account at slot j. On the other hand, the station successfully sending the first RTS transfers its state to the waiting state as depicted in Eq.(5c). Consider the situation in Eq.(5d), when a collision of RTS frames occurs at backoff stage $i-1$, the backoff stage increases, and the new initial backoff value is uniformly chosen from $\{0, 1, \ldots, W_i\}$. Furthermore, Eq.(5e) models the fact that once the backoff stage reaches the value m, it does not increase in consecutive time slot. If the second RTS frame is successfully sent, the waiting station will revive and randomly choose a backoff value from $\{0, 1, \ldots, W_i\}$, as depicted in Eq.(5f). Otherwise, the waiting station keeps waiting as Eq.(5g). The meaning of Eqs.(5h)~(5k) is alike to Eqs.(5a), (5b), (5d) and (5e), respectively; the only differences are the layer where the state locates and the transfer probability. Finally, Eq.(5l) presents the fact that the station that successfully sends the second RTS returns to the initial state; that is, it uniformly chooses a backoff slot in the set {0, 1, …, W_0}.

Theoretical analysis

Let $P_{i,j,k}=\lim_{t\to\infty} P\{\alpha(t)=i,\beta(t)=j,\gamma(t)=k\}$ (i=0, 1; j=0, 1, …, m; k=0, 1, …, W_j-1), P_w the stationary distribution of the chain, and n the number of stations. Assume m=0 so that we can analyze the Markov chain more conveniently. We can enumerate the state equations based on the Markov chain.

From Eq.(5), we can easily deduce that

$$P_{0,0,W_0-1}=P_w c/W_0+P_{0,0,0}b/W_0+P_{1,0,0}(1-a)/W_0, \quad (6)$$

$$P_{1,0,W_0-1}=P_{1,0,0}a/W_0, \quad (7)$$

$$P_{0,0,i}=P_{0,0,W_0-1}+(1-s)P_{1,0,i+1}+pP_{0,0,i+1},\ i=0, 1, \ldots, W_0-2, \quad (8)$$

$$P_{1,0,i}=P_{1,0,W_0-1}+(1-p)P_{0,0,i+1}+sP_{1,0,i+1},\ i=0, 1, \ldots, W_0-2, \quad (9)$$

$$P_w=(1-b)P_{0,0,0}+(1-c)P_w. \quad (10)$$

From Eq.(10), we can also easily infer that

$$P_w=P_{0,0,0}(1-b)/c. \quad (11)$$

Obviously, all state probabilities can be written as functions of $P_{0,0,W_0-1}$, $P_{1,0,W_0-1}$, p, s, b, c, which depend on the stationary distribution.

To find the value of p, it should be noted that the probability $1-p$ represents a successful RTS sent at a specific slot when all stations locate at layer 0. Specifically, there is no other station in the $n-1$ remaining stations locating at state (0, 0, 0) while all stations locate at layer 0. Thus,

$$p=1-nP_{con1}(1-P_{con1})^{n-2}, \quad (12)$$

where $P_{con1}=P_{0,0,0}\Big/\sum_{i=1}^{n}P_{0,0,i}$.

However, from another angle, the parameter b can also be viewed as the conditional collision probability, which means that, when a station transmits a packet, at least one of the $n-1$ remaining stations transmits a packet as well. At the stationary state, each remaining station transmits a packet with a conditional probability P_{con1}. Thus, we can deduce that

$$b=1-(1-P_{con1})^{n-1}. \quad (13)$$

In the same way, s and a can be expressed as follows:

$$s=1-nP_{con2}(1-P_{con2})^{n-3}, \quad (14)$$

$$a=1-(1-P_{con2})^{n-2}, \quad (15)$$

where $P_{con2}=P_{1,0,0}\Big/\sum_{i=1}^{n}P_{1,0,i}$.

Note that the exponential index decreases by 1 due to the waiting station.

Another important fact involved in the situation is that, because the two stations send data simultaneously, the transition probabilities from either waiting state or layer 1 to layer 0 are equal. Therefore, c and s yield

$$c=1-s. \quad (16)$$

Finally, the sum of stationary probabilities should be equal to 1,

$$\sum_{i=0}^{1}\sum_{j=0}^{W_0-1}P_{i,0,j}+P_w=1. \quad (17)$$

Eqs.(12)~(17) are complements to Eqs.(6)~(11), which include only six independent unknown variables, that is, $P_{0,0,W_0-1}$, $P_{1,0,W_0-1}$, p, s, b, c. Obviously this nonlinear equation group can be solved using numerical techniques.

Let S be the normalized system throughput. We can express S as the ratio

$$S=E_1/E_2, \quad (18)$$

where E_1 is the payload transmitted in a slot time and E_2 is the length of a slot time.

Let P_{tr} be the probability that there are successful simultaneous data transmissions. If one station transfers its state from layer 1 to layer 0, it means a successful data transmission, i.e.,

$$P_{tr}=nP_{1,0,0}(1-a). \quad (19)$$

Let P_{col} be the probability of occurrence for a collision. Specifically, the system has more than two RTS sent in a slot. Since this collision may be located on either layer 0 or layer 1, we can deduce P_{col} on conditional probability.

$$P_{col}=P(\text{layer }0)P(\text{col}|\text{layer }0)+P(\text{layer }1)P(\text{col}|\text{layer }1), \quad (20)$$

where

$$P(\text{layer }0)=\sum_{i=1}^{n}P_{0,0,i},$$

$$P(\text{col}|\text{layer }0)=1-(P_{\text{con}1})^{n}-nP_{\text{con}1}[1-(P_{\text{con}1})^{n-1}],$$

$$P(\text{layer }1)=\sum_{i=1}^{n}P_{i,0,i},$$

$$P(\text{col}|\text{layer }1)=1-(P_{\text{con}2})^{n-1}-(n-1)P_{\text{con}2}[1-(P_{\text{con}2})^{n-2}].$$

Here $P_{\text{con}1}$ and $P_{\text{con}2}$ are the same as in Eq.(12) and Eq.(14), respectively.

Being $E(P)$ the average packet payload size, the average amount of payload information successfully transmitted in a time slot is $2P_{tr}E(P)$. Hence, Eq.(18) becomes

$$S=\frac{2P_{tr}E(P)}{\sigma+P_{tr}T_{s}+P_{col}T_{c}}, \quad (21)$$

where T_s is the average time when the channel is sensed busy due to a successful transmission, T_c is the average time when the channel is sensed busy during a collision, and σ denotes the length of a time slot. And we have

$$\begin{cases}T_{s}=t_{RTS}+t_{SIFS}+\delta+t_{CTS}+t_{SIFS}+\delta\\ \quad +E(P)+t_{SIFS}+\delta+t_{ACK}+t_{DIFS}+\delta,\\ T_{c}=t_{RTS}+t_{DIFS}+\delta,\end{cases} \quad (22)$$

where δ is the propagation delay.

Based on the stationary distribution of the Markov chain and Eqs.(21)~(22), we can obtain the analytical results of S.

SIMULATION AND DISCUSSION

We considered a WLAN in which all nodes are in a saturated state, i.e., the stations always have packets to send. All traffic goes from nodes to AP. The values of the parameters used to obtain numerical results, for both the analytical model and the numerical simulation, are summarized in Table 1.

Table 1 Parameters used to obtain numerical results for the analytical model and the numerical simulation

Parameter	Value
Packet payload (bit)	8184
MAC header (bit)	272
PHY header (bit)	128
ACK (bit)	240
RTS (bit)	288
CTS (bit)	240
Preamble (bit)	160
Channel bit rate (Mb/s)	1
Propagation delay (μs)	1
Slot time (μs)	50
SIFS (μs)	28
DIFS (μs)	128

First we investigated the BER performance vs different numbers of antennas compared with the single input single output (SISO) performance. As illustrated in Fig.3, when the number of antennas is large, the BER performance using the MUD technology is better than that using the conventional SISO scheme. However, the performance gap between MUD and the conventional scheme becomes narrow when the number of antennas decreases. And the conventional scheme even outperforms MUD especially when a small antenna array is adopted, e.g., a 1×2 antenna array.

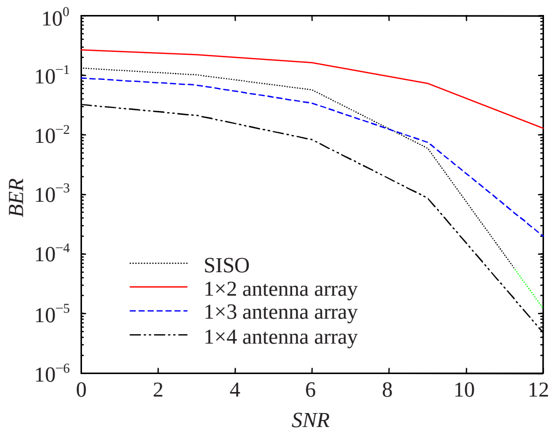

Fig.3 *BER* vs *SNR* in different antenna arrays

According to (Huang and Letaief, 2007),

$$FER=1-(1-BER)^L,$$

where L is the length of a packet. We can reach the conclusion that the FER performance of MUD is better than that of the conventional scheme when the number of antennas is large enough, e.g., a 1×4 antenna array.

Fig.4 illustrates the average number of wait slots between the two successful RTS-CTS handshakes in our protocol vs different network sizes. We can notice that the average number of wait slots is no more than 20 when the number of nodes is below 70. Fig.5 illustrates the probability that the number of wait slots is equal to 1 when the number of nodes varies from 10 to 100, while Fig.6 demonstrates the probability of different numbers of wait slots when the number of nodes is 50. Fig.6 shows that the probability that the number of wait slots exceeds 30 is be low 0.01, while the length of a packet transmission takes 180 slots during which the CSI is viewed as constant. Thus, the assumption that the channel remains constant during the wait slots is reasonable.

Fig.7 illustrates the system throughput when m=0, W_0=32 and a 1×4 antenna array is adopted. It can be noticed that the analytical results coincide approximately with the simulation results. The difference between the analytical results and the simulation results is due to an important approximation in the analytical model; that is, when a collision occurs in a slot, the collided stations begin to contend for the channel in the next slot. However, in the simulation model, the stations will revive after a T_c period (Bianchi, 2000). Fig.7 shows that the system throughput in our scheme outperforms that in the conventional 802.11 scheme when the number of nodes is below 100. When the number of nodes increases, the performance of our protocol decreases however. The reason of this phenomenon involves that the time to obtain two successful RTS in our system is much longer due to the heavy traffic as demonstrated in Fig.4.

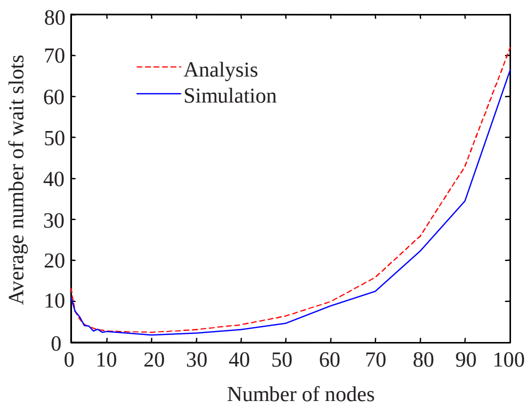

Fig.4 Average number of wait slots vs different network sizes

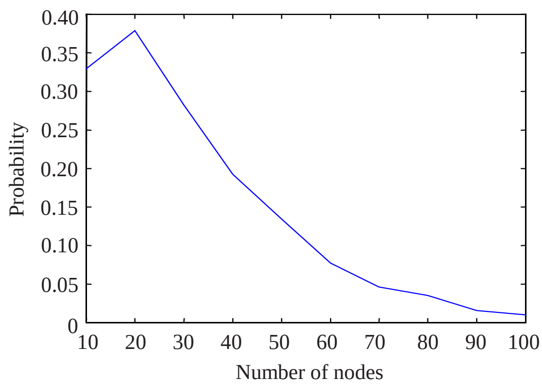

Fig.5 The probability that there is only one wait slot

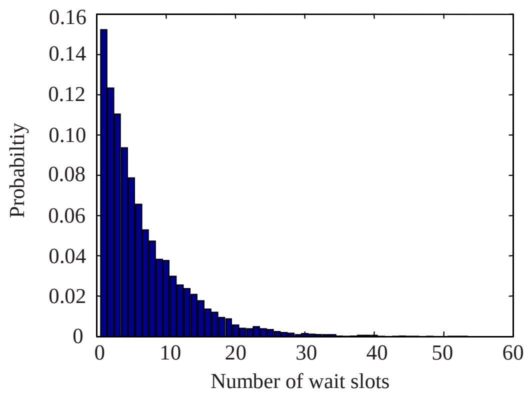

Fig.6 The distribution of wait slots when the number of nodes is 50

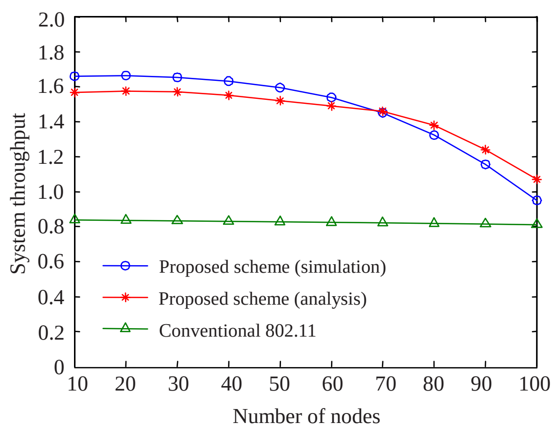

Fig.7 System performance when m=0 and W_0=32 (1×4 antenna array and SNR=12 dB)

CONCLUSION

In this paper, we present a CSMA/CA based uplink MAC protocol to exploit SDMA in WLAN via a cross-layer approach. Spatial reuse has been facilitated by allowing two simultaneous uplink data transmissions. Our proposed protocol solves the problems existing in utilizing MIMO, such as how to deploy preamble data used for channel estimation and how to enable simultaneous data transmission. Simulation results show that our scheme outperforms the conventional 802.11 protocol when the number of nodes is below 100. The enhancement of the proposed MAC protocol by allowing more simultaneous data transmissions as possible will be our future work.

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