IEEE 802.11 Performance Enhancement by MIMO Spatial Multiplexing

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Abstract—IEEE 802.11 wireless LANs are evolving into a high speed system by adopting MIMO technologies. Currently the standard deals with transmission for one user over a link. In this paper, we consider the MIMO technique of spatial multiplexing that enables multiple users to receive packets over the downlink simultaneously. It takes advantage of multiuser diversity in the space and time domains, supposing that each antenna independently performs link adaptation for each subchannel. Through analysis, we show that multiuser transmission has performance improvement over the single-user case. However, by using adaptive data splitting over spatial multiplexing, the performance of the single-user transmission is enhanced, and even better than that of multiuser case for small multiuser diversity. To exploit the multiuser diversity extensively, we apply a scheduling algorithm that considers channel condition of each subchannel. Simulation results show the multiuser transmission has higher link utilization than the single-user case for large multiuser diversity. To implement this, the system requires further considerations to modify ACK policy, and to mix conventional and MIMO-capable stations.

I. INTRODUCTION

For the last decade, wireless networks such as wireless LANs have been widely deployed and cellular networks have also begun the packet data service. Especially, IEEE 802.11 wireless LANs have evolved into a high transmission system with QoS support [2]. The 802.11n group plans to design a high-throughput wireless LAN by combining multiple-input-multiple-output (MIMO) and wideband adaptive OFDM technology [3]. In this paper we exploit multiuser diversity in space and time domains for a wireless LAN system.

The conventional 802.11 system supports just a single user transmission at once by an access point (AP), that is, either from an AP to a user station (STA), or from a STA to an AP. In our work, we pursue a possibility of multiuser transmission over the downlink (i.e., from an AP to multiple STAs) without fundamental change of MAC architecture. The multiuser transmission is possible because the MIMO system creates multiple subchannels.

Generally the MIMO system takes advantage of two types of gains, spatial diversity and spatial multiplexing. First, spatial diversity makes it possible to overcome fading channel condition [4], [5]. By receiving the same packet over various paths, the receiver can attain an original packet with higher probability. Instead of exploiting diversity gain, the system can increase data rate by sending independent information streams over several transmit-receive antenna pairs simultaneously [6]. Especially, spatial multiplexing can be combined with multiuser diversity in the space and time domains [7]. The multiuser diversity is an efficient way to maximally utilize spatial multiplexing since each path experiences different channel condition [8], [9]. Therefore we investigate efficient spatial multiplexing for both cases: single-user transmission and multiuser transmission.

To the best of our knowledge, there have been no works regarding multiuser transmission in 802.11 environments except directional antennas. In [10], using directional antennas in ad-hoc networks increases the network capacity. Our new framework needs support of a subchannel assignment algorithm. Some related works like [8] and [9] exploit substream assignment for MIMO cellular systems. The approach in [8] uses round robin scheduling after selecting a set of users in advance that has the same transmit antennas in number. In [9], we extended it to the general proportionally fair and maximal capacity schedulers for a MIMO system. Unlike those works, the scheduling algorithm in this work considers transmission duration for user grouping.

Although the existing 802.11 system supports a single user transmission, our framework does not require fundamental change of MAC architecture. Here we do not consider RTS-CTS exchange, ACK policy and uplink transmission. The multiuser transmission over the uplink is difficult because it is impossible to acquire synchronization among transmit stations for MIMO antennas. On the other hand, CTS and ACK procedures over the uplink can be solved by AP coordination of transmission time, which requires further considerations.

We organize the remainder of this paper as follows. Section II illustrates the system model. Section III analyzes multiuser transmission by comparing it with single-user transmission, followed by numerical results. Section IV applies a scheduling algorithm and investigates its performance through simulation. Finally, Section V concludes this paper with comments about MIMO perspective of 802.11 systems.

II. SYSTEM MODEL

We consider a 802.11 system where each terminal and AP have N transmit and N receive antennas. We assume that there are N i.i.d. logical subchannels between each terminal and AP, and they can be distributed to multiple users at the same time as shown in Fig. 1. More detailed MIMO channel model is found in [8]. The 802.11 specification defines
feasible data rates according to the modulation type and the coding rate. While 802.11b operates at 1, 2, 5.5, and 11Mbps, 802.11a/g can operate at 6, 9, 12, 18, 24, 36, 48, and 54Mbps. Transmission rate is selected by a link adaptation scheme that is widely studied for single antenna systems [11], [12]. In our system model, we assume each transmit antenna can determine its data rate independently of other transmit antennas. It means that subchannels may have different data rates according to their own’s link adaptation. Here we do not focus on the link adaptation scheme.

The general procedure to transmit an MPDU (MAC protocol data unit) is RTS-CTS-DATA-ACK, where RTS-CTS is an optional choice [1]. However, RTS and CTS incur overhead when the MPDU size is small or the hidden terminal problem does not hinder transmission. In the legacy system, a mobile terminal responds with ACKs optionally when they receive packets from the AP. To support multiuser transmission, the AP can coordinate the ACK or CTS time for each receiver. Here we do not consider RTS-CTS exchange and ACK policy because multiple transmission requires trivial MAC modification, which is beyond our scope. Fig. 2 shows a simple comparison about MPDU transmission between the single-user and the multiuser transmission. It does not include the other parts since our main consideration is in the transmission duration of MPDUs.

The IEEE 802.11 system uses CSMA/CA (carrier sensing medium access with collision avoidance) as its access mechanism. A random backoff number generated by contending stations determines the number of slots to wait and is decreased by one per contention. The mechanism is also called DCF (distributed coordination function). Whenever the contending stations sense that the link is idle for DIFS (DCF interframe space) interval plus its backoff time, they try transmission. If any two backoff numbers are unlucky the same, they regenerate the backoff number by increasing the upper limit. To give priority to successive frame transmissions such as ACK or fragmented data, they are transmitted after SIFS (short IFS) that is smaller than DIFS. In our analysis, we do not consider the contending period, DIFS and backoff time, but only SIFS period between any two MPDUs for simplicity.

Fig. 1. The multiuser transmission in a MIMO system.

Fig. 2. Comparison between single and multiple transmission.

To support multiuser transmission by MIMO subchannels, the other stations who cannot decode MIMO signals should detect the multiuser transmission. It is solved by adding definition of a common frame header that includes multiple destination addresses and every station can decode regardless of its antenna type. The CSMA/CA mechanism also uses NAV (network allocation vector), a virtual carrier sensing mechanism in the MAC level. Hence, upon reading the frame header, the other nodes except transmitter and receivers set the NAV not to interrupt the current transmission during the NAV duration.

III. PERFORMANCE ANALYSIS

In this section, we analyze the performances for both cases of Fig. 2. For simple analysis, we assume that there are N STAs and they have the same average SNR level. Given MPDUs of fixed size, the transmission duration is determined by the subchannel of minimum data rate unless the data size is adjusted for the channel conditions. First, we investigate the transmission duration of single-user and multiuser transmission without considering the data-size adjustment. Next, we design an enhanced version of single-user transmission, where the data are split into multiple substreams by considering each channel condition. We assume that there are M available data rates and denote them as \( \{ r_1, r_2, \ldots, r_M \} \in R_{tx} \) where \( R_{tx} \) is the data rate set and the element is sorted in ascending order. Also, we define a threshold set \( T_{SNR} = \{ t_1, t_2, \ldots, t_{M-1} \} \) where each element is the SNR threshold as the upper bound supporting each data rate.

A. Single-user transmission

First we calculate the average service time of N STAs in the single-user selection without considering data-size adjustment. Hence, the data rate is determined by the minimum data rate
among that of \( N \) channels. Then \( T_s \) is given as following.

\[
T_s = N \cdot \text{(Average service time of one user)} + (N - 1) \text{SIFS} \\
= N \cdot \sum_{r_{tx} \in R_{tx}} \frac{L/N}{r_{tx}} \Pr(\text{Transmission rate} = r_{tx}) \\
+ (N - 1) \text{SIFS}
\]  

(1)

where \( L \) is the packet length, and \( T_s \) is composed of the service time of \( N \) STAs and \( N - 1 \) times of SIFS periods. The probability of transmission rate \( r_{tx} \) implies that the minimum transmission rate among \( N \) antennas is \( r_{tx} \). So the probability of transmission rate \( r_{tx} \) can be obtained in turn as follows.

\[
\Pr(r_{tx} = r_M) = \left[ \Pr(\text{rate of one antenna} = r_M) \right]^N \\
= \left[ \Pr(\text{SNR} \geq t_{M-1}) \right]^N \\
\vdots \\
\Pr(r_{tx} = r_1) = 1 - \sum_{i=2}^M \Pr(r_{tx} = r_i). 
\]

(2)

B. Multiuser transmission

The average service time of \( N \) STAs in the multiuser selection, \( T_m \), is given by

\[
T_m = \sum_{r_{tx} \in R_{tx}} \frac{L}{r_{tx}} \Pr(\text{Transmission rate} = r_{tx}). 
\]

(3)

To calculate \( T_m \), we need to know the probability that a subchannel (i.e., a transmit antenna) has a transmission rate. We assume that the link adaptation is properly performed, thus each channel condition is already known exactly.

First, we consider \( \Pr(r_{tx} = r_M) \), the probability that every antenna can support the maximum transmission rate \( r_M \), which is expressed by

\[
\Pr(r_{tx} = r_M) = \Pr(a_N = r_M, a_{N-1} = r_M, \ldots, a_1 = r_M). 
\]

(4)

where \( a_i \) is the transmission rate of \( i \)-th antenna. By chain rule, the above is given as following.

\[
\Pr(r_{tx} = r_M) = \Pr(a_N = r_M | a_{N-1} = r_M, \ldots, a_1 = r_M) \\
\ldots \Pr(a_2 = r_M | a_1 = r_M) \Pr(a_1 = r_M).
\]

(5)

The probability \( \Pr(a_1 = r_M) \) can be obtained by excluding the event that every transmission rates of \( N \) antennas are not \( r_M \). Hence we obtain the probability:

\[
\Pr(a_1 = r_M) = 1 - \left[ \Pr(\text{N antennas’ rate} < r_M) \right] \\
= 1 - \left[ \Pr(\text{SNR} < t_{M-1}) \right]^N.
\]

(6)

For \( N - 1 \) remaining STAs, the probability of the second antenna is

\[
\Pr(a_2 = r_M) = 1 - \left[ \Pr(\text{N-1 antennas’ rate} < r_M) \right] \\
= 1 - \left[ \Pr(\text{SNR} < t_{M-1}) \right]^{N-1}.
\]

(7)

Similarly, we can calculate the probabilities for other remaining antennas. Therefore, (4) is given by

\[
\Pr(r_{tx} = r_M) = \prod_{i=1}^N \left[ 1 - \left\{ \Pr(\text{SNR} < t_{M-1}) \right\}^i \right]. 
\]

(8)

Similarly, we obtain the following.

\[
\Pr(r_{tx} = r_m) = \prod_{i=1}^N \left[ 1 - \left\{ \Pr(\text{SNR} < t_{m-1}) \right\}^i \right] \\
- \sum_{i=m+1}^M \Pr(r_{tx} = r_i) \text{ for } (2 \leq m \leq M - 1)
\]

(9)

C. Enhanced single-user transmission

Now we enhance the single-user transmission by splitting the data such that every transmission of the transmit antennas completes at the same time. Therefore we obtain its transmission rate \( r_{tx}^* \) by summing each antenna’s transmission rate. That is, \( r_{tx}^* = \sum_{m=1}^{M} a_i \), where \( a_i (\in R_{tx}) \) is the transmission rate of \( m \)-th antenna. Then we obtain the average service time \( T_s \) as following.

\[
T_s = N \cdot \text{(Average service time of one user)} + (N - 1) \text{SIFS} \\
= N \cdot \sum_{r_{tx} \in R_{tx}} \frac{L}{r_{tx}} \Pr(\text{Transmission rate} = r_{tx}^*) \\
+ (N - 1) \text{SIFS}
\]

(10)

where \( L \) is the packet length, and \( T_s \) is composed of the service time of \( N \) STAs and \( N - 1 \) times of SIFS periods. The sum of probabilities of per-antenna transmission rates becomes the
probability of total transmission rate \( r_{tx} \). Hence the average service time \( T_s \) can be rewritten as follows.

\[
T_s = N \cdot \sum_{a_1 \in R_{tx}} \cdots \sum_{a_M \in R_{tx}} \frac{L}{\sum_{m=1}^{M} a_m} \Pr(a_1, \ldots, a_M) + (N - 1) SIFS
\]  

(11)

**D. Numerical Results**

We compare the multiuser selection with the single-user selection by using the previous results. Assume that \( N \) is 4 and the length of packet is fixed at 1500 bytes. We use the data rate set, threshold set, and SIFS value (16 \( \mu \) sec) given in IEEE 802.11a. For a fixed mean SNR, each antenna follows Gaussian model with 8 dB variation. Fig. 3 shows the cumulative probability function according to transmission rates under average SNR of 20 dB. The multiuser transmission (“Multiple”) has higher probability to transmit at high rate than the single-user transmission (“Single”).

Depicting the average service time of 4 STAs according to the average SNR, Fig. 4 compares the enhanced single-user transmission (“E-single”) with the original version (“Single”) as well as multiuser transmission (“Multiple”). The average service time of multiuser selection is shorter than that of single-user selection because the multiuser selection has more chances to select a good channel. Also, the multiuser selection has no interframe spaces (IFSs) such as SIFS during one transmission interval. In our analysis, three SIFSs, 48 \( \mu \) sec, are added for the single-user selection, but the effect turns to be relatively small according to Fig. 4.

Interestingly, the enhanced single-user transmission has better performance than the multiuser transmission. This is because the link is wasted by different transmission durations of the multiple users, while the enhanced single-user transmission has no such a problem. To compare them widely, we obtained the average service time according to \( N \), the number of antennas (that is equivalent to the number of STAs in our analysis) in Table I. When the average SNR is high (i.e., 20 dB), the multiuser transmission has better performance than the enhanced single-user transmission. However, the performance is reversed when the average SNR is low (i.e., 10 dB).

The reason is that multiuser diversity is not fully utilized in the multiuser transmission in our analysis, especially at small SNR or at small \( N \). This is due to the assumption, for our simple analysis, there are STAs as many as subchannels.

**IV. SCHEDULING ALGORITHM AND SIMULATION RESULTS**

Our analysis thus far reflects the number of antennas but not the multiuser diversity above the number of antennas. Now, we measure the effect of multiuser diversity with a scheduling algorithm by simulation evaluation.

**A. Scheduling Algorithm**

In our analysis, we simply compare the effect of multiuser transmission under the assumption of no RTS-CTS exchange and no ACKs. Such assumptions can be applied to the multimedia streams which need not ACK and RTS-CTS exchange because they are tolerant to a loss. Hence we suppose that an AP has tens of multimedia streams to deliver, and the scheduler chooses a set of appropriate users as many as transmit antennas. For each station, each antenna acquires an available data rate by the link adaptation. Then the scheduler allocates the transmission chances by a scheduling algorithm. In this work, we devise a two-step algorithm as shown in Table II.

The first algorithm selects the most urgent user determined by earliest deadline first (EDF) and assigns the best channel since the multimedia stream is normally sensitive to delay. Instead of EDF, this step can choose a certain user by round robin or other scheduling policies. Second, the scheduler assigns the residual antennas to other users which belong to the same group as the user selected by the first step. The group has user members per each antenna that have similar transmission duration to the firstly selected user. The reason of grouping can be explained by Fig. 2 where the transmission durations for 4 stations are the same. If there exist distinctive differences among the transmission durations of four users, the capacity will decrease due to the link waste. This grouping,
V. Concluding Remarks

In this paper, we investigated a possibility of multiuser transmission for a 802.11 wireless LAN with MIMO antennas. When each antenna performs its own link adaptation independently, the scheduler can exploit multiuser diversity in the space and time domains. To avoid link waste maximally, it selects user-antenna pairs with the same transmission duration. Through analysis and simulation results, we showed that the multiuser transmission system performs better than the legacy single-user selection system when multiuser diversity is fully exploited. It is because the multiuser diversity has more chances to select a good channel and reduces the number of channel access. Also, we designed an enhanced spatial multiplexing mechanism for single-user transmission, which is suitable for small multiuser diversity.

To implement the spatial multiplexing, however, there remain three problems to be solved. First, the proposed wireless LAN system should be with modified MAC structure to support multiple transmission. Second, link adaptation should have a good mechanism to estimate channel condition properly. Last, there exists a fundamental limit in supporting MIMO systems. Since SISO (single-input-single-output) antennas cannot interpret the MIMO signals, MIMO systems may degrade the performance of the SISO terminals. When the MIMO technology is adopted for the 802.11 system after overcoming these problems, it can significantly enhance the system performance.

References


