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Exploiting Multiuser MIMO in the IEEE 802.11 Wireless LAN Systems

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Abstract By adopting multiple-input-multiple-output (MIMO) antenna technologies, IEEE 802.11 wireless LANs are evolving into high speed systems. While only one user can transmit at a time in the conventional IEEE 802.11 systems, we investigate the possibility of multiuser transmission by using MIMO antennas, which is now known as *multiuser MIMO*. The multiuser MIMO technique enables multiple users to receive packets over the downlink simultaneously, but it should be carefully used in the IEEE 802.11 systems for interoperation with non-MIMO legacy terminals. Through analysis and simulation evaluation, we demonstrate that multiuser transmission with a scheduling algorithm and single-user transmission with enhanced spatial multiplexing achieve enhanced performance by exploiting multiuser diversity in the space and time domains. Especially, when the number of stations is large, multiuser transmission shows better performance than enhanced single-user transmission.

Keywords Wireless networking · 802.11 · MIMO · Multiuser diversity · Multiuser transmission · Scheduling

1 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. While 802.11b supports various data rate up to 11 Mbps, 802.11a/g can support data rate up to 54 Mbps by using orthogonal frequency division multiplexing (OFDM) technology [1,2]. Moreover, 802.11 has some standard groups for QoS support (802.11e), security (802.11i), dynamic frequency selection and transmit power control (802.11h), and inter-access point protocol (802.11f). Especially, the 802.11n group has designed a high-throughput wireless LAN by combining multiple-input-multiple-output (MIMO) antennas and wideband adaptive OFDM technology [3].

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In this paper multiuser diversity is extended in space and time domains for a wireless LAN system.

The conventional 802.11 system supports just a single user transmission at once between an access point (AP) and a user station (STA). In this work, we pursue a possibility of multiuser transmission over the downlink (i.e., from an AP to multiple STAs) without changing the MAC architecture. The multiuser transmission is made possible owing to the capability of the MIMO system in creating multiple subchannels.

Generally a MIMO system takes advantage of two types of gains, spatial diversity and spatial multiplexing. First, spatial diversity is used to overcome fading channel condition [4,5]. By receiving the same packet over various paths, the receiver can reconstruct the original packet with higher probability. Instead of exploiting the diversity gain, the system can increase data rate by sending independent 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 maximize the effect of spatial multiplexing since each path experiences different channel condition [8,9]. Therefore we investigate spatial multiplexing for both single-user transmission and multiuser transmission.

Multiuser transmission in IEEE 802.11 environments has been studied in the literature. In [10], the network capacity has been increased by directional antennas in ad-hoc networks. Our new framework needs the support of a subchannel assignment algorithm. Some related approaches like [8] and [9] exploit substream assignment in multiuser MIMO cellular systems. The work in [8] uses round robin scheduling after selecting a set of users in advance with the same number of transmit antennas. In [9], this is extended to a general proportionally fair and maximal capacity scheduler for a MIMO system. Unlike these methods, the scheduling algorithm in this work considers transmission duration by grouping users. Although the existing 802.11 system supports a single user transmission, our framework does not require fundamental change of MAC architecture. We only consider downlink transmission here because the uplink multiuser MIMO is still a challenging problem to achieve synchronization among transmit stations.

We organize the remainder of this paper as follows. Section 2 illustrates the system model. Section 3 analyzes multiuser transmission by comparing it with single-user transmission, followed by numerical results. Section 4 applies a scheduling algorithm and investigates its performance through simulations. Finally, Section 5 concludes this paper with comments about the MIMO perspective in 802.11 systems.

2 System Model

We consider an IEEE 802.11 system where each STA as well as the AP has N transmit and N receive antennas. Assume that there are N i.i.d. logical subchannels between each STA and AP, then they can be distributed to multiple users at the same time, such that a STA accesses to one logical subchannel. More detailed MIMO channel models are given 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 11 Mbps, 802.11a/g can operate at 6, 9, 12, 18, 24, 36, 48, and 54 Mbps. A transmission rate is selected by a link adaptation scheme that is widely studied for single antenna systems [11,12]. In our model, we assume each transmit antenna determines its data rate independently of other transmit antennas. It means that subchannels may have different data rates according to their own link adaptation.

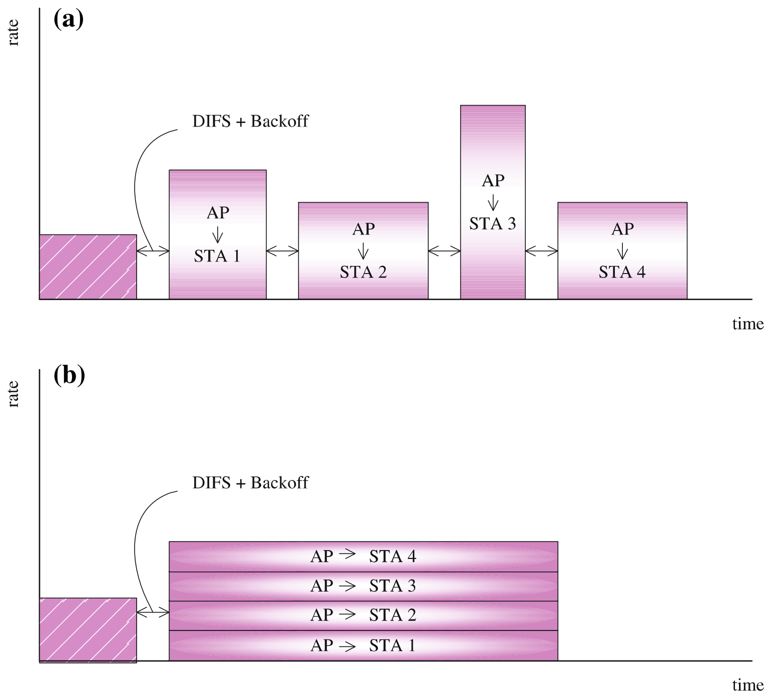

Fig. 1 Comparison between single and multiple transmission. **a** Single-user transmission; **b** Multi-user transmission

The general procedure for an MAC protocol data unit (MPDU) transmission is *RTS–CTS–DATA–ACK*, where *RTS–CTS* is an optional choice [1]. RTS and CTS exchange incurs some overhead when the MPDU size is small and the hidden terminal problem does not occur. In the legacy system, a STA responds with ACKs optionally after they receive packets from the AP. To support multiuser transmission, the AP can coordinate ACK or CTS time for each receiver. Here we do not consider the RTS–CTS exchange and ACK policy, because multiuser transmission requires trivial MAC modification which is beyond our scope. Figure 1 shows a simple comparison for MPDU transmission between single-user and multiuser transmissions. Figure 1a represents that all the channels (antennas) are allocated for one user at a time, while Fig. 1b shows that antennas are allocated for some selected user group according to the given scheduling rule.

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

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

3 Performance Analysis

In this section, we analyze the performances for both cases in Fig. 1. 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 is split into multiple substreams by considering each channel condition. This concept of enhanced single-user transmission has been proposed as per antenna rate control (PARC) in 3GPP [13], and we analyze it for the 802.11 system.

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.

3.1 Single-User Transmission

First we calculate the average service time of serving N STAs by the single-user selection, each with the fixed MPDU length of L. When a user is selected, he is allocated for all the N channels. Note that there are N channels between a user and the AP. Then the AP simply divides the MPDU size of L by N and transmits each segment over each channel. To compare the performance of single user transmission with that of multiuser transmission, we assume that N users are served one by one.

Letting the minimum channel rate among N channels for the selected user be r_{tx}, the MPDU transmission is complete after the serving time of $L/(Nr_{tx})$. Therefore we obtain T_s to finish N jobs as follows:

$$\begin{aligned} T_s &= N \cdot (\text{Average service time for one user}) + (N-1)\, SIFS \\ &= N \cdot \sum_{r_{tx} \in R_{tx}} \frac{L/N}{r_{tx}} \Pr(\text{Transmission rate} = r_{tx}) + (N-1)\, SIFS \end{aligned} \quad (1)$$

where 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} can be obtained as follows.

$$\begin{aligned} \Pr(r_{tx} = r_M) &= [\Pr(\text{rate of one antenna} = r_M)]^N \\ &= \left[\Pr(\text{SNR} \geq t_{M-1})\right]^N \\ &\quad \ldots \end{aligned}$$

$$\Pr(r_{tx} = r_m) = [\Pr(\text{rate of all antennas} \geq r_m)]^N - \sum_{i=m+1}^{M} \Pr(r_{tx} = r_i) \quad (2)$$

$$= \left[\Pr(\text{SNR} \geq t_{m-1})\right]^N - \sum_{i=m+1}^{M} \Pr(r_{tx} = r_i)$$

$$\cdots$$

$$\Pr(r_{tx} = r_1) = 1 - \sum_{i=2}^{M} \Pr(r_{tx} = r_i).$$

3.2 Multiuser Transmission

In this case, the AP transmits the MPDU size of L for N users simultaneously. The service time ends when the user with minimum rate among N users finish receiving the MPDU. The average service time of N STAs in the multiuser selection, T_m, is given by

$$T_m = \sum_{r_{tx} \in R_{tx}} \frac{L}{r_{tx}} \Pr(\text{Transmission rate} = r_{tx}). \quad (3)$$

To calculate T_m, we need to know the probability that a subchannel (i.e., a transmit antenna) has a specific transmission rate. Assuming that the link adaptation is appropriately fulfilled, the AP knows the channel condition exactly before transmission.

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

$$\Pr(r_{tx} = r_M) = \Pr(a_N = r_M, a_{N-1} = r_M, \ldots, a_1 = r_M), \quad (4)$$

where a_i is the transmission rate of i-th antenna. From the chain rule, the above is rewritten as follows.

$$\Pr(r_{tx} = r_M) = \Pr(a_N = r_M | a_{A-1} = r_M, \ldots, a_1 = r_M) \cdots \Pr(a_2 = r_M | a_1 = r_M) \Pr(a_1 = r_M). \quad (5)$$

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

$$\Pr(a_1 = r_M) = 1 - \left[\Pr(\text{every antenna rate} < r_M)\right] = 1 - \left[\Pr(\text{SNR} < t_{M-1})\right]^N. \quad (6)$$

Regarding $N-1$ remaining STAs,

$$\Pr(a_2 = r_M) = 1 - [\Pr(\text{N} - 1 \text{ antennas' rate} < r_M)] = 1 - \left[\Pr(\text{SNR} < t_{M-1})\right]^{N-1}. \quad (7)$$

Similarly, we can calculate the probabilities regarding the other remaining antennas. Therefore, Eq. 4 is given by

$$\Pr(r_{tx} = r_M) = \prod_{i=1}^{N} \left[1 - \{\Pr(\text{SNR} < t_{M-1})\}^i\right]. \quad (8)$$

Also, we obtain

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

$$\Pr(r_{tx} = r_1) = 1 - \sum_{i=2}^{M} \Pr(r_{tx} = r_i). \tag{9}$$

3.3 Enhanced Single-User Transmission

Now we enhance the single-user transmission by adjusting the data length over each channel adaptively to make every transmission of the transmit antennas complete at the same time. This means that a good channel will be allocated a higher data transmission rate than that allocated in a bad channel. Therefore we obtain the transmission rate r^s_{tx} by summing each antenna's current transmission rate. That is, $r^s_{tx} = \sum_{m=1}^{N} \alpha_i$ where α_i is the transmission rate of m-th antenna and $r^s_{tx} \in R'_{tx}$. Then we obtain the average service time T_s as follows.

$$T_s = N \cdot (\text{Average service time for one user}) + (N-1)\, SIFS$$
$$= N \cdot \sum_{r^s_{tx} \in R'_{tx}} \frac{L}{r^s_{tx}} \Pr\left(\text{Transmission rate} = r^s_{tx}\right) + (N-1)\, SIFS. \tag{10}$$

As the combinatorial sum of each antenna's transmission rate becomes the total transmission rate r^s_{tx}, T_s can be rewritten as follows.

$$T_s = N \cdot \sum_{r^s_{tx} \in R'_{tx}} \frac{L}{\sum_{m=1}^{N} \alpha_m} \Pr\left(\alpha_1 + \cdots + \alpha_N = r^s_{tx}\right) + (N-1)\, SIFS. \tag{11}$$

3.4 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 1,500 bytes. We use the data rate set, threshold set, and SIFS value (16 µs) given in IEEE 802.11a [14]. For a fixed mean SNR, each antenna follows Gaussian model with 8dB variation. Figure 2 shows the cumulative probability distribution function (CDF) according to the transmission rate under the average SNR of 20 dB. The multiuser transmission ("Multiple") has higher probability of transmission than the single-user transmission ("Single") at high rates.

Depicting the average service time of four STAs according to the average SNR, Fig. 3 compares the enhanced single-user transmission ("E-single") with the original version ("Single") as well as the 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 in selecting 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 µs, are added for the single-user selection, but the effect turns out to be relatively small as shown in Fig. 3.

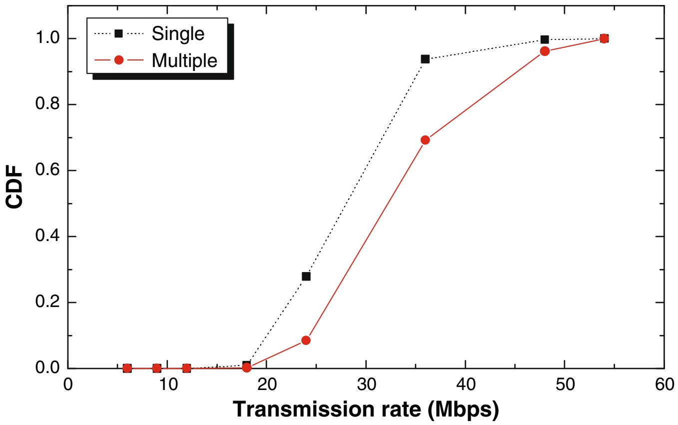

Fig. 2 Cumulative distribution function (average SNR = 20 dB)

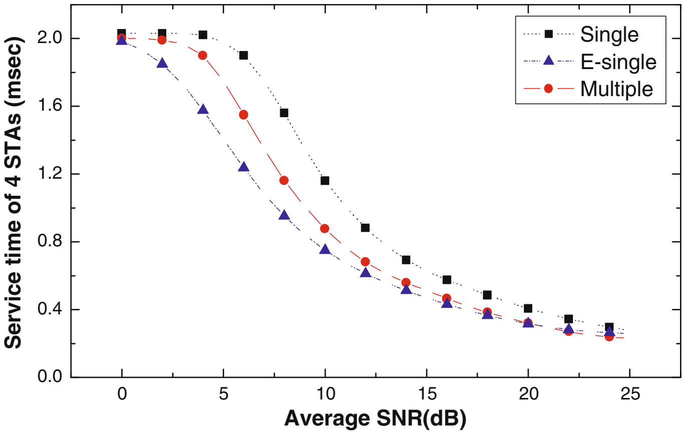

Fig. 3 Average service time of four STAs (N = 4)

Interestingly, the enhanced single-user transmission outperforms the multiuser transmission. This is because different transmission durations of the multiple users linger the finishing time, which make some channels idle for some time resulting link waste, while the enhanced single-user transmission has no such a problem. Note that in multiuser transmission the finishing time is affected by the worst channel user because of the assumption of transmitting the same size of frame.

To compare them, we obtained the average service time according to N and show the results in Table 1. When the average SNR is high (i.e., 20 dB), the multiuser transmission shows 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 has not been fully utilized in the multiuser transmission in our analysis, especially at small SNR or small N. This is caused by the assumption that there are STAs as many as transmission antennas at the AP.

Table 1 Average service time according to *N*

N	SNR = 10 dB		SNR = 20 dB	
	E-single	Multiple	E-single	Multiple
4	0.751	0.878	0.316	0.321
6	0.764	0.880	0.335	0.323
8	0.781	0.881	0.354	0.323
10	0.799	0.881	0.374	0.323
12	0.817	0.881	0.394	0.323

4 Scheduling Algorithm and Simulation Results

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

4.1 Scheduling Algorithm

In our analysis, we simply compare the effect of multiuser transmission under the assumption of neither RTS–CTS exchange nor ACKs. Such assumptions can be applied to the multimedia streams which need not ACK and RTS–CTS exchange because they are tolerant to loss. Suppose that an AP has dozens of streams to deliver, and the scheduler chooses a set of appropriate users as many as transmit antennas. For a STA, a corresponding antenna at the AP acquires an available data rate by the link adaptation. Then the scheduler decides the transmission order according to its own algorithm. In this work, we devise a two-step algorithm as shown in Table 2.

First, this algorithm selects the most urgent user determined by Earliest Deadline First (EDF) and assigns the best channel (i.e., antenna) since the delay sensitive traffic normally requires high and stable bandwidth. Unlike EDF, this step can choose a certain user by round robin or some other scheduling policies. Second, the scheduler assigns the residual antennas to other users which belong to the same group as the user selected in the first step. Each group contains some users for each antenna that require similar transmission duration to the firstly selected user. The reason of grouping can be explained in Fig. 1 where the transmission durations for four stations are the same. If there exist distinctive difference among the trans-

Table 2 Scheduling algorithm

A. Urgent-user scheduling:

1. Select an urgent user by EDF
2. Assign a best channel to the urgent user
3. Group users per antenna with transmission duration similar to this user

B. Fit-user selection:

4. For each residual antenna, select the most urgent user belonging the group

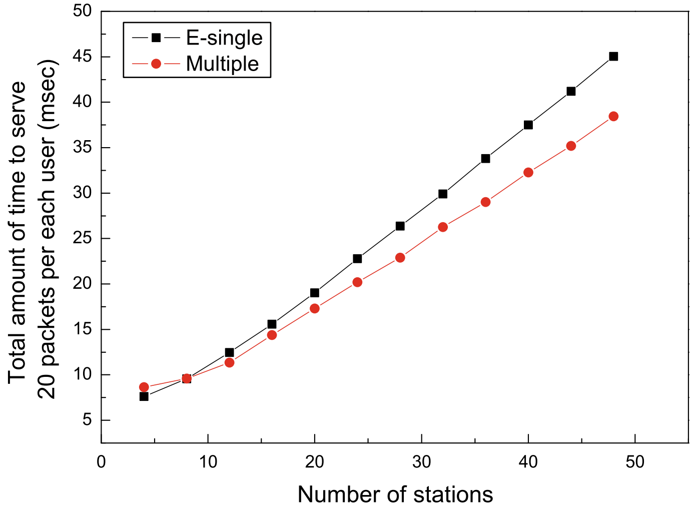

Fig. 4 Simulation comparison between single-user and multiuser selections for 2 × 2 MIMO system

mission durations of four users, the capacity decreases due to the unbalanced link use. This grouping, together with the multiuser diversity, improves the performance of multiuser transmission, compared to the analysis results. In the second step, the most urgent user belonging to the same group is selected per antenna. Thus, the scheduler in the AP chooses a destination station per antenna.

4.2 Simulation Results

To evaluate the scheduling algorithm for the multiuser transmission, we perform simulations and compare the simulation results with that of the enhanced single-user transmission without taking any contention period into account. We assume that the AP only exploits the link until it transmits 20 packets per station.[1] We also suppose that the eight data rates of 802.11a/g are available and packets are generated by Poisson process with the mean interarrival time of 1 ms without experiencing any queueing drop. Each receive antenna has a channel gain following a Gaussian distribution of which mean is uniformly distributed between 0 and 25 dB with 8 dB variation. We change the number of STAs from 8 to 48.

Figures 4 and 5 plot the total amount of time to serve 20 packets for each station, which is averaged for 1,000 iterations, with 2 × 2 and 4 × 4 MIMO systems, respectively. Both cases show a similar tendency for the enhanced single-user ("E-single") and the multiuser transmission ("Multiple"). As shown in Fig. 3, enhanced single-user transmission outperforms multiuser transmission when the number of STAs is less than 8 for 2 × 2 MIMO, and 12 for 4 × 4 MIMO. As the number of STAs increases, multiuser transmission shows better performance than enhanced single-user transmission. This implies that the multiuser transmission exploits the channel condition effectively by taking advantage of multiuser diversity with more users involved, thereby resulting in better link utilization.

[1] In actual 802.11e systems, an AP can transmit multiple MPDUs by transmission opportunity [2].

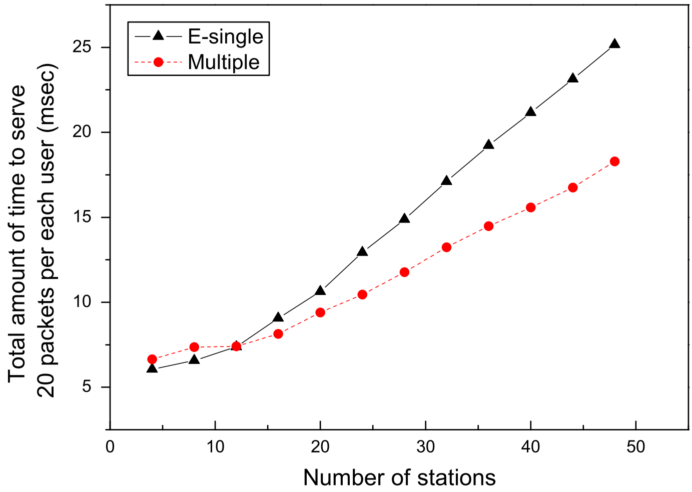

Fig. 5 Simulation comparison between single-user and multiuser selections for 4×4 MIMO system

5 Concluding Remarks

In this paper, we investigated a possibility of multiuser transmission for an IEEE 802.11 wireless LAN with MIMO antennas. When each antenna performs the link adaptation independently, the scheduler can exploit multiuser diversity in the space and time domains. To enhance link utilization, the scheduler selects user-antenna pairs that have similar transmission duration. Through analysis and simulation, we showed that the multiuser transmission system performs better than the legacy single-user selection system when the multiuser diversity is fully exploited. This is because the multiuser diversity has more chances to select a good channel and reduces the number of channel accesses. Also we designed an enhanced spatial multiplexing mechanism for single-user transmission which is suited for overcoming small multiuser diversity.

To implement the spatial multiplexing, however, there remain some problems to be resolved. First, the proposed wireless LAN system should be accompanied by a modified MAC protocol that supports multiple transmissions. Second, link adaptation should have a good channel estimation mechanism for each antenna. Last, as single-input-single-output (SISO) antennas cannot interpret MIMO signals, MIMO systems may degrade the performance of SISO terminals. When the MIMO technology is adopted for the 802.11 system after overcoming these problems, it can significantly enhance overall system performance.

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