Capacity Analysis of Simple and Opportunistic Feedback Schemes in OFDMA Systems

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***Abstract*— We mathematically analyze the system capacity of one simple feedback scheme and two opportunistic feedback schemes: simple-feedback, max-feedback, and max-n-feedback schemes, in orthogonal frequency division multiple access (OFDMA) systems. The maximum signal-to-noise ratio (SNR) scheduling strategy can be used as a scheduling criterion at base stations (BSs). In the simple-feedback scheme, each user sends the received SNRs of all sub-bands to the BS for frequency domain scheduling (FDS) at the BS. In two opportunistic feedback (OFB) schemes: max-feedback and max-n-feedback schemes, each user sends the reduced number of SNR values among the SNR values of all sub-bands in order to reduce the feedback overhead. In this paper, we derive the system capacity of the simple-feedback and max-feedback schemes in a closed-form. In addition, we derive the upper-bound of the system capacity of the max-n-feedback scheme. The analytical results agree with computer simulation results. Furthermore, the results show that the OFB schemes can reduce the feedback overhead, while the multiuser diversity can be maintained as the number of user increases.**

I. Introduction

Knopp and Humblet [1] first introduced multiuser diversity as a means to provide diversity against channel fading in multi-user communication systems. The performance gain of multiuser diversity increases as the number of active users in the system becomes large [2]. However, the feedback overhead also increases with an increasing number of users.

Various approaches have been proposed to reduce feedback overhead. A multiuser diversity scheme using quantized channel feedback was proposed and multiuser diversity gain could still be achieved even with a few quantization levels (or threshold) [3]. On the other hand, various opportunistic feedback (OFB) schemes have been proposed [4]–[6]. In the OFB schemes, users send a feedback message if their SNR values are greater than a threshold. Through these schemes, the feedback overhead can be effectively reduced while multiuser diversity gain is maintained. However, in the OFB schemes, the scheduler selects one user with the maximum signal-to-noise ratio (SNR) value among the users who sent their SNR values to the BS. A fairness problem can occur here because the users near BS transmit their SNR values in most cases when the same threshold is used among all users. Furthermore, the number of users who feed back their channel gain information varies and the amount of feedback overhead is time-varying. Practical systems require the signaling channel bandwidth to be fixed.

The above feedback overhead reduction schemes have been mainly proposed for single-carrier systems. However, orthogonal frequency division multiplexing (OFDM) based wireless communication systems are being considered for next generation wireless communication systems [7]–[13]. In these systems, the scheduler can exploit the frequency domain selectivity of wireless channel and the time domain selectivity. All subcarriers are divided into several sub-bands and each sub-band is allocated to users. The channel response of each sub-band can be considered as a flat fading channel. However, this frequency domain scheduling (FDS) requires a large amount of feedback information for indicating the channel state information over frequency domain. Thus, the feedback overhead reduction schemes have been proposed [14]–[17]. However, the previous work did not provide the rigorous mathematical analysis of the system capacity of the opportunistic feedback schemes in OFDMA systems. They performed computer simulations or showed limited approximate analysis of the system capacity.

In this paper, we introduce one simple feedback scheme and two opportunistic feedback schemes and mathematically analyze the capacity of the simple feedback scheme and the two opportunistic feedback schemes in OFDMA systems. Through analysis in this paper, we can estimate the relation between feedback overhead and capacity gain and expect the effect of the reduced feedback overhead on the multiuser diversity gain in the OFDMA systems. The rest of this paper is organized as follows: In Section II, we introduce one simple and two opportunistic feedback schemes in OFDMA systems and compare these schemes. In Section III, we analyze the average system capacity with the three different feedback schemes. In Section IV, the performance of the three different feedback schemes is compared with simulation results. Finally, conclusions are presented in Section V.

II. System Model

Fig. 1 shows a downlink OFDMA system with U mobile users served by a base station (BS). Each user channel follows an i.i.d Rayleigh fading channel for mathematical simplicity. The entire frequency band is divided into N sub-bands and each sub-band is assumed to experience frequency-flat fading. The fading of each sub-band is assumed to be independent. The signal received in the i-th sub-band at user u is given by

$$y_{u,i} = h_{u,i} s_i + n_{u,i} \ (1 \le u \le U, 1 \le i \le N), \tag{1}$$

where $h_{u,i}$ and $n_{u,i}$ represent the channel coefficient and the thermal noise at the i-th sub-band of the u-th user. The wireless channel is assumed to be Rayleigh-distributed, i.e., $h_{u,i} \sim \mathcal{CN}(0,1)$, and $n_{u,i} \sim \mathcal{CN}(0,N_0)$. The term s_i indicates the transmitted signal with $\mathbb{E}[|s_i|^2] = P$ from the BS through the i-th sub-band . In fact, a sub-band consists of several subcarriers in real systems. However, in this paper, we assume that each sub-band consists of one-subcarrier because each sub-band experiences frequency-flat fading and all subcarriers in the sub-band have the same SNR value. The received SNR at user u in the i-th sub-band is given by $\textit{SNR}_{u,i} \triangleq |h_{u,i}|^2 P/N_0$. Therefore, the probability density function (PDF) $f_s(x)$ and the cumulative density function (CDF) of the received SNR of the i-th sub-band at the u-th user are given by

$$f_s(x) = \frac{1}{\rho} \exp\left(-\frac{x}{\rho}\right), \tag{2}$$

$$F_s(x) = 1 - \exp\left(-\frac{x}{\rho}\right), \tag{3}$$

where $\rho = P/N_0$ is the input SNR. Note that the random variables representing the received SNR are i.i.d not only for $u = 1, \cdots, U$ but also for $i = 1, \cdots, N$.

If each user feedbacks the SNR values of all sub-bands to the BS, the total amount of required feedback per user becomes $(N \cdot Q)$ bits, where Q indicates the required bits for quantizing the SNR value of each sub-band. This is called the ***simple-feedback*** scheme. The feedback overhead of the simple feedback strategy increases proportionally as the number of users increases. On the other hand, if we consider an opportunistic feedback scheme where each user feedbacks the SNR values of some sub-bands, not all sub-bands, then the feedback overhead can be reduced. For example, if each user feedbacks the maximum SNR values among N sub-bands and the index of the sub-band, then the total amount of required feedback per user becomes $(Q + \log_2 N)$. This is called the ***max-feedback*** scheme. This scheme can greatly reduce the feedback overhead; however, it may induce a scheduling outage event for a specific sub-band especially when there exist a few users in a cell. The scheduling outage event represents the case that no feedback is received for a specific sub-band. In the scheduling outage event, the scheduler may assume that the previous best user remains optimal. However, in this paper, we assume that the BS does not transmit any data in the case of a scheduling outage event. Finally, if each user feedbacks n higher SNR values among N sub-bands, the total amount of required feedback per user becomes $(n \cdot (Q + \log_2 N))$. This scheme is called the ***max-n-feedback*** scheme. This scheme is in fact the generalized version of the max-feedback scheme.

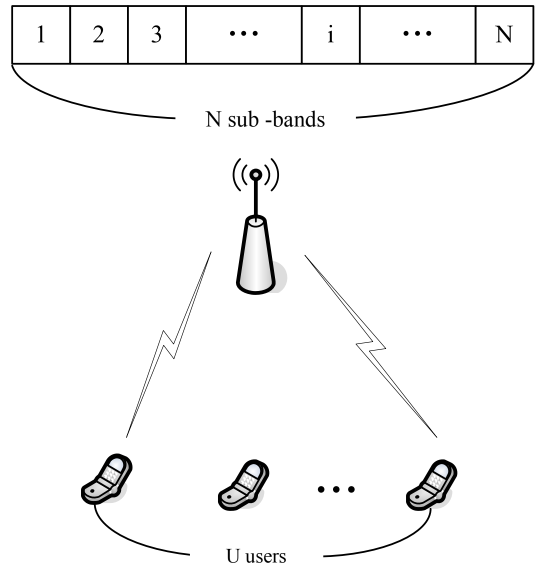

Fig. 1. System model

For each sub-band, the scheduler at the BS selects one user with the largest signal-to-noise ratio (SNR) among the users who sent their SNR value of the sub-band. The capacity of the i-th sub-band is defined as:

$$C_i \triangleq \log_2 \left(1 + \max_{1 \le u \le U_i} \widetilde{\textit{SNR}}_{u,i}\right), \tag{4}$$

where U_i denotes the number of users who sent the SNR value for the i-th sub-band and $\widetilde{\textit{SNR}}_{u,i}$ indicates the SNR value which was sent from the u-th user for the i-th sub-band. When the simple-feedback scheme is used, U_i is always equal to U and $\widetilde{\textit{SNR}}_{u,i}$ has the same distribution as the received SNR at each user, $\textit{SNR}_{u,i}$. However, in the other two feedback schemes, each user sends the SNR values which were selected among the SNR values of N sub-bands and the SNR values reported from each user have different distributions.

As noted before, the $\textit{SNR}_{u,i}$ is i.i.d for $1 \le i \le N$ and for each user. Hence, we focus on the capacity analysis of the i-th sub-band since the other sub-bands have the identical throughput. In this paper, we assume that each of BS and mobile users has a single antenna. However, the system with multiple antennas can be analyzed in a similar way.

III. Information Theoretic Capacity of Three Feedback Schemes

Hereafter, we derive an analytical expression for the average capacity using Eq. (4). The average capacity of three feedback schemes can be written as:

$$\mathbb{E}\left[C_i\right] = \mathbb{E}\left[\log_2\left(1 + \max_{1\le u\le U_i} \widetilde{SNR}_{u,i}\right)\right]. \quad (5)$$

Using the order statistics, the PDF of $\max_{1\le u\le U_i} \widetilde{SNR}_{u,i}$ is given as [18]:

$$f_{\max,U_i}(x) = U_i f_{\tilde{s}}(x) F_{\tilde{s}}^{U_i-1}(x), \quad (6)$$

where $f_{\tilde{s}}(x)$ and $F_{\tilde{s}}^{U_i-1}(x)$ indicate the PDF and the cumulative density function (CDF) of the SNR which was sent from the users for the i-th sub-band, respectively. For a given feedback strategy, as mentioned before, the distribution of the $\widetilde{SNR}_{u,i}$ is the same for all users since we assume that all user have identical channel characteristics.

A. Simple-Feedback Scheme

In the simple-feedback scheme, U_i is equal to U and $\widetilde{SNR}_{u,i}$ has the same distribution as $SNR_{u,i}$, which was given in Eq. (2). Hence, the average capacity is obtained as:

$$\begin{aligned}
\mathbb{E}\left[C_i^{SF}\right] &= \mathbb{E}\left[\log_2\left(1 + \max_{1\le u\le U} SNR_{u,i}\right)\right] \\
&= \int_0^\infty \log_2(1+x)\cdot U\left(1-e^{(-x/\rho)}\right)^{U-1}\frac{1}{\rho}e^{(-x/\rho)}dx \\
&= \frac{U}{\rho\ln(2)}\int_0^\infty \ln(1+x)\cdot\sum_{k=0}^{U-1}\binom{U-1}{k} \\
&\quad \times(-1)^k e^{-\frac{x}{\rho}(k+1)}dx \\
&= U\log_2(e)\sum_{k=0}^{U-1}\binom{U-1}{k}\frac{(-1)^k}{(k+1)}e^{\frac{k+1}{\rho}}E_1\left(\frac{k+1}{\rho}\right) \quad (7)
\end{aligned}$$

where we use the binomial expansion and the integral equality defined as [19]:

$$\int_0^\infty e^{-\mu x}\ln(1+\beta x)dx = \frac{1}{\mu}e^{\mu/\beta}E_1\left(\frac{\mu}{\beta}\right). \quad (8)$$

Note that there exists no scheduling outage in the simple feedback scheme because each user sends SNR values for all sub-bands.

B. Max-Feedback Scheme

In this feedback scheme, each user selects the sub-band with the largest channel gain among N sub-bands and sends back the index of the sub-band and its SNR value to the BS. Thus, the PDF and CDF of the received SNR from each user regardless of the index of the sub-band is given as:

$$\begin{aligned}
f_{\tilde{s}}^{\max}(x) &= N f_s(x) F_s^{N-1}(x), \quad (9) \\
F_{\tilde{s}}^{\max}(x) &= F_s^N(x), \quad (10)
\end{aligned}$$

where $f_s(x)$ and $F_s(x)$ denote the PDF and CDF of the received SNR at users for a sub-band. We also focus on the i-th sub-band. Let U_i users have the largest SNR values on the i-th sub-band and want to be scheduled on that sub-band. The scheduler at the BS selects one user which has the largest SNR value among U_i users and the average capacity for a given U_i is given as:

$$\begin{aligned}
\mathbb{E}\left[C_i^{\max}(U_i)\right] &= \mathbb{E}\left[\log_2\left(1 + \max_{1\le u\le U_i} \widetilde{SNR}_{u,i}\right)\right] \\
&= \int_0^\infty \log_2(1+x)\cdot U_i\left[F_{\tilde{s}}^{\max}(x)\right]^{U_i-1} f_{\tilde{s}}^{\max}(x)dx \\
&= \int_0^\infty \log_2(1+x)\cdot NU_i\left(1-e^{(-x/\rho)}\right)^{NU_i-1}\frac{1}{\rho}e^{(-x/\rho)}dx \\
&= \frac{NU_i}{\rho\ln 2}\int_0^\infty \ln(1+x)\cdot\sum_{k=0}^{NU_i-1}\binom{NU_i-1}{k} \\
&\quad \times(-1)^k e^{-\frac{x}{\rho}(k+1)}dx \\
&= \frac{NU_i}{\ln 2}\cdot\sum_{k=0}^{NU_i-1}\binom{NU_i-1}{k}\frac{(-1)^k}{(k+1)}e^{\frac{k+1}{\rho}}E_1\left(\frac{k+1}{\rho}\right).
\end{aligned} \quad (11)$$

We now derive the average capacity of the max-feedback scheme using Eq. (11). U_i can vary from 0 to U and the probability that each user selects the i-th sub-band is equal to $1/N$. Hence, the average capacity of the max-feedback scheme can be expressed as:

$$\begin{aligned}
\mathbb{E}\left[C_i^{\max}\right] &= \sum_{U_i=0}^{U}\Pr\{U_i|U\}\cdot\mathbb{E}\left[C_i^{\max}(U_i)\right] \\
&= \sum_{U_i=0}^{U}\binom{U}{U_i}\left(\frac{1}{N}\right)^{U_i}\left(1-\frac{1}{N}\right)^{U-U_i}\mathbb{E}\left[C_i^{\max}(U_i)\right],
\end{aligned} \quad (12)$$

where $\Pr\{U_i|U\}$ represents the probability that U_i users among total U users select the i-th sub-band. The i-th sub-band may have the largest SNR value among N sub-bands in the U_i users. We can derive the closed-form expression of the average capacity in the max-feedback scheme by substituting Eq. (11) for $\mathbb{E}\left[C_i^{\max}(U_i)\right]$ in Eq. (12). If $U_i = 0$, a scheduling outage event occurs on the i-th sub-band and Eq. (11) becomes 0. The probability of this event in the max-feedback scheme is given by

$$P_{i,\text{out}}^{\max} = \left(1-\frac{1}{N}\right)^U. \quad (13)$$

This probability decreases as the number of users in a cell increases.

C. Max-n-Feedback Scheme

Thus far, we have analyzed the capacity of both the simple-feedback scheme and the max-feedback scheme. The simple-feedback scheme yields the better performance since each user sends the SNR values of all sub-bands, but it induces significant signaling overhead in uplink. The max-feedback scheme can effectively reduce the signaling overhead through the opportunistic feedback concept which sends the SNR value of the sub-band having the maximum SNR among all sub-bands. However, scheduling outage events may occur especially when there are a few users in a cell. We now analyze the capacity of the max-n-feedback scheme which is a generalized version of the max-feedback scheme. Let $f_{r:N}(x)$ be the PDF of the r-th largest random variable among N random variables which are independently and identically distributed.

$$f_{r:N}(x) = \frac{N!}{(N-r)!(r-1)!} F(x)^{N-r} f(x) \left[1 - F(x)\right]^{r-1}, \quad (14)$$

where $f(x)$ and $F(x)$ denote the PDF and CDF of the individual random variable [18]. If we first select n largest random variables among N random variables and select one among the selected-n random variables, the PDF of the selected random variable is expressed as:

$$f_{\max -n}(x) = \sum_{r=1}^{n} \frac{1}{n} f_{r:N}(x). \quad (15)$$

Each sub-band experiences Rayleigh fading and, in this case, Eq. (14) is rewritten as

$$f_{r:N}(x) = \frac{N!}{(N-r)!(r-1)!} \left(1 - e^{-\frac{x}{\rho}}\right)^{N-r} \cdot \frac{1}{\rho} e^{-\frac{rx}{\rho}}. \quad (16)$$

Hence, the PDF of the $\widetilde{SNR}_{u,i}$ in the max-n-feedback scheme can be expressed as:

$$\begin{aligned} f_{\tilde{s}}^{\max -n}(x) &= \sum_{r=1}^{n} \frac{1}{\rho n} \frac{N!}{(N-r)!(r-1)!} \left(1 - e^{-\frac{x}{\rho}}\right)^{N-r} e^{-\frac{rx}{\rho}} \\ &= \frac{1}{\rho n} \sum_{r=1}^{n} \frac{N!}{(N-r)!(r-1)!} \left(1 - e^{-\frac{x}{\rho}}\right)^{N-r} e^{-\frac{rx}{\rho}}. \end{aligned} \quad (17)$$

Using Eq. (17), we can derive the CDF of the $\widetilde{SNR}_{u,i}$.

$$\begin{aligned} F_{\tilde{s}}^{\max -n}(x) &= \int_0^x f_{\tilde{s}}^{\max -n}(x) dx \\ &= \frac{1}{\rho n} \sum_{r=1}^{n} \frac{N!}{(N-r)!(r-1)!} \cdot \int_0^x \left(1 - e^{-\frac{x}{\rho}}\right)^{N-r} e^{-\frac{rx}{\rho}} dx \\ &= \frac{1}{n} \sum_{r=1}^{n} \frac{N!}{(N-r)!(r-1)!} \sum_{i=0}^{N-r} \binom{N-r}{i} \\ &\quad \times \frac{(-1)^i}{i+r} \left[1 - e^{-\frac{(i+r)x}{\rho}}\right]. \end{aligned} \quad (18)$$

Let U_i users have the largest SNR values on the i-th sub-band and want to be scheduled on that sub-band. The scheduler at the BS selects one user which has the largest SNR value among U_i users and the average capacity for a given U_i is expressed as:

$$\begin{aligned} \mathbb{E}\left[C_i^{\max -n}(U_i)\right] &= \mathbb{E}\left[\log_2\left(1 + \max_{1 \le u \le U_i} \widetilde{SNR}_{u,i}\right)\right] \\ &= \int_0^\infty \log_2(1+x) \cdot U_i \left[F_{\tilde{s}}^{\max -n}(x)\right]^{U_i - 1} f_{\tilde{s}}^{\max -n}(x) dx. \end{aligned} \quad (19)$$

Unfortunately, Eq. (19) has no closed-form solution and we derive a performance bound of Eq. (19). The terms μ and σ^2 denote the mean and variance of the capacity of single user systems, respectively. The average capacity for a given U_i is bounded as [18]:

$$\mathbb{E}\left[C_i^{\max -n}(U_i)\right] \le \mu + \frac{(U_i - 1) \cdot \sigma}{\sqrt{2U_i - 1}}. \quad (20)$$

The mean of the capacity of single user systems is obtained as:

$$\begin{aligned} \mu &= \mathbb{E}\left[\log_2(1+x)\right] \\ &= \int_0^\infty \log_2(1+x) f_{\tilde{s}}^{\max -n}(x) dx \\ &= \frac{1}{n(\ln 2)} \sum_{r=1}^{n} \frac{N!}{(N-r)!(r-1)!} \sum_{i=0}^{N-r} \binom{N-r}{i} \\ &\quad \times \frac{(-1)^i}{i+r} e^{\frac{i+r}{\rho}} E_1\left(\frac{i+r}{\rho}\right). \end{aligned} \quad (21)$$

In addition, the variance of the capacity of single user systems is expressed as:

$$\begin{aligned} \sigma^2 &= \mathbf{Var}\left[\log_2(1+x)\right] \\ &= \mathbb{E}\left[(\log_2(1+x))^2\right] - \mathbb{E}\left[\log_2(1+x)\right]^2 \\ &= \int_0^\infty (\log_2(1+x))^2 f_{\tilde{s}}^{\max -n}(x) dx - \mu^2 \quad (22) \\ &\le \log_2(1 + \mathbb{E}[x])^2 - \mu^2, \quad (23) \end{aligned}$$

where the inequality in Eq. (23) comes from Jensen's inequality based on the fact that $\log((\cdot))^2$ is a concave function and $\mathbb{E}[x]$ is given by

$$\begin{aligned} \mathbb{E}[x] &= \int_0^\infty x \cdot f_{\tilde{s}}^{\max -n}(x) dx \\ &= \frac{1}{n} \sum_{r=1}^{n} \frac{N!}{(N-r)!(r-1)!} \sum_{i=0}^{N-r} \binom{N-r}{i} \frac{(-1)^i \cdot \rho}{(i+r)^2}. \end{aligned} \quad (24)$$

On the other hand, the Shannon capacity can be approximated by $\log_2(1+x) \sim \log_2(x)$ for high values. In this case, Eq. (22)

can be approximated as:

$$\begin{aligned}\sigma^2 &\sim \int_0^\infty (\log_2(x))^2 f_{\tilde{s}}^{\max-n}(x)dx - \mu^2 \\ &= \frac{1}{n}\sum_{r=1}^{n}\frac{N!}{(N-r)!(r-1)!}\sum_{i=0}^{N-r}\left(\begin{array}{c} N-r \\ i \end{array}\right)\cdot\frac{(-1)^i}{(\ln 2)^2(i+r)} \\ &\quad\times\left[\frac{\pi^2}{6}+\left(\mathbf{C}+\ln\left(\frac{i+r}{\rho}\right)\right)^2\right]-\mu^2, \end{aligned} \quad (25)$$

where $\mathbf{C}$ $(= 0.57721566\cdots)$ denotes the Euler constant. In Eq. (25), we use the integral identity expressed as [19]:

$$\int_0^\infty e^{-\mu x}(\ln x)^2 dx = \frac{1}{\mu}\left[\frac{\pi^2}{6}+(\mathbf{C}+\ln(\mu))^2\right]. \quad (26)$$

We now derive the average capacity of the max-n-feedback scheme using Eq. (20). U_i can vary from 0 to U and the probability that each user selects the i-th sub-band is equal to n/N. Hence, the average capacity of the max-n-feedback scheme can be expressed as:

$$\begin{aligned}\mathbb{E}\left[C_i^{\max-n}\right] &= \sum_{U_i=0}^{U}\Pr\{U_i|U\}\cdot\mathbb{E}\left[C_i^{\max-n}(U_i)\right] \\ &= \sum_{U_i=0}^{U}\left(\begin{array}{c} U \\ U_i \end{array}\right)\left(\frac{n}{N}\right)^{U_i}\left(1-\frac{n}{N}\right)^{U-U_i}\mathbb{E}\left[C_i^{\max-n}(U_i)\right], \\ &\le \sum_{U_i=0}^{U}\left(\begin{array}{c} U \\ U_i \end{array}\right)\left(\frac{n}{N}\right)^{U_i}\left(1-\frac{n}{N}\right)^{U-U_i}\cdot\left[\mu+\frac{(U_i-1)\cdot\sigma}{\sqrt{2U_i-1}}\right]. \end{aligned} \quad (27)$$

The probability of scheduling outage event in the max-n-feedback scheme is given by

$$P_{i,\text{out}}^{\max-n} = \left(1-\frac{n}{N}\right)^U. \quad (28)$$

This probability decreases as the number of users in a cell increases and n increases.

IV. Numerical Examples

Figure 2 shows the average capacity of the simple-feedback scheme and the max-feedback scheme for varying the number of users in a cell. The max-feedback scheme approaches to the simple-feedback scheme as the number of users increase. The lines without symbols represent the analytical results and the symbols without lines indicate the simulation results. The analytical results derived in this paper agree very well with the simulation results. When the number of users in a cell is more than 20, the max-feedback scheme can be a very efficient feedback scheme.

Figure 3 shows the average capacity of the simple-feedback scheme and the max-n-feedback scheme for varying the number of users in a cell. We assume that $\rho = 10$dB for all users and the number of sub-bands is equal to 10. Each user sends the largest-2 SNR values among SNR values of all

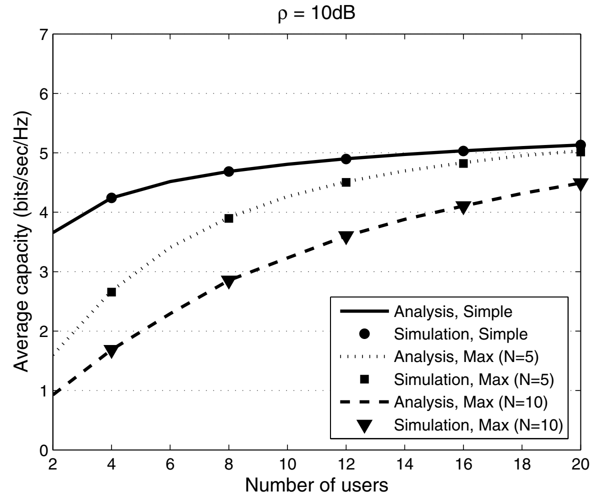

Fig. 2. Average capacity of the simple-feedback scheme and the max-feedback scheme

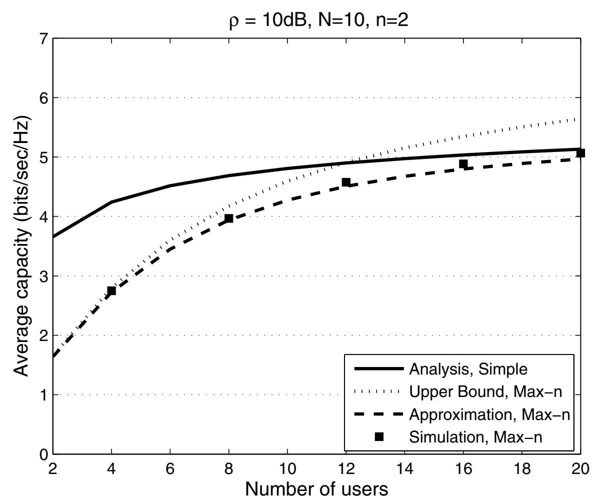

Fig. 3. Average capacity of the simple-feedback scheme and the max-n-feedback scheme

sub-bands ($n = 2$). Comparing Fig. 3 with Fig. 2, we can observe that the max-n-feedback scheme approaches to the simple-feedback scheme more quickly as the number of users in a cell increases. Furthermore, Fig. 3 illustrates that the proposed bound in Eq. (20) is quite useful. Especially, using the approximation of σ as described in Eq. (25) provides an accurate closed-form solution, while the bound of σ as noted in Eq. (23) yields a tight bound only in the case that the number of users in a cell is small.

V. Conclusions

We analyze the average capacities of one simple feedback scheme and two opportunistic feedback schemes: max-feedback and max-n-feedback schemes, in OFDMA systems. We derive the closed-form expression of the average capacity of the OFDMA system for both the simple-feedback scheme and the max-feedback scheme, and propose a tight performance bound using order statistics for the OFDMA system for the max-n-feedback scheme. The numerical examples show that the analytical results agree very well with the simulation results.

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