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Research Article

Throughput Analysis of Band-AMC Scheme in Broadband Wireless OFDMA System

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In broadband wireless Orthogonal Frequency Division Multiple Access (OFDMA) systems where a set of subcarriers are shared among multiple users, the overall system throughput can be improved by a band-AMC mode that assigns each suband, a set of contiguous subcarriers within a coherence bandwidth, to individual user with the better channel quality. As long as channel qualities for the subbands of all users are known a priori, multiuser and multiband gains can be simultaneously achieved with opportunistic scheduling. This paper presents an analytical means of evaluating the maximum system throughput for a band-adaptive modulation and coding (AMC) mode under the various system parameters. In particular, the practical features of resource management for OFDMA system are carefully modeled within the current analytical framework. Our numerical results demonstrate that band-AMC mode outperforms the diversity mode only by providing the channel qualities for a subset of good subbands, confirming the multiuser and multiband diversity gain that can be achieved by the band-AMC mode.

1. Introduction

Demands for high bandwidth multimedia information in the mobile environment have spawned the development of various mobile broadband wireless access (BWA) systems for high-speed communication. Particular examples include the mobile WiMAX, which is based on the IEEE 802.16e Mobile Wireless MAN technologies, and 3GPP's new standards for 3G long-term evolution (LTE). The IEEE 802.16e standard aims to unify the underlying solutions [1], specifying two flavors of OFDM systems: one simply identified as Orthogonal Frequency Division Multiplexing (OFDM), the other Orthogonal Frequency Division Multiple Access (OFDMA). OFDMA is considered to be one of the most spectrally efficient multiple access alternatives for mobile BWA systems. It has the ability to dynamically assign a subset of the subcarriers to individual users, attuning the technology to the particular mobility requirement. This scheme fully takes advantage of multiuser diversity, in conjunction with the frequency diversity inherent in the OFDM scheme. In fact, the mobile BWA system must contend with fluctuations across the frequency band, in addition to time variations. In the multiuser scenarios upon a multicarrier system, a subcarrier in deep fading to one user may be of good quality to another user, which lends support to dynamic subcarrier allocation on improving system throughput [2–5]. The different signal quality (e.g., carrier-to-interference ratio or CIR) seen at each subcarrier governs the capacity of each subcarrier. Ideally, a different modulation and coding level should be selected for each subcarrier in order to maximize the capacity. This particular approach is referred to as an adaptive modulation and coding (AMC) scheme.

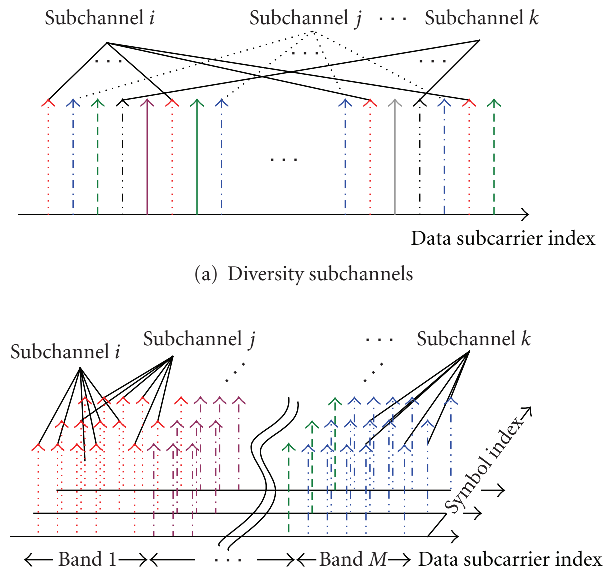
For the fast selective AMC scheme, Channel Quality Indication (CQI) must be reported immediately for all subcarriers within the entire bandwidth, which allows for selecting the appropriate modulation and coding level for each subcarrier without incurring a channel mismatching problem. It usually involves unrealistic feedback overhead, especially under the fast fading channel. Fortunately, however, recent broadband measurements indicate that per-subcarrier information is typically not necessary [2]. Namely, the feedback coefficient is sufficient for a group of several subcarriers in the fast selective AMC process, while the coherence bandwidth of the channel is larger than that of subband. In general, further enhancement can be realized by providing CQI reports a set of optimum subcarriers. This particular approach is specified as a band-AMC mode in IEEE 802.16 Task Group e standard. Due to the frequency-selective characteristics of a time-varying nature in the broadband channel, it is not straightforward to evaluate the average throughput of the OFDMA system, without resorting to the computer simulation. Furthermore, it becomes more involved as many parameters are configured to optimize system performance. For example, the number of bands selected for reporting CQI information is one important parameter that governs overall average system throughput.

The objective of this paper is to develop an analytical means of evaluating the maximum system throughput of band-AMC mode. In particular, practical features of resource management for the OFDMA system are carefully modeled within the proposed analytical framework. We consider order statistics to model the statistical nature of multiuser/multiband diversity in the OFDMA system. Order statistics have been a unique research area for statisticians for some time, with special application in statistical estimation. Recently, a more general case of order statistics has captured the attention of researchers in the area of signal processing and wireless communication systems [6, 7].

The remainder of this paper is organized as follows. In Section 2, the operational concept of band-AMC mode, is described, formulating the scheduling problem under consideration. In Section 3, the maximum average throughput of the band-AMC system is derived, using the order statistics. Then, Section 4 presents the numerical results to demonstrate the advantage of using the band-AMC mode with the sufficient number of CQI reports for the selection bands. Furthermore, the maximum throughput bounds that depend on the multi-user diversity and multiband effect are provided. Finally, concluding remarks are provided in Section 5.

2. System Description

2.1. Diversity Mode versus Band-AMC Mode. In the OFDMA system, all available subcarriers are shared by multiple users in each symbol, as opposed to the OFDM system where all subcarriers must be assigned to a single user. In general, the advantage of the OFDMA system is the multiuser diversity gain that can be obtained by selecting only good subcarriers for individual user, so as to fill the whole band with the multiple users. In other words, a "water-pouring" type of adaptive subcarrier and bit allocation algorithms can be evoked for maximizing system capacity [8]. However, this involves reporting the channel quality indicator (CQI) for each subcarrier of every user. In practice, it may cost a prohibitive amount of overhead, especially under the fast fading channel condition in the mobile communication. Instead, a subset of subcarriers can be randomly selected in each symbol, which can warrant a frequency diversity effect over a frequency-selective fading channel. Toward this end, a subchannel is defined as a basic unit of resource allocation, which consists of a finite number of subcarriers, for example, 48 subcarriers in the IEEE 802.16e standard.



(a) Diversity subchannels

(b) Band-AMC subchannels

Figure 1: Construction of diversity and band-AMC subchannels.

Two different types of subchannel allocation modes are defined in the IEEE 802.16e OFDMA specifications: diversity and band-AMC modes. As shown in Figure 1, the difference between these two modes depends on how subcarriers are selected to form a subchannel. In the diversity mode, the sub-carriers belonging to a subchannel are randomly distributed over the entire bandwidth, facilitating the frequency diversity effect over a frequency-selective fading channel in the broadband OFDMA system. In this case, the channel quality of each subchannel is determined by taking the average SNR over all corresponding subcarriers. In the band-AMC mode, on the other hand, a subchannel consists of a set of contiguous subcarriers and furthermore, a whole channel bandwidth can be divided into the multiple number of subbands (also, referred to as a *band* for short in the sequel). A finite number of contiguous subchannels form a subband, which spreads within the coherence bandwidth, thus requiring only a single value of CQI for each band to specify the channel condition. Therefore, the band-AMC mode does not incur too much feedback overhead cost, especially when a channel condition does not change too rapidly as in a fixed or low mobility environment [3]. It is opposed to the diversity mode which is more appropriate to mobile application under the fast fading channel condition.

2.2. Multiple-Access Interference and CIR Distribution. For users with similar propagation environments, the mean carrier-to-interference ratio can be represented as

$$\frac{C}{I} = \frac{\beta P_T/(r_d/r_0)^n}{\sum_{i\neq d}\beta P_T/(r_i/r_0)^n} = \frac{r_d^{-n}}{\sum_{i\neq d} r_i^{-n}}, \quad (1)$$

where the r_* is the distance separating the transmitter from the receiver and the subscript d denotes the desired user and $i \neq d$ corresponds to the interfering cochannel users, β is the

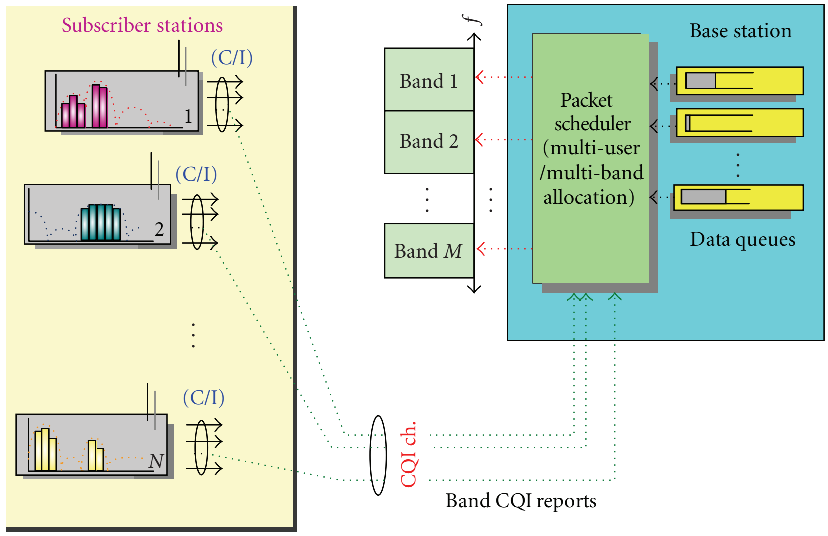


Figure 2: Band-AMC system model.

loss at distance r_0, and n is a pathloss exponent that depends on the propagation environment.

If channel measurements are taken at a number of random locations, then the received amplitude typically follows a Rayleigh distribution. Assuming that instantaneous interference is constant, a carrier-to-interference ratio for each subband is shown to be exponentially distributed in a frequency nonselective channel. In particular, if γ_0 is the mean value of the carrier-to-interference ratio at a specified distance r_d from the transmitter, then the distribution of the observed carrier-to-interference ratio γ has the following probability density function [9]:

$$f(\gamma) = \begin{cases} \dfrac{1}{\gamma_0} e^{-\gamma/\gamma_0}, & \gamma \geq 0, \\ 0, & \text{otherwise.} \end{cases} \tag{2}$$

2.3. Multi-user and Multi-band Scheduling Problem. Assume that there are N active users in a band-AMC system with M subbands. Figure 2 illustrates a system model of a downlink band-AMC scheduler with multiple bands that are shared among the different users. Based on CQI for an individual subband, a packet scheduler in the base station must determine which band to be assigned to each user along with the corresponding MCS level. A reasonable amount of resources must be reserved for CQI report, while ensuring that too much overhead does not overwhelm the overall system efficiency. Meanwhile, in the case that the number of band-AMC users is not sufficiently large in each cell, multi-user and multi-band diversity gain tends to be strictly limited, degrading the overall system throughput performance. Therefore, an optimum portion of band-AMC region must be configured in each frame. In sequel, however, we just focus on the scheduling problem, assuming that some portion of frame is reserved solely for the band-AMC mode users.

Note that each user experiences a varying channel quality for each band. Let $\gamma_{i,j}$ be the carrier-to-interference ratio (CIR) of the band j for the user i. We assume that each user measures the CQI for all bands in terms of the CIR $\{\gamma_{i,j}\}$ and then selects a preferred subset of bands with the μ-best CIR's ($\mu = 1, 2, \ldots, M$) for the CQI feedback. The partial CQI report reduces the feedback overhead cost while trading off the throughput performance. Some users may select the same band within the same time slot. Let Ω_j denote a set of users who have chosen the band j in their CQI reports in the same frame. We assume that the packet scheduler is designed to select a single user for each band so that the overall bandwidth utilization can be maximized, that is,

$$i_j^* = \arg \max_{i \in \Omega_j} \gamma_{i,j} \quad \text{for } j = 1, \ldots, M. \tag{3}$$

This particular scheduler, frequently referred to as a max C/I-scheduler, is one of the most typical opportunistic packet schedulers in the broadband wireless mobile systems.

3. System-Level Performance Analysis

In this section, the average throughput performance of the band-AMC system is evaluated. It is assumed that a full buffer traffic model is used, that is, infinite traffic waiting for each user. Depending on the channel quality, it is assumed that each user belongs to one of L groups. The channel quality of all users in the same group is identically distributed. Let B_t and B_c represent the total bandwidth and coherence bandwidth, respectively. Then, the total number of independent subbands can be given approximately by $M' = \lceil B_t/B_c \rceil$. Note that the optimal number of subbands may be greater than or equal to $\lceil B_t/B_c \rceil$. For example, it has been demonstrated in [5] that the optimum contribution to performance improvement is found for $B_c \approx 4 \cdot B_s$, where B_s denotes the bandwidth of subband. Nevertheless, M' can be still fixed to the minimum number of independent subbands, that is, M' is just large enough to warrant the independence of channel qualities between the adjacent subbands. Determining a proper M' is beyond the scope of this paper.

Now let a vector $\gamma_i^{(l)} = \{\gamma_{i,1}^{(l)}, \gamma_{i,2}^{(l)}, \ldots, \gamma_{i,M'}^{(l)}\}$ represent the sampled values of a channel quality for user i in group l. Note that M' is not always necessarily equal to M. Therefore, we consider two different cases: $M < M'$ and $M = M'$. For the case of $M = M'$, there is no correlation between those samples, that is, the channel quality for each subband is independent of each other. Denoting $m_j^{(l)}$ as the expected value of CIR for band j in group l, then the following probability density function (PDF) for CIR of the corresponding band under the condition that $M = M'$ can be obtained:

$$f_{\gamma_{i,j}^{(l)}}(\gamma) = \frac{1}{m_j^{(l)}} e^{-\gamma/m_j^{(l)}}. \tag{4}$$

For the diversity channel, meanwhile, CIR for each user i in group l is given by taking average of CIRs for all subbands, that is, $\overline{\gamma}_i^{(l)} = (1/M')\sum_{j=1}^{M'}\gamma_{i,j}^{(l)}$. In the case that $\gamma_{i,j}^{(l)}$ are identically distributed over a whole bandwidth, $\{\overline{\gamma}_i^{(l)}\}$ turns out to be the normalized M'-Erlang random variables.

The design of band-AMC system depends on the bandwidth of each subband, channel characteristics, the number of users served by band-AMC mode, the feedback overhead to report the CQI of subbands, and so on. Consider the situation that the bandwidth of subband, B_s, chosen by band-AMC system is subject to the nonflat fading characteristics. This particular situation can be specified by $B_t/M \approx g \times B_c$ for $g > 1$, which corresponds to the case of $M < M'$. Then, the observed channel quality for each subband cannot be represented by (4). When the bandwidth B_s is divided into several adjacent segments, each with the bandwidth of B_c, it can be now approximated as $\Gamma_{i,j}^{(l)} \approx (1/g)\sum_{k=1}^{g}\gamma_{i,(j-1)\cdot g+k}^{(l)}$, $j = 1, 2, \ldots, [M'/g]$. Then, (4) is replaced with the following PDF:

$$\begin{aligned} &f_{\Gamma_{i,j}^{(l)}}(\gamma) \\ &\quad = g \cdot \left\{ f_{\gamma_{i,(j-1)\cdot g+1}^{(l)}}(x) * f_{\gamma_{i,(j-1)\cdot g+2}^{(l)}}(x) * \cdots f_{\gamma_{i,j\cdot g}^{(l)}}(x) \right\} \Big|_{x=g\cdot\gamma}, \end{aligned} \tag{5}$$

where $*$ denotes the convolution operation: $x(t) * h(t) = \int_0^\infty x(\tau)h(t-\tau)d\tau$.

3.1. CQI Report for Band-AMC Mode. Suppose that every band-AMC user feedbacks μ-best CQI reports to the base station in every scheduling interval. To represent the chance that each subband is selected for feedback, define a band selection vector for user i as follows:

$$\Lambda_i^{(l)}(\mu) = \left\{\lambda_{i,1}^{(l)}(\mu), \lambda_{i,2}^{(l)}(\mu), \ldots, \lambda_{i,M}^{(l)}(\mu)\right\}, \tag{6}$$

where $\lambda_{i,j}^{(l)}(\mu)$ is the probability that user i in group l has a preference to the band j within μ chances, that is, $\sum_{j=1}^{M}\lambda_{i,j}^{(l)}(\mu) = \mu$. In the case that samples in the subband are independent and identically distributed, it is obvious that $\Lambda_i^{(l)}(\mu) = \{\mu/M, \mu/M, \ldots, \mu/M\}$. However, consideration must be taken, that the dependence assumption is retained when the γ's are no longer identically distributed, that is, for the *inid* case.

Let $F_{i,(\mu:\mathbf{M}-\{j\})}^{(l)}(\gamma; F)$ denote the CDF of μth-order statistics, exclusive of band j within the entire band pool, where $\mathbf{M}$ represents a band set of the system, that is, $\mathbf{M} = \{1, 2, \ldots, M\}$. Hence, the probability that the user i in group l selects the band j is given by

$$\begin{aligned} \lambda_{i,j}^{(l)}(\mu) &= \Pr\left\{\gamma_{i,j}^{(l)} > \gamma_{i,(M-\mu:\mathbf{M}-\{j\})}^{(l)}\right\} \\ &= \int_0^\infty F_{i,(M-\mu:\mathbf{M}-\{j\})}^{(l)}(\gamma; F) f_{\gamma_{i,j}^{(l)}}(\gamma)d\gamma, \\ &\qquad \text{for } 1 \le \mu \le M-1. \end{aligned} \tag{7}$$

The CDF of the kth-order statistic $\gamma_{(k)}$ is generalized to

$$F_{(k:M)}(\gamma; F) = \sum_{i=k}^{M}\sum_{S_i}\prod_{l=1}^{i}F_{j_l}(\gamma)\prod_{l=i+1}^{M}\left[1 - F_{j_l}(\gamma)\right], \tag{8}$$

where the summation S_i extends over all permutations $(j_1, \ldots, j_n)$ of $1, \ldots, n$ for which $j_1 < \cdots < j_i$ and $j_{i+1} < \cdots < j_n$ [10]. For the distribution of order statistics in the *inid* case, however, the density of every possible order must be found out separately on a case-by-case basis, which makes (8) involve the complicated and tedious calculation, especially as the number of bands increases. Fortunately, an alternative method for computing $F_{(k:M)}(\gamma; F)$ has been provided by Cao and West [7]. It is acceptable to have results and recurrence relations valid in the *iid* case, requiring only simple modification to hold quite generally. For convenience of notation, let $1 - F_i(\gamma)$ denote the $\overline{F}_i(\gamma)$. Starting with

$$F_{1:m}(\gamma) = 1 - \prod_{i=1}^{m}\overline{F}_i(\gamma), \tag{9}$$

they prove the following relation:

$$F_{k:m}(\gamma) = F_{k-1:m}(\gamma) - H_k(\gamma)\left[1 - F_{1:m}(\gamma)\right], \tag{10}$$

where $H_1(\gamma) = 1$, and

$$H_k(\gamma) = \frac{1}{k-1}\sum_{i=1}^{k-1}(-1)^{i+1}L_i H_{k-i} \quad \text{for } k = 2, \ldots, m \tag{11}$$

with

$$L_k = \sum_{i=1}^{m}\left[\frac{F_i(\gamma)}{\overline{F}_i(\gamma)}\right]^k. \tag{12}$$

Now from (7) and (9)–(12), the band selection vector can be directly determined. It is obvious that $\Lambda_i^{(l)}(\mu) = \{1, 1, \ldots, 1\}$ is obtained with $\mu = M$, which corresponds to the case of full CQI feedback.

3.2. Maximum System Throughput in Band-AMC Mode. Let n_l denote the total number of users in group l. The probability that band j is simultaneously selected by $x_j^{(l)}$ users can be written as follows:

$$\Pr\left(x_j^{(l)} = x\right) = {}_{n_l}C_x \cdot \left(\lambda_{i,j}^{(l)}\right)^x \cdot \left(1-\lambda_{i,j}^{(l)}\right)^{n_l - x}, \quad (13)$$

where ${}_{n_l}C_x = n_l!/x!(n_l - x)!$.

Similarly, a vector $\mathbf{x}_j = [x_j^{(1)}, x_j^{(2)}, \ldots, x_j^{(L)}]$ is defined to represent the distribution of order statistics in the corresponding band j. By means of the max C/I-scheduling scheme, the received signal quality γ_j^* is then expressed as

$$\begin{aligned}\gamma_j^* = \max_{\gamma}\Big\{&\gamma_{1,j}^{(1)}, \gamma_{2,j}^{(1)}, \ldots, \gamma_{x_{1,j},j}^{(1)}, \gamma_{1,j}^{(2)}, \gamma_{2,j}^{(2)}, \ldots, \\ &\gamma_{x_{2,j},j}^{(2)}, \ldots, \gamma_{1,j}^{(L)}, \gamma_{2,j}^{(L)}, \ldots, \gamma_{x_{L,j},j}^{(L)}\Big\}.\end{aligned} \quad (14)$$

In general, the optimum signal quality in band j is expected as the number of users selecting the corresponding band increases. By order statistics, the conditional CDF of the received CIR in band j given $\mathbf{x}_j$ can be calculated as

$$\begin{aligned}&\Pr\left(\gamma_j^* < \gamma \mid \mathbf{x}_j\right) \\ &\quad = \Pr\left(\gamma_{1,j}^{(1)} < \gamma\right) \cdots \Pr\left(\gamma_{x_{1,j},j}^{(1)} < \gamma\right) \\ &\qquad \cdots \Pr\left(\gamma_{1,j}^{(L)} < \gamma\right) \cdots \Pr\left(\gamma_{x_{L,j},j}^{(L)} < \gamma\right) \\ &\quad = \prod_{l=1}^{L} \Pr\left(\gamma_{*,j}^{(l)} < \gamma \mid x_j^{(l)}\right),\end{aligned} \quad (15)$$

where $\gamma_{*,j}^{(l)} = \max_\gamma\{\gamma_{1,j}^{(l)}, \gamma_{2,j}^{(l)}, \ldots, \gamma_{x_{i,j},j}^{(l)}\}$ and

$$\Pr(\gamma_{*,j}^{(l)} < \gamma \mid x_j^{(l)}) = \left[F_j^{(l)}(\gamma)\right]^{x_j^{(l)}}. \quad (16)$$

Therefore, the CDF of the received CIR in band j can be expressed as

$$\begin{aligned}S_j(\gamma) &= \Pr\left(\gamma_j^* < \gamma\right) \\ &= \sum_{\forall \mathbf{x}_j} \Pr\left(\mathbf{x}_j = \left[x_j^{(1)}, x_j^{(2)}, \ldots, x_j^{(L)}\right]\right) \\ &\quad \cdot \prod_{l=1}^{L} \Pr\left(\gamma_{*,j}^{(l)} < \gamma \mid x_j^{(l)}\right).\end{aligned} \quad (17)$$

When the existing cellular systems are considered, in which multi-path fading is dominant, the rate function of the Shannon type with the log-based linear relationship between rate and CIR may not be valid. In practice, a link-level simulation is performed in order to determine the required CIR for a given data rate, so as to meet the target frame error rate (FER). Let $\mathbf{A}$ denote a set of MCS levels with the corresponding data rates $\{R_m\}$, with the data rate for MCS level m defined by R_m. To meet the given level of FER, a range of CIR is prescribed for each data rate R_m. More specifically, the CIR required for R_m is prescribed as $\Gamma_m \le \gamma_j^* \le \Gamma_{m+1}$. For the given target FER, the average system throughout of band j is defined as follows:

$$\begin{aligned}U_j &= \sum_{m \in \mathbf{A}} R_m \cdot \Pr\left(\Gamma_m \le \gamma_j^* \le \Gamma_{m+1}\right) \\ &= \sum_{m \in \mathbf{A}} R_m \cdot \left\{S_j(\Gamma_{m+1}) - S_j(\Gamma_m)\right\}.\end{aligned} \quad (18)$$

Table 1: Basic OFDMA system parameters.

Parameters	Value
Frequency	2.3 GHz
System bandwidth	8.75 MHz
FFT size	1024
Number of data subcarriers	768
Number of symbols per frame	Downlink: 27 symbols Uplink: 15 symbols
Channel coding	Convolutional turbo code
Frame duration	5 ms
Symbol duration	115.2 μs
Number of subcarriers per subchannel	48
Number of subcarriers per CQI channel	48

Considering overall bandwidth, therefore, the average throughput of band-AMC system is provided by $U = \sum_{j=1}^{M} U_j$.

4. Numerical Results

Extensive numerical solutions are studied for evaluating a theoretical system throughput in this section. The multi-users diversity effect on system level performance are investigated by varying the number of user groups, for example, $L = 1, 3$. For $L = 3$, users are divided into 3 groups with a mix of 0.2:0.3:0.5. Furthermore, the number of total active users ranges from 10 to 70, that is, $N = 10, \ldots, 70$. We consider the OFDMA parameters for the WiBro system, a mobile version of WiMAX, derived from the IEEE 802.16d wireless MAN standard [1]. The corresponding parameters are listed in Table 1. Furthermore, an example of the transmission scheme for AMC under investigation is summarized in Table 2. In Table 2, data rate R_m is for downlink transmission when the ratio of DL:UL is given by 27:15. It also specifies the minimum required CIR to achieve a target FER of 1%.

It is important to note that system throughput is dependent on not only the mean channel quality but also in the user distribution. In the current numerical analysis, we consider the scenarios with the mean channel qualities given by $\mathbf{m}_1 = (9.1\,\text{dB})$, $\mathbf{m}_3 = (12\,\text{dB}, 10\,\text{dB}, 6\,\text{dB})$ for $L = 1$ and $L = 3$, respectively. To impartially compare the performance according to various users' distributions, the mean channel quality on the same overall cases needs to be kept. Furthermore, it is assumed that $M' = 12$ while $M = 12$, 6, and 3, respectively.

Figures 3 and 4 present a comparison of average throughout for the band-AMC and diversity schemes by varying the number of users with $M = 12$ for $L = 1$ and $L = 3$, respectively. From these results, a multiuser diversity gain is clearly observed, that is, the system throughput increases with the number of users in the system. Furthermore, it is shown that the band-AMC mode outperforms the diversity mode, when each user provides a sufficient number of band CQI reports. For the results in Figure 3, more than 20% of throughput is improved by the band-AMC mode with a full

Table 2: Transmission modes for AMC.

MCS level m	Modulation	Coding rate	CIR for 1% FER (dB)	Data rate* R_m (kbps)
1	QPSK	1/12	−2.2	614.4
2	QPSK	1/6	0.1	1,228.8
3	QPSK	1/3	2.9	2,457.6
4	QPSK	1/2	6.0	3,686.4
5	QPSK	2/3	10.2	4,915.2
6	16QAM	1/2	10.9	7,372.8
7	16QAM	2/3	15.2	9,830.4
8	64QAM	2/3	20.2	14,745.6
9	64QAM	5/6	28.6	18,432

*Data Rate R_m is for DL transmission when the ratio of DL:UL is given by 27:15.

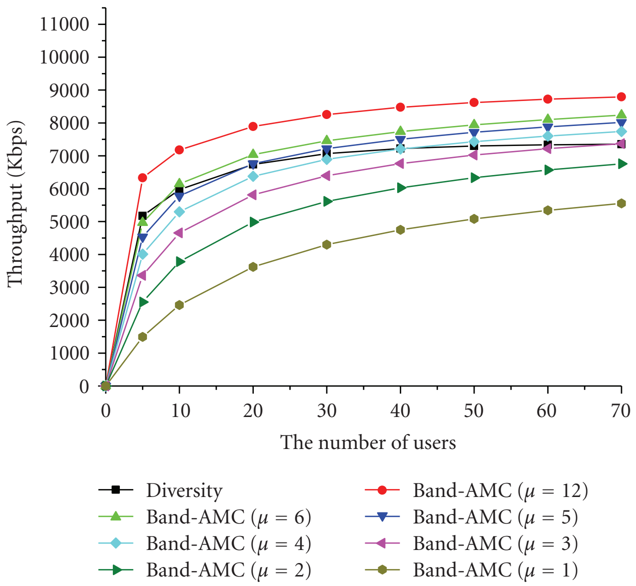


Figure 3: Average system throughput performance: $L = 1$.

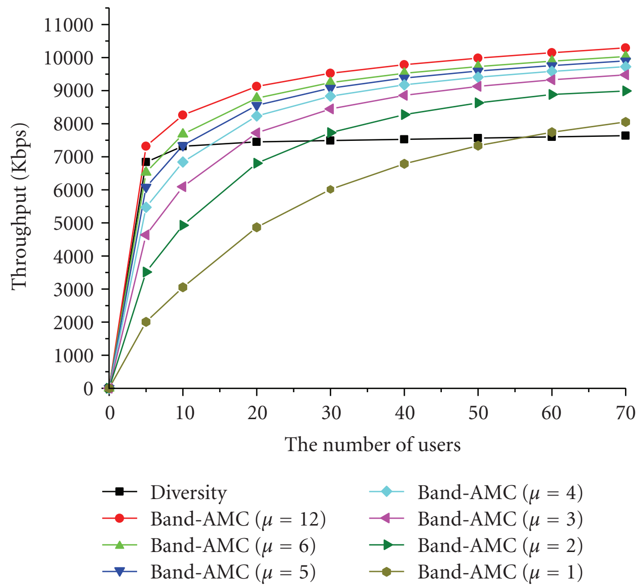


Figure 4: Average system throughput performance: $L = 3$.

CQI report, that is, $\mu = 12$, over the diversity mode. For a partial band CQI report of $\mu \leq 3$, however, the band AMC mode performs worse than the diversity mode, suffering from a significant performance loss as compared to that with full band CQI feedback. For $\mu > 3$, the band-AMC mode outperforms the diversity mode as long as there are a sufficient number of users, implying that its performance is mainly governed by the multi-user diversity gain.

As for $L = 3$, it is observed from Figure 4 that not much multiuser gain can be achieved with the diversity mode. We note that band-AMC mode is almost always superior to the diversity mode, even with a very small number of band CQI reports, as long as there are sufficient number of users in the system. It is also found that the maximum multiuser and multiband diversity gain has been achieved by the band-AMC mode, corresponding to an increase in the average throughput of 2.54 Mbps.

Let us now consider a CQI signaling overhead cost associated the band-AMC mode. If the CQI report period is 30 milliseconds, overhead for full band CQI feedback in WiBro can be approximated by $0.0694N \cdot \mu(\%)$. For example, feedback overhead in the uplink becomes 10.41% when $N = 30$ and $\mu = 5$. In Figures 3 and 4, note that a diminishing gain is observed as the number of band CQI reports increases. Taking the overhead associated with the CQI report for each band into account, a reasonable number of CQI reports exists to warrant the maximum system throughput, for example, $\mu = 5$ and 6, with a sufficient number of band-AMC users. Adopting the same test parameters as in Figure 4, the mean channel quality of each band for each group is given by Figure 5.

Figure 6 presents the probability that each subband is not chosen by any user, that is, the probability of unfilled band, computed for the cases of *iid* and *inid*, respectively. From

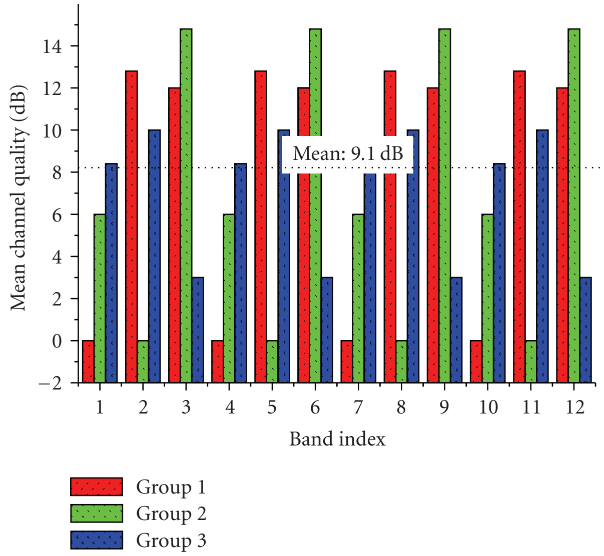


Figure 5: Example of mean channel quality: $L = 3$.

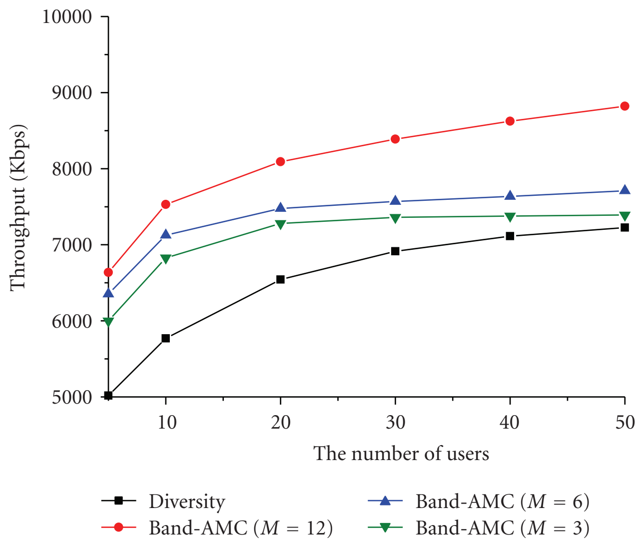


Figure 7: Average system throughput performance as varying the number of bands available($L = 1, M = \mu$).

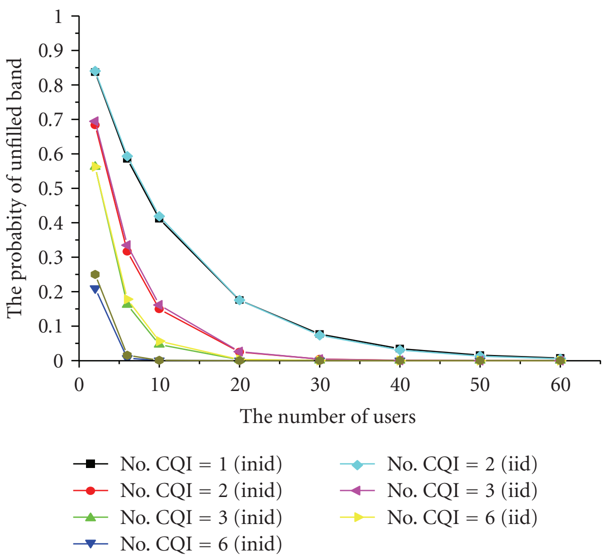


Figure 6: The probability of unfilled band: $L = 3$.

a practical viewpoint, depending on the amount of band CQI reports for each user and the number of users, some subbands may be not selected such that a part of bandwidth is wasted. This particular point is obviously observed in Figure 6. When $N = 10$ and $\mu \leq 6$, more than 40% of the entire bandwidth is not used. Furthermore, it is found that there is not much difference between the *iid* case and *inid* case.

Figure 7 presents a throughput performance as varying the number of bands, that is, $M = 3$, 6, and 12, when $L = 1$ and $\mu = M$. As expected, the band-AMC system with 12 bands demonstrates the best throughput performance. Meanwhile, as the number of bands decreases, throughput curves approach that of the diversity scheme. Since the multi-band diversity effect mainly depends on the number of independent subbands, note that no further improvement will be found even if M is greater than M'.

5. Conclusions

In this paper, the maximum possible throughput of the band-AMC mode in the OFDMA system has been numerically evaluated using the order statistics for various system-level parameters, including the number of band CQI reports, the total number of available bands, and mean channel qualities. A conventional system-level simulation involves too much complexity associated with various physical parameters and thus the proposed analytical approach will be useful for dimensioning the system and configuring the optimal set of parameters. Our numerical results confirm the multiuser and multiband diversity gain that can be achieved by the band-AMC mode. It has been shown that the band-AMC mode outperforms the diversity mode only by providing the channel qualities for a subset of good subbands. Depending on the average CINR for each subband and how fast the channel varies for individual subband, for example, measured in terms of standard deviation of CINR for each subband, the band-AMC and diversity modes can be adaptively combined, so as to maximize the overall system throughput. Toward that end, the current analytical framework can be a useful basis for operation of the band-AMC mode under the varying traffic and CQI report constraints.

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