# A Cooperative Multicast Scheduling Scheme for Multimedia Services in IEEE 802.16 Networks

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***Abstract*—Multicast communications is an efficient mechanism for one-to-many transmissions over a broadcast wireless channel, and is considered as a key technology for supporting emerging broadband multimedia services in the next generation wireless networks, such as Internet Protocol Television (IPTV), mobile TV, etc. Therefore, it is critical to design efficient multicast scheduling schemes to support these multimedia services. In this paper, we propose a cooperative multicast scheduling scheme for achieving efficient and reliable multicast transmission in IEEE 802.16 based wireless metropolitan area networks (WMAN). By exploiting the multi-channel diversity across different multicast groups and user cooperation among group members, the proposed scheme can achieve higher throughput than existing multicast schemes, for subscriber stations in both good and bad channel conditions. In addition, it has good fairness performance by considering the normalized relative channel condition of each multicast group. An analytical model is developed to evaluate the performance of the proposed scheme, in terms of service probability, power consumption, and throughput of each group member and multicast groups. The efficiency of the proposed scheme and the accuracy of the analytical model are corroborated by extensive simulations.**

***Index Terms*—Cooperative communication, multicast scheduling, IEEE 802.16.**

## I. INTRODUCTION

EMERGING broadband multimedia services, e.g., Internet Protocol Television (IPTV) and mobile TV, are expected to contribute immense market value to the service providers in the next generation IEEE 802.16 based wireless metropolitan area networks (WMAN) [1]-[4]. Multicast communications is an efficient mechanism for one-to-many transmissions over wireless channels and offers great opportunity for service providers to broadcast TV, film, and other information (e.g., emergency alerts, software installation) to multiple users simultaneously. In recent years, multicast services have attracted great attentions from both academia and industry. The Multimedia Broadcast Multicast Service (MBMS) has been standardized in the third generation partnership project (3GPP) and is currently under active investigation [5]–[6]. On the other hand, effective scheduling plays a key role to improve the wireless resource utilization and provide quality of service (QoS) for multimedia services. Therefore, it is critical to design efficient scheduling for reliable multicast services.

Manuscript received March 26, 2008; revised August 12, 2008; accepted August 24, 2008. The associate editor coordinating the review of this paper and approving it for publication was X. Zhang.

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This work has been supported in part by a Strategic Grant from the Natural Sciences and Engineering Research Council (NSERC) of Canada.

Digital Object Identifier 10.1109/TWC.2009.080417

In a multicast network, users requesting the same data can be logically grouped as a multicast group (MGroup). For instance, all subscribers watching the same TV channel form an MGroup, and the total number of MGroups in the network equals that of TV channels. Since subscribers are distributed at different locations and experience different fading and path-loss due to time-varying wireless channels, it remains challenging to provide satisfactory multicast services to all subscribers. A multicast scheduling scheme is proposed for cellular networks, using a pre-defined default transmission rate for all MGroups which are served in the round-robin fashion. For instance, the CDMA 2000 1xEV-DO networks use the fixed data rate of 204.8 Kbps for multicast transmissions. Another approach is to select the minimal supported rate of all MGroup members, i.e., the rate all group members can successfully decode the data. Thus, the group member with the worst channel condition becomes the bottleneck and results in conservative resource utilization. This approach is especially inefficient when most users are in good channel conditions and capable for high rate transmissions; while only a small fraction of users are far away from the base station (BS) or suffer deep fading. These two multicast scheduling schemes underutilized wireless resources because they use conservative transmission rates to assure reliable multicast transmissions.

On the other hand, cooperative communication is a promising technology that can greatly improve the system performance by exploring the broadcasting nature of wireless channels and cooperation among multiple users. Cooperative communication used for unicast transmissions has been extensively studied in the literature [7]-[13]. However, little work applies cooperative communication technique for multicast transmissions. In this paper, we propose a cooperative multicast scheme to efficiently exploit spatial diversity among multiple users, based on a two-phase cooperative transmission model. In the first phase, the BS multicasts data at a high rate; and users in good channel conditions help relay the received data to the remaining users in the second phase. The proposed multicast cooperative scheme is different from unicast cooperative schemes in many aspects. First, the partner(s) or cooperator(s) in unicast cooperative transmission are usually fixed, e.g., pre-placed relay stations, for protocol design and implementation simplicity. In a multicast scenario with all users in an MGroup requesting the same data, any user with good channel conditions can forward the received data to the remaining users in the same group, and thus the cooperative transmitters are variable. Second, most previous studies in unicast cooperative transmission focus on the performance study in the physical layer (PHY), in terms of outage probability, bit error rate (BER), and optimal power allocation, etc. In a network scenario, users may have their own data to transmit besides forwarding the data of their partners. The key issue in this case is how to choose proper partners and efficiently coordinate the transmissions of relay data and the origin data for each user. It is very difficult, if not impossible, to analytically study the *network* performance of unicast cooperative schemes, and it becomes even harder when the number of cooperative transmitters are not fixed. In addition, different from unicast transmissions, multicast transmissions are inherently unreliable (due to no acknowledgement), and it is important to determine critical parameters for multi-user cooperation to assure high throughput for all users.

The main contributions of this paper are threefold: 1) We first propose a cooperative multicast scheduling scheme for reliable multicast services in IEEE 802.16 networks. The proposed scheme can achieve high throughput for all group members and maintain good fairness performance by exploiting the spatial diversity gain and considering the normalized relative channel conditions of each MGroup; 2) An analytical model is developed to study the performance of the proposed cooperative multicast scheduling scheme, in terms of the service probability, power consumption, and throughput of each user, MGroup and the whole network; 3) We further investigate how to set critical protocol parameters to maximize the network throughput, which can provide useful guidelines for multicast services deployment. Extensive simulations are performed to verify the analysis and demonstrate the effectiveness and efficiency of the proposed scheduling scheme.

The remainder of the paper is organized as follows. Section II introduces the related work. The system model is presented in Section III. In Section IV, we describe the cooperative multicast scheduling scheme. An analytical model is developed to investigate its performance in Section V. Simulation results are given in Section VI, followed by concluding remarks and future research issues in Section VII.

## II. Related Work

In general, fairness, throughput and reliability are three main metrics for evaluating the performance of a multicast service. A number of scheduling algorithms have been proposed for achieving high throughput and good fairness performance. A proportional fair scheduling scheme is proposed in [14], where an MGroup and its corresponding transmission rate are dynamically selected based on the proportional fair policy, rather than the worst channel condition of group members. In [15], the inter-group proportional fairness scheme is proposed, where the BS selects MGroup and the transmission rate in such a way that the summation of $log(T_k^g)$ for all MGroups is maximized, where $T_k^g$ is the group throughput for MGroup $k$. These two schemes achieve a good trade-off between the throughput and the fairness, but they do not consider how to deal with the negative impacts of bad channel conditions on the achieved throughput. Meanwhile, it is difficult to conduct a quantitative analysis since the selection of MGroups depends on the average throughput of each group member in each MGroup. In [16], a bandwidth efficient multicast mechanism is proposed to minimize the bandwidth consumption by optimally selecting the cell and wireless access networks. An adaptive power and rate allocation scheme is proposed in [17]. By jointly considering the superposition coding, the scheme can achieve high throughput. In addition, a selective retransmission strategy is developed to avoid unnecessary data reception in multicast scenario. However, only two-receiver scenario is considered for problem formulation and performance evaluation. When the number of group members increases, the complexity of the scheme also increases significantly. An utility-based resource allocation scheme is developed for layer-encoded multicast transmissions in [18], where the number of transmission layers is adjusted according to the channel conditions, available network resource, and the utility contribution of each layer. How to properly define a utility function for video stream is still an open issue.

For reliable mutlicast services, most existing studies focus on designing reliable routing protocols in the network layer [19]–[22] or efficient error-control and recovery schemes in the transport layer [23]–[25]. Little work has been carried out on reliable multicast scheduling at the media access control (MAC) layer. In [26], MGroups are served in the round-robin fashion with a fixed rate supported by the user at the edge of the cell. This scheme provides reliable multicast transmission at the expense of satisfying the high capacity of users in good channel conditions.

To improve the network resource utilization, one possible approach is to split an MGroup into several subgroups which can transmit at different rates. In [27], a scheme has been proposed to divide a cell into two service regions. The BS transmits two data streams with different power levels such that users near the BS can successfully receive both of them while the users away from the BS only receive one data stream. This scheme achieves a higher throughput than that in [26] due to the consideration of different channel conditions. The scheme in [27] does not give details on how to efficiently select MGroups and how to guarantee the reliable transmission to users far from the BS. In [28], a threshold based multicast scheme is proposed, in which the sender transmits only when a sufficient number of group members can successfully receive the data. In [29], the relationship between the stability and throughput based on the threshold multicast scheduling is studied, which indicates the proposed scheme in [28] may lead to an unstable system when the threshold is not set properly.

The aforementioned scheduling schemes aim to improve the group throughput at the expense of the reliability of the group members in bad channel conditions. However, in most cases, it is necessary to provide satisfactory services to all users who subscribe multicast services such as IPTV, no matter when their channel conditions are good or bad. Therefore, our design objective is to achieve high throughput for all users, and in the meantime, maintain good fairness among MGroups.

## III. System Model

We consider an IEEE 802.16 network consisting of a BS and multiple subscriber stations ($SSs$), as shown in Fig.1. An $SS$ could be a mobile user, a residential customer, or an

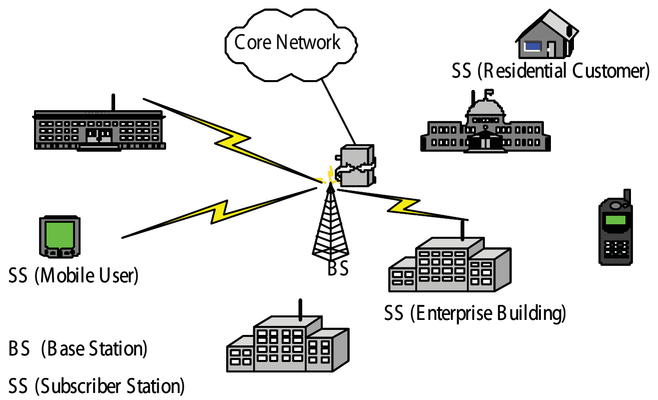



Fig. 1. The illustration of an IEEE 802.16 network.

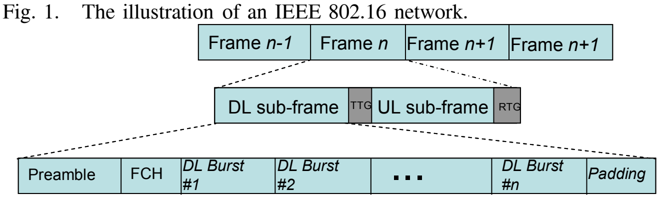



Fig. 2. MAC structure for a conventional IEEE 802.16 network.

office building. IEEE 802.16 standards support two modes: mesh mode and Point-to-MultiPoint (PMP) mode. Currently, the PMP mode is widely deployed due to its infrastructure support for qualified multimedia services. In this paper, we focus on the PMP mode.

### A. Media Access Control

Generally, IEEE 802.16 standards specify two uplink/downlink duplexing modes: time division duplexing (TDD) and frequency division duplexing (FDD). In this paper, we consider the TDD-OFDM/TDM MAC structure, as shown in Fig. 2. The time domain is divided into MAC frames with equal duration, each of which is composed of a downlink sub-frame (DL sub-frame), an uplink sub-frame (UL sub-frame), a transmit/receive transition gap (TTG), and a receive/transmit transition gap (RTG). The transition gaps are placed between DL sub-frames and UL sub-frames to allow the receive section or transmit section in BS and $SSs$ to be activated. A DL sub-frame consists of a preamble signal, which is used for synchronizing the $SSs$ with the BS, followed by frame control header (FCH), downlink MAP (DL-MAP), uplink MAP (UL-MAP) messages, and several downlink transmission bursts. DL-MAP and UL-MAP messages specify the allocation of the transmission bursts among $SSs$, including the corresponding time duration and burst profiles such as the modulation level and coding rate.

In a conventional IEEE 802.16 network, $SSs$ only receive data from the BS in DL sub-frames. To achieve cooperative multicasting, we divide a transmission burst assigned for multicast transmission into two phases, as shown in Fig. 3(a). In Phase I, the BS transmits data to all $SSs$ in an MGroup at a high data rate and only a portion of the $SSs$ can successfully receive the data; and in Phase II, those $SSs$ successfully received the data in Phase I transmit the same copy of the received data to the remaining $SSs$ of the MGroup. The starting time and transmission rates of Phases I and II are

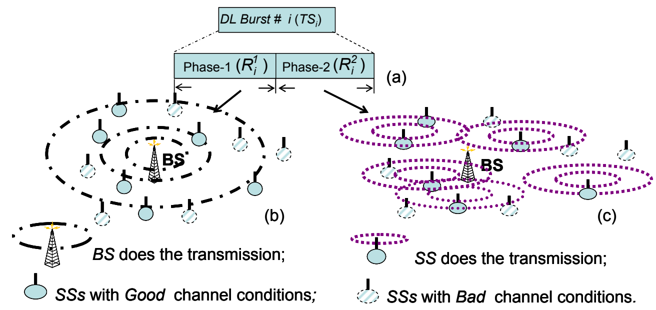



Fig. 3. The illustration of the cooperative multicast scheduling.

specified in the burst profile of DL-MAP messages. There are two main categories of cooperative schemes, *amplify-and-forward* (AF) and *decode-and-forward* (DF). In this paper, we focus on DF since in a multicast scenario, all MGroup members need to decode the received data and decoding procedure involved in the DF scheme does not increase the complexity of MGroup members.

### B. Channel Model

Radio signals are transmitted over a propagation wireless channel, and suffer from signal reflection, diffraction, and scattering. In the paper, we consider both large-scale path-loss attenuation and small-scale fading in the channel model. Path-loss attenuation is determined by the geographical environment and distance between the receiver and the transmitter, which can be modeled as (in decibels) [31]

$$PL(d) = PL(d_0) + 10\ k\ log_{10}(\frac{d}{d_0}), \tag{1}$$

where $PL(d)$ is the total path loss at distance d, $PL(d_0)$ is the pass loss at the close-in reference distance $d_0$, $k$ is the path loss exponent, and $d$ is the transmission distance between the receiver and transmitter.

Small-scale fading is caused by multiple versions of a transmitted signal with different delays that occur spontaneously in the time span with a random duration and depth, and is also considered independent of the large scale path loss. The commonly used Rayleigh flat fading channel is applied to describe the small-scale fading, where the perceived signal-to-noise ratio (SNR) of an $SS$ at each frame is a random variable following an exponential distribution, with the probability density function (p.d.f.)

$$f(\gamma) = \frac{1}{\overline{\gamma}} e^{-\gamma/\overline{\gamma}}\ , \tag{2}$$

where $\gamma$ and $\overline{\gamma}$ represent the instantaneous and average received SNR, respectively.

## IV. Cooperative Multicast Scheduling Scheme

In multicast networks, multiple $SSs$ are grouped into different MGroups according to their subscribed services. For instance, for IPTV service, an MGroup corresponds to a group of users requesting the same TV channel. An $SS$ could be a residential house or office building, which may contain multiple end users watching different channels. Therefore, an $SS$ may access multiple channels simultaneously and thus belongs to several MGroups.

For multicast scheduling, the first key step is to select an appropriate MGroup for service at the beginning of each MAC frame; then the BS can efficiently multicast data to all group members in the selected MGroup, which are elaborated further as follows.

### A. Multicast group selection

In this section, we introduce two approaches to select MGroups for services: the random MGroup selection and the channel-aware MGroup selection. The former one is straightforward and easy to implement, whereas the latter one can further improve the network performance by exploiting the diversity gain of multi-group channels.

*1) Random MGroup selection:* The BS randomly selects an MGroup for service with a pre-defined probability. The probability for MGroup $i$ to be served in a MAC frame can be decided based on the total number of MGroups, $M$, *e.g.*, each group is served with the same probability $1/M$ for achieving a good fairness performance. The random MGroup selection scheme is easy to implement. In addition, flexible scheduling with service differentiation can also be easily achieved by setting different service probabilities to multiple MGroups according to a certain service differentiation policy.

*2) Channel-aware MGroup selection:* To further improve the throughput, we propose a channel-aware MGroup selection mechanism. Different MGroups have different sets of group members distributed at different locations. Generally, group members experience different long-term channel conditions. In addition, due to small-scale fading, different group members may experience different instantaneous channel conditions in each frame, even if they have similar long-term channel conditions. In the proposed multicast scheduling scheme, to exploit the multi-group channel diversity gain, the selection of an MGroup should consider the channel conditions on the group basis, rather than a single group member. If the selection of MGroup is based on the best channel condition among all members in an MGroup, ignoring the channel conditions of the remaining group members, the achievable group throughput may not be high since the remaining members in bad channel conditions may fail to decode the data. If an MGroup is selected based on the overall channel conditions of the group members, it may lead to serious unfairness because MGroups which are close to the BS usually have good channel conditions, and thus are more likely to be scheduled for service and dominate the bandwidth consumption. By taking into account fairness while exploiting the multi-group channel diversity, we propose a criterion of MGroup selection based on the normalized relative channel condition, which is given by

$$i^* = \arg\max_i X_i \,, \tag{3}$$

$$X_i = \frac{\sum_{j \in G_i} \gamma_{i,j} / \overline{\gamma}_{i,j}}{N_i} \,, \tag{4}$$

where $X_i$ represents the normalized relative channel condition of MGroup $i$, $G_i$ represents the set of all group members in MGroup $i$, $N_i$ is the total number of group members in MGroup $i$, $\overline{\gamma}_{i,j}$ and $\gamma_{i,j}$ denote the average channel condition and the instantaneous channel condition of the $j$-th group member in MGroup $i$, respectively.

Based on (3), the BS selects MGroup $i^*$, which has the maximum value of the normalized relative channel condition, for service in each MAC frame. To implement the channel-aware MGroup selection, the BS should have the knowledge of the channel state information (CSI) of each MGroup member. In IEEE 802.16 networks, the uplink channel quality indication channel (UL CQICH) is allocated for $SSs$ to send CSI feedback. Some $SSs$ in IEEE 802.16 are stationary, e.g., office buildings or residence houses, and their channel conditions are relatively less fluctuant, which may reduce the demand for CSI feedback. Based on the CSI of each MGroup member, we can obtain the preference metric vector $\overline{X} = [X_1, X_2, \cdots, X_M]$ from (4), and update $\overline{X}$ at the beginning of each frame. The BS selects the MGroup with the largest value of preference metric according to (3) and allocates the corresponding transmission bursts to this MGroup.

By exploiting the multi-group channel diversity, the channel-aware MGroup selection can further improve the network performance of the proposed multicast scheduling scheme. On the other hand, by averaging out the long-term channel conditions and normalizing the total number of MGroup members, the proposed scheduling scheme can achieve a good fairness performance as well. Notice that the proposed channel-aware MGroup selection can achieve higher network throughput than the random MGroup selection at the cost of more overhead, including signaling of CSI exchange, channel estimation and computation, etc.

### B. Cooperative Multicast Transmission

After an MGroup is selected, the next step is to efficiently multicast data to all group members in the selected MGroup. If the rate is too high, some group members with bad channel conditions may not be able to successfully decode the data. On the contrary, if the rate is determined based on the MGroup members with bad channel conditions, the wireless resources are underutilized since the MGroup members with good channel conditions can support a higher data rate. This dilemma is caused by the diverse channel conditions of group members in the same MGroup. To exploit the diversity gain of wireless channels, a two-phase transmission scheme is used to efficiently multicast data in the downlink transmissions, where a downlink burst is divided into two phases. For instance, MGroup $i$ is selected for service in a frame and can access channel during the downlink burst $TS_i$. The time interval of $TS_i$ is divided into two phases. In Phase I with time duration $T_i^1$, the BS multicasts data to all group members of MGroup $i$ at a high data rate of $R_i^1$ such that only a certain portion of group members in MGroup $i$ can successfully decode the data, as shown in Fig. 3(b). Due to the high data rate, the remaining group members with bad channel conditions may not be able to successfully decode all the data in Phase I. Therefore, in Phase II, the cooperative communications are used to assure reliable transmissions of the remaining group members with bad channel conditions. Let $S_i^g$ and $S_i^b$ denote the set of group members that can and cannot successfully receive the data in Phase I, respectively. In Phase II with time duration $T_i^2$ , all members in $S_i^g$ transmit the received data to the members in $S_i^b$ at the high rate of $R_i^2$ that satisfies $R_i^1 * T_i^1 = R_i^2 * T_i^2$ to assure all members in the group can receive the same data, as shown in Fig. 3(c). In this way, group members located in different locations form a virtual multiple-input-multiple-output (MIMO) system, in which group members in $S_i^g$ are transmitters and those in $S_i^b$ are receivers. For a member in $S_i^b$, although the channel condition from the BS is relatively poor during this frame, the channel conditions between itself and some members in $S_i^g$ may be good due to independent geographical locations of different group members. By exploiting the spatial diversity of wireless channel, group members in $S_i^b$ are more likely to successfully receive the data in Phase II even at a high data rate, and the transmission rate for reliable multicast transmission can be significantly improved.

One main advantage of the cooperative multicast transmission is that it can achieve high throughput not only for group members with good channel conditions, but also for group members with bad channel conditions, by exploiting the spatial diversity gain of multiple channels. Notice that $R_i^1$ and $R_i^2$ are much higher than the conservative rate determined by the group member with the worst channel condition and the two-phase high rate transmission can outperform one phase conservative rate transmission [30]. Basically, it is conceptually possible to extend the two-phase transmissions to $m$-Phase transmissions ($m > 2$). However, a large $m$ involves more parameters and computation overhead, e.g., $R_i^1$, $R_i^2$, ... $R_i^m$, and may not always yield desirable network performance in terms of throughput and power consumption.

The transmission rates in Phases I and II (i.e., $R_i^1$ and $R_i^2$) are critical to the system performance. In the proposed scheme, $R_i^1$ and $R_i^2$ are determined based on the long-term channel conditions of all group members in MGroup $i$, instead of instantaneous channel conditions. With less fluctuant long term channel conditions, the BS does not need to compute and distribute the transmission rates for group members frequently. We define the coverage ratio, $C$, as the percentage of group members that can support $R_i^1$. For instance, $C = 50\%$ means that the BS transmits at the rate of $R_i^1$ such that on average half of the group members in MGroup $i$ can receive the data successfully in Phase I, and $R_i^2$ should be set in such a way that the remaining half of group members can successfully receive the same data in Phase II.

## V. Performance Analysis

In this Section, an analytical model is developed to investigate the performance of the proposed scheme, in terms of service probability of each MGroup, power consumption of the system, and throughput of each user, each MGroup and the whole network, respectively. The notations used in the paper are listed in Table I for easy reference.

### A. Service Probability for MGroup $i$

Service probability is defined as the probability that an MGroup is selected for service in a MAC frame when the system is stable. For the random MGroup selection, each MGroup is served by a pre-defined probability, and the steady-state service probability of MGroup $i$, $\pi_i$, is an operation parameter. For the channel-aware MGroup selection, according to (3), the MGroup with the largest normalized relative channel condition is selected. Define $Y_{i,j} = g_i(\gamma_{i,j}) = \frac{\gamma_{i,j}/\overline{\gamma}_{i,j}}{N_i}$, and $X_i = \sum_{j \in G_i} Y_{i,j}$. Based on [32], the p.d.f. of $Y_{i,j}$ is given by

$$\phi(Y_{i,j} = y) = N_i e^{-N_i y}, \tag{5}$$

and $X_i$ follows a Gamma distribution, i.e., $X_i \sim Gamma(N_i, \frac{1}{N_i})$.

Let $h_i$ and $H_j$ be the p.d.f. of $X_i$ and the cumulative distribution function (C.D.F.) of $X_j$, respectively. Thus, the service probability for MGroup $i$ is given by (6).

### B. Throughput Analysis

*1) Throughput analysis based on channel capacity:* For a received SNR, the achievable data rate with a negligible error probability is $\log_2(1 + SNR)$ for unit bandwidth [33], [34]. Therefore, given $R_i^1$ and $R_i^2$, the probability that a group member in MGroup $i$, $SS_{i,j}$, can successfully receive the data in Phase I, is given by

$$Pr\left(E_{i,j}^1 \geq (2^{R_i^1} - 1)N_0\right) = e^{-((2^{R_i^1}-1)N_0)/\overline{E}_{i,jB}}, \tag{7}$$

where $E_{i,j}^1$ is the received signal power of $SS_{i,j}$ in Phase I, and $N_0$ is the white Gaussian noise level.

If $SS_{i,j}$ fails to receive the data in Phase I, it is still possible to successfully receive data in Phase II. The received SNR of $SS_{i,j}$ in Phase II depends on the number of transmitters and the received signal power from each transmitter. Since all $SSs$ in MGroup $i$, except $SS_{i,j}$, are possible transmitters in Phase II, $G_i^g$ could be any combination of these $SSs$, and we have

$$G_i^g \subseteq \{SS_{i,k}, k = 1, 2, ..., N_i; k \neq j\}. \tag{8}$$

Let $C_{i,j}$ be the set of all possible $G_i^g$ for $SS_{i,j}$. The total number of all possible $G_i^g$ is

$$|C_{i,j}| = \sum_{k=1}^{N_i - 1} \binom{N_i - 1}{k} = 2^{N_i - 1} - 1. \tag{9}$$

Consider MGroup $i$ is composed of four users: $SS_{i,1}$, $SS_{i,2}$, $SS_{i,3}$, $SS_{i,4}$. For $SS_{i,1}$, the possible group members that can be its transmitters are $SS_{i,2}$, $SS_{i,3}$, and $SS_{i,4}$. Thus, the set of all possible $G_i^g$ is $C_{i,1} = (\{SS_{i,2}\}, \{SS_{i,3}\}, \{SS_{i,4}\}, \{SS_{i,2}, SS_{i,3}\}, \{SS_{i,2}, SS_{i,4}\}, \{SS_{i,3}, SS_{i,4}\}, \{SS_{i,2}, SS_{i,3}, SS_{i,4}\})$, and the number of possible $G_i^g$ for $SS_{i,1}$ is $|C_{i,j}| = \sum_{k=1}^{3} \binom{3}{k} = 7$. Given a MAC frame, the probability for any $G_i^g$ to be the set of transmitters in Phase II can be determined by their channel conditions. For instance, $G_i^g = \{SS_{i,2}, SS_{i,3}\}$ when only $SS_{i,2}$ and $SS_{i,3}$ can decode the data in Phase I. Thus, the probability of $G_i^g = \{SS_{i,2}, SS_{i,3}\}$ is given by (10).

Let $E_{i,j}^2$ be the received signal power of $SS_{i,j}$ in Phase II, and $Pr(G_i^g)$ be the probability that $G_i^g$ is the set of cooperative transmitters in Phase II. Thus, the probability that $SS_{i,j}$ can successfully receive the data in Phase II is given by

$$\begin{aligned} &Pr\left(E_{i,j}^2 \geq (2^{R_i^2} - 1)N_0\right) \\ &= \sum_{G_i^g \in C_{i,j}} Pr(G_i^g) Pr\left(E_{i,j}^2 \geq (2^{R_i^2} - 1)N_0 | G_i^g\right). \end{aligned} \tag{11}$$

TABLE I
TABLE OF NOTATIONS

| | |
|---|---|
| $M$ | The total number of MGroups |
| $G_i$ | The set of all members belonging to MGroup $i$ |
| $N_i$ | The total number of group members in MGroup $i$ |
| $G_i^g$ | A set of members in MGroup $i$ that can successfully receive data in Phase I |
| $G_i^b$ | A set of members in MGroup $i$ that fail to receive data in Phase I |
| $X_i$ | The normalized average channel condition of MGroup $i$ |
| $SS_{i,j}$ | The j-th group member in MGroup $i$ |
| $\overline{\gamma}_{i,j}$ | The average SNR of $SS_{i,j}$ |
| $\gamma_{i,j}$ | The instantaneous SNR of $SS_{i,j}$ |
| $E_{i,j}^1$ | The received signal power for $SS_{i,j}$ in Phase I |
| $E_{i,j}^2$ | The received signal power for $SS_{i,j}$ in Phase II |
| $\overline{E}_{i,jB}$ | The average received signal power for $SS_{i,j}$ from BS |
| $\overline{E}_{i,jk}$ | The average received signal power for $SS_{i,j}$ from $SS_{i,k}$ |
| $N_0$ | The noise power |
| $R_i^1$ | The rate of the BS in Phase I for MGroup $i$ |
| $R_i^2$ | The rate of each cooperative transmitter in Phase II for MGroup $i$ |
| $T_i^1$ | The transmission time of Phase I for MGroup $i$ |
| $T_i^2$ | The transmission time of phase II for MGroup $i$ |
| $\alpha$ | Time ratio for multicast transmission |
| $C$ | Coverage ratio used to decide $R_i^1$ |
| $Th_{i,j}^{CMS}$ | The throughput of $SS_{i,j}$ for the proposed CMS scheme |
| $Th_{i,j}^{W}$ | The throughput of $SS_{i,j}$ for the scheme $Conserve$ |
| $Th_i^{CMS}$ | The group throughput of the MGroup $i$ for the proposed CMS scheme |
| $Th_i^{W}$ | The group throughput of the MGroup $i$ for the scheme $Conserve$ |

$$\begin{aligned}\pi_i &= Pr\left(X_i = max(X_1, X_2, ..., X_M)\right)\\ &= \int_0^\infty \left[h_i(X_i = x)(\prod_{j=1,j\neq i}^{M} H_j(X_j = x))\right] dx\\ &= \int_0^\infty \left[\frac{{N_i}^{N_i}}{(N_i-1)!}x^{N_i-1}e^{-N_i x}\prod_{j=1,j\neq i}^{M}(1-e^{-N_j x}\sum_{k=0}^{N_j-1}\frac{(N_j x)^k}{k!})\right] dx\end{aligned} \tag{6}$$

$$\begin{aligned}&Pr\left(E_{i,2}^1 \geq (2^{R_i^1}-1)N_0\right) Pr\left(E_{i,3}^1 \geq (2^{R_i^1}-1)N_0\right) Pr\left(E_{i,4}^1 < (2^{R_i^1}-1)N_0\right)\\ &\qquad = e^{-\frac{\left(2^{R_i^1}-1\right)N_0}{\overline{E}_{i,2B}}} e^{-\frac{\left(2^{R_i^1}-1\right)N_0}{\overline{E}_{i,3B}}}\left(1-e^{-\frac{(2^{R_i^1}-1)N_0}{\overline{E}_{i,4B}}}\right)\end{aligned} \tag{10}$$

$$f(E_{i,j}^2) = \sum_{SS_{i,k}\in G_i^g}\left[\frac{\overline{E}_{i,jk}}{\prod\limits_{SS_{i,h}\in G_i^g}\overline{E}_{i,jh}}\left(\prod_{SS_{i,z}\in G_i^g;z\neq k}(\frac{1}{\overline{E}_{i,jz}}-\frac{1}{\overline{E}_{i,jk}})^{-1}\right)\frac{1}{\overline{E}_{i,jk}}e^{-\frac{E_{i,j}^2}{\overline{E}_{i,jk}}}\right] \tag{12}$$

$$F(E_{i,j}^2) = \sum_{SS_{i,k}\in G_i^g}\left[\frac{\overline{E}_{i,jk}}{\prod\limits_{SS_{i,h}\in G_i^g}\overline{E}_{i,jh}}\left(\prod_{SS_{i,z}\in G_i^g;z\neq k}(\frac{1}{\overline{E}_{i,jz}}-\frac{1}{\overline{E}_{i,jk}})^{-1}\right)(1-e^{-\frac{E_{i,j}^2}{\overline{E}_{i,jk}}})\right] \tag{13}$$

The received signal power in Phase II, $E_{i,j}^2$, is the sum of signal powers from all transmitters. For Rayleigh fading, the received signal power of $SS_{i,j}$ from a cooperative transmitter $SS_{i,k}, (k \in G_i^g)$ follows an exponential distribution. Thus, given $G_i^g$, $E_{i,j}^2$ is the sum of multiple random variables following independent exponential distributions. The close-form expression for the sum of squared Nakagami random variables is given in [35]. For Rayleigh fading channel, the p.d.f and C.D.F. of $E_{i,j}^2$ can be obtained by (12) and (13), respectively, where $E_{i,jk}$ is the received signal power of $SS_{i,j}$ from $SS_{i,k}$, and $\overline{E}_{i,jk}$ is the mean of $E_{i,jk}$.

If $SS_{i,j}$ can support the transmission rate $R_i^1$, it will successfully receive $T_i^1 R_i^1$ bits during the interval $T_i^1 + T_i^2$. The probability that $SS_{i,j}$ can successfully receive the data in Phase I is $Pr(E_{i,j}^1 \geq (2^{R_i^1} - 1)N_0)$. If data transmission fails in Phase I but succeeds in Phase II, which has the probability $Pr\left(E_{i,j}^1 < (2^{R_i^1} - 1)N_0\right) Pr\left(E_{i,j}^2 \geq (2^{R_i^2} - 1)N_0\right)$, the throughput of $SS_{i,j}$ is $\alpha \, T_i^2 R_i^2/(T_i^1 + T_i^2)$. Thus, the average throughput of $SS_{i,j}$ is given by (14).

The group throughput achieved by MGroup $i$, which is the summation of the throughput of all group members in MGroup $i$, is given by

$$Th_i^{CMS} = \sum_{j=1}^{N_i} Th_{i,j}^{CMS}. \tag{15}$$

The network throughput, which is the total throughput of all MGroups in the network, is given by

$$Th^{CMS} = \sum_{i=1}^{M} Th_i^{CMS}. \tag{16}$$

We further study two extreme cases where all group members in MGroup $i$ can or cannot support the sending rate $R_i^1$. The probability of these two cases are given in (17) and (18), respectively.

$$\prod_{SS_{i,j} \in G_i} Pr\left(E_{i,j}^1 \geq (2^{R_i^1} - 1)N_0\right) = \prod_{SS_{i,j} \in G_i} e^{-\frac{(2^{R_i^1}-1)N_0}{\overline{E}_{i,jB}}} \tag{17}$$

$$\begin{aligned} &\prod_{SS_{i,j} \in G_i} Pr\left(E_{i,j}^1 < (2^{R_i^1} - 1)N_0\right) \\ &= \prod_{SS_{i,j} \in G_i} \left(1 - e^{-\frac{(2^{R_i^1}-1)N_0}{\overline{E}_{i,jB}}}\right) \end{aligned} \tag{18}$$

Analytical results show that the probabilities of these two extreme cases are less than $10^{-11}$. Therefore, the impact of the extreme cases on the throughput is negligible, which is also verified by simulation.

*2) Throughput analysis with the adaptive modulation and coding:* In addition to the analysis based on the channel capacity, we further investigate the impact of the promising adaptive modulation and coding (AMC) technique at the physical layer, which has been widely deployed in the wireless networks, *e.g.*, IEEE 802.16, IEEE 802.11x, Ultra-Wideband (UWB), etc.

With the AMC technique, the received SNR is divided into several disjoint regions, based on a set of boundaries. Let $b_n$ and $I_n$ represent the lower boundaries of SNR and information bit carried by an orthogonal frequency division multiplex (OFDM) symbol for the state $n$, respectively. $b_n$ and $I_n$ of different modulation and coding levels are given in Table II. State 0 represents the state that no transmission is allowed, which occurs when the channel condition is very poor. The transmission rate corresponding to different modulation and coding levels is given by $r_n = I_n/T_s$, where $T_s$ is the time duration of an OFDM symbol. Therefore, with discrete-rate AMC, the selection of $R_i^1$ and $R_i^2$ satisfies $R_i^1, R_i^2 \in \{r_n, \ n = 1, 2, \cdots, 7\}$. Given $R_i^1 = r_n$, the probability that $SS_{i,j}$ can successfully receive the data in Phase I is given by

$$Pr(E_{i,j}^1 \geq b_n N_0) = e^{-(b_n N_0)/\overline{E}_{i,jB}}. \tag{19}$$

Given $R_i^2 = r_m$, the probability that $SS_{i,j}$ can successfully receive the data in Phase II is given by

$$Pr(E_{i,j}^2 \geq b_m N_0) = \sum_{G_i^g \in C_{i,j}} Pr(G_i^g) Pr(E_{i,j}^2 \geq b_m N_0 | G_i^g), \tag{20}$$

where $b_n, b_m \ (n, m = 1, 2, \cdots, 7)$ represent the lower bounds of the received SNR for the modulation and coding level $n$ and $m$, respectively.

Similar to (14), the throughput achieved by the group member $SS_{i,j}$ using AMC technique is given by (21).

TABLE III
SYSTEM PARAMETERS

| | |
|---|---|
| The total number of $SSs$ in the system | 50 |
| The number of MGroups $M$ | 10 |
| The number of group members in each MGroup $N_i$ | 20 |
| Transmission power of BS's | 43 dBm |
| Transmission power of $SS$'s | 34.8 dBm |
| DL/UL sub-frame duration | 1.25 ms/1.25 ms |
| OFDM symbol duration $\tau$ | 23.8$\mu$s |
| Bandwidth | 10 MHz |
| Noise power | $-128$ dBm |
| Pass loss exponent $k$ | 4.375 |
| Close-in reference distance | 100 m |
| Frequency band | 3.5GHz |
| Coverage ratio $C$ | 50% |
| Time ratio for multicast transmission $\alpha$ | 25% |

## VI. SIMULATION RESULTS

We compare the performance of the proposed multicast scheduling scheme (denoted as $CMS$) with the scheme specified in 3GPP (denoted as $Conserve$) by extensive simulations with Matlab. The IEEE 802.16 network is composed of one BS and 50 $SSs$. $SSs$ are randomly distributed in the coverage area of the BS, which is a circle centered at the BS with a radius of 8 km. Rayleigh flat fading channel described in Sec. III-B is applied. There are 10 MGroups in the system and each group includes 20 members which are randomly selected from the 50 $SSs$. The main system parameters are listed in Table III. We repeat the simulation 50 times with different random seeds and calculate the average value.

The throughput performance is illustrated in Fig. 4. The vertical axis is the achieved throughput normalized by the maximum value in the experiments. Fig. 4(a) shows the throughput of each MGroup. Due to different geographical locations and channel conditions of each member in MGroups, the throughput varies in different groups. It is observed that

$$
\begin{aligned}
Th_{i,j}^{CMS} &= \pi_i \left[ \frac{\alpha\, T_i^1 R_i^1}{T_i^1 + T_i^2} Pr\left(E_{i,j}^1 \geq (2^{R_i^1} - 1)N_0\right) + \frac{\alpha\, T_i^2 R_i^2}{T_i^1 + T_i^2} Pr\left(E_{i,j}^1 < (2^{R_i^1} - 1)N_0\right) Pr\left(E_{i,j}^2 \geq (2^{R_i^2} - 1)N_0\right)\right] \\
&= \pi_i \left[ \frac{\alpha\, T_i^1 R_i^1}{T_i^1 + T_i^2} e^{-\frac{(2^{R_i^1}-1)N_0}{\overline{E}_{i,j}}} + \frac{\alpha\, T_i^2 R_i^2}{T_i^1 + T_i^2} (1 - e^{-\frac{(2^{R_i^1}-1)N_0}{\overline{E}_{i,j}}}) \sum_{G_i^g \in C_{i,j}} Pr(G_i^g)\ [1 - F(E_{i,j}^2 = (2^{R_i^2} - 1)N_0 | G_i^g)] \right]
\end{aligned} \quad (14)
$$

$$
\begin{aligned}
Th_{i,j}^{CMS} &= \pi_i \left[ \frac{\alpha\, T_i^1 R_i^1}{T_i^1 + T_i^2} Pr(E_{i,j}^1 \geq b_n N_0) + \frac{\alpha\, T_i^2 R_i^2}{T_i^1 + T_i^2} Pr(E_{i,j}^1 < b_n N_0) Pr(E_{i,j}^2 \geq b_m N_0)\right] \\
&= \pi_i \left[ \frac{\alpha\, T_i^1 R_i^1}{T_i^1 + T_i^2} e^{-\frac{b_n N_0}{\overline{E}_{i,j}}} + \frac{\alpha\, T_i^2 R_i^2}{T_i^1 + T_i^2} (1 - e^{-\frac{b_n N_0)}{\overline{E}_{i,j}}}) \sum_{G_i^g \in C_{i,j}} Pr(G_i^g)\ \left[1 - F(E_{i,j}^2 = b_m N_0 | G_i^g)\right] \right]
\end{aligned} \quad (21)
$$

TABLE II
STATE BOUNDARIES AND CORRESPONDING AMC LEVELS FOR IEEE 802.16 NETWORKS

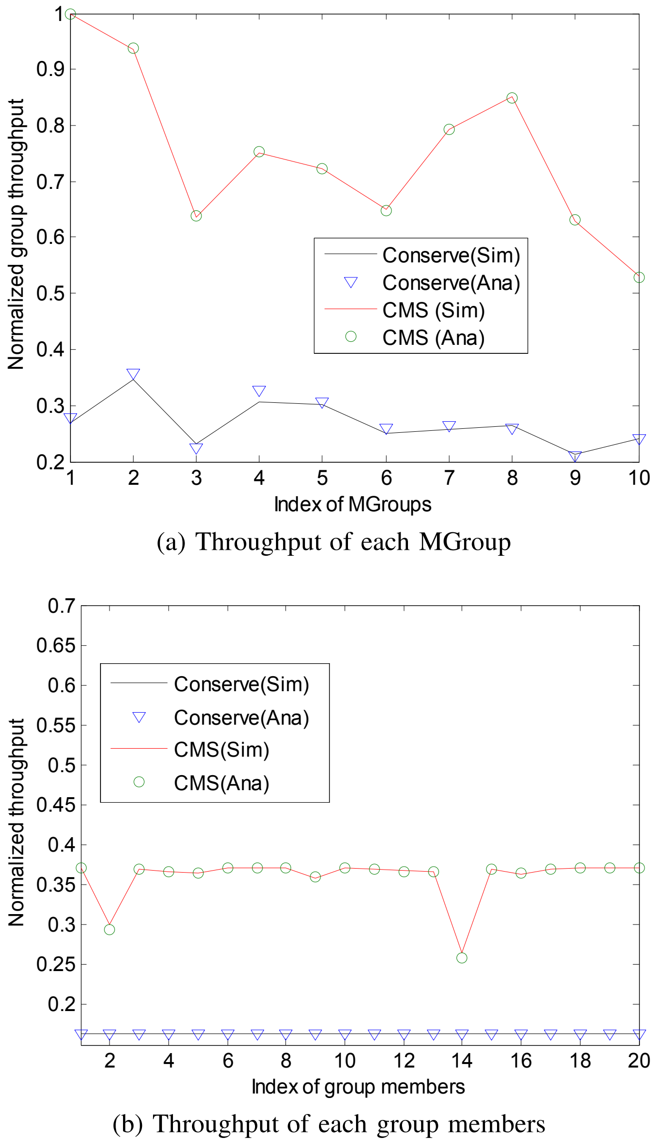
| State ID | Modulation and coding level | $b_n$(dB) | Information bits /OFDM symbol ($I_n$) |
|---|---|---|---|
| 0 | silent | 0 | 0 |
| 1 | BPSK(1/2) | 3 | 96 |
| 2 | QPSK(1/2) | 6 | 192 |
| 3 | QPSK(3/4) | 8.5 | 288 |
| 4 | 16 QAM(1/2) | 11.5 | 384 |
| 5 | 16 QAM(3/4) | 15 | 576 |
| 6 | 64 QAM(2/3) | 18.5 | 768 |
| 7 | 64 QAM(3/4) | 21 | 864 |

$CMS$ outperforms $Conserve$ for all MGroups. The normalized throughput of each group member in an MGroup is shown in Fig. 4(b). We observe that some isolated and faraway $SSs$ achieve relatively lower throughput than other $SSs$. Generally, multimedia applications use scalable coding techniques, e.g., multi-layered video coding, and can tolerate some throughput fluctuations. For example, the group members with high throughput may receive both the base layer and enhancement layer information and thus can recover a high quality video, while other group members receive the base layer information and can only recover the basic quality video. With $Conserve$, all group members achieve the same throughput because they use the conservative transmission rate to ensure the successful transmissions of all $SSs$. By taking advantages of the spatial diversity and cooperation, the proposed $CMS$ scheme significantly improves the throughput of all group members. Similar to Fig. 4(b), the throughput performance based on the AMC is shown in Fig. 5.

The performance of the proposed channel-aware MGroup selection scheme (denoted as $CMS\_C$) is investigated and compared with $CMS$ and $Conserve$ in Fig. 6. The network throughputs of $CMS$ and $CMS\_C$ are much higher than that of $Conserve$. The more number of group members in the network, the greater throughput improvement we can achieve. This is because higher diversity gain can be exploited among a larger number of group members. In addition, $CMS\_C$ outperforms $CMS$ by taking advantage of the multi-group channel diversity with channel-aware MGroup selection. In Fig. 7, we study the fairness performance of the proposed $CMS\_C$ in terms of the service probability of each MGroup. It is shown that each MGroup obtains almost the same service probability, which demonstrates that the proposed channel-aware MGroup scheme can achieve good fairness performance in terms of channel access.

Besides throughput and fairness, power consumption is another important performance metric. The total power consumption in the network, $P$, is defined as the power consumed by all transmitters, i.e., the BS and the involved transmitters in Phase II. As shown in Fig. 8, the power consumption is a constant with $Conserve$, but it increases with the number of group members with $CMS$ and $CMS\_C$. This is because only the BS consumes power for downlink transmissions with $Conserve$. For cooperative multicast scheduling schemes, although the BS does not transmit during Phase II, more $SSs$ are likely to be involved in Phase II transmissions and result in a higher total power consumption. Comparing Fig. 6 and Fig. 8, we observe that $CMS$ and $CMS\_C$ outperform $Converve$ in terms of both throughput and power consumption when the number of group members in each MGroup is less than 15. With more group members, significant throughput improvement can be achieved with $CMS$ and $CMS\_C$ at the expense of increased power consumption. As shown in Fig. 6 and Fig. 8, when the number of group member is 40, the power consumption of the proposed $CMS$ is around 1.7 times of that of $Conserve$, but the throughput of $CMS$ is more than 10 times of that of $Conserve$.

We further study the impact of the coverage ratio $C$ on the network throughput in Fig. 9. The network throughput of the proposed scheme under different $C$ values are always higher than that with $Conserve$. For the proposed $CMS$, the highest network throughput is achieved with $C = 0.55$, i.e., 55% $SSs$ in a group forward the received data to the remaining $SSs$




(a) Throughput of each MGroup

(b) Throughput of each group members

Fig. 4. Throughput performance

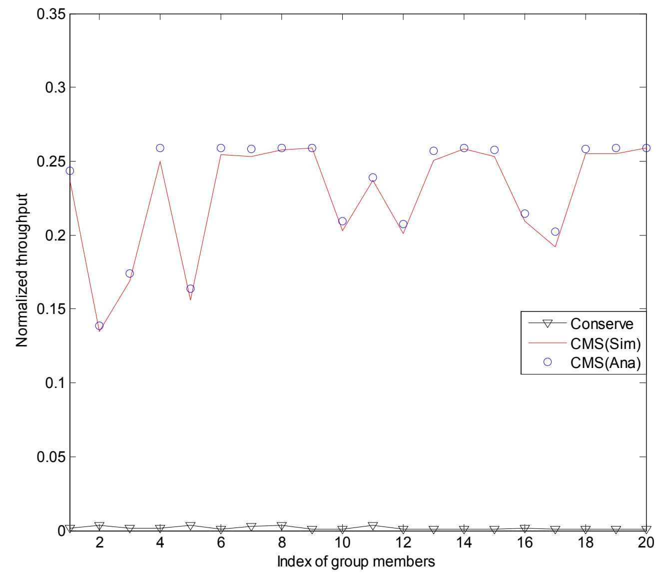



Fig. 5. Throughput of each group member with AMC.

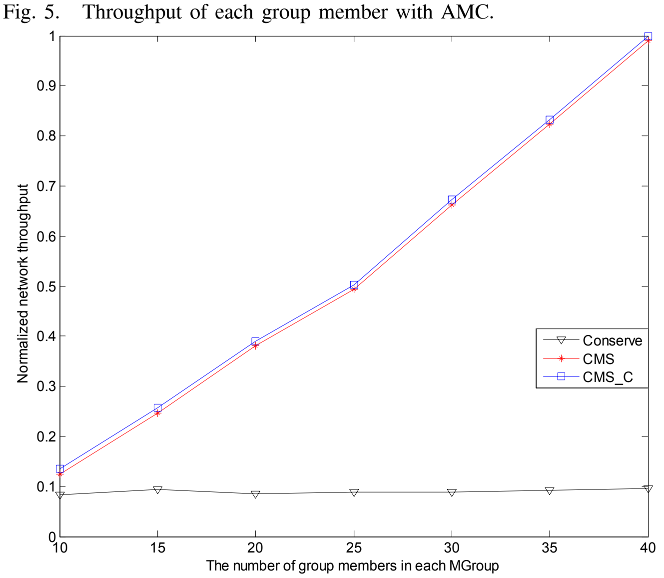



Fig. 6. Network throughput versus the total number of group members in each MGroup.

in Phase II. Simulation results validate the accuracy of our analysis.

## VII. Conclusions

We have proposed a cooperative multicast scheduling scheme for multimedia services in IEEE 802.16 networks. By using two-phase transmissions to exploit the spatial diversity of multiple users in the multicast scenario and the channel-aware MGroup selection mechanism, the proposed scheme can achieve high throughput and maintain good fairness performance. We have also developed an analytical model to evaluate the network performance, which can provide useful guidelines for future multicast services' deployment. How to consider the impact of the mobility and provide service differentiation in multicast services is under investigation.

## Appendix: Throughput Analysis of *Conserve* Scheme

Multicast scheduling scheme, *Conserve*, is used for comparison purpose in the paper, where the BS selects a conservative rate such that all group members in the selected MGroup can support this rate. Let $\gamma_i$ denote the worst received SNR among all group members in MGroup $i$, which is given by

$$\gamma_i = min[\gamma_{i,1},\ \gamma_{i,2}, \cdots, \gamma_{i,N_i}], \tag{22}$$

where $\gamma_{i,j}(j = 1, 2, \cdots N_i)$ denotes the received SNR for $SS_{i,j}$. For Rayleigh fading channel, $\gamma_{i,j}$ follows the exponential distribution and its p.d.f is given by

$$f(\gamma_{i,j}) = (1/\overline{\gamma}_{i,j})\ e^{\gamma_{i,j}/\overline{\gamma}_{i,j}}, \tag{23}$$

where $\overline{\gamma}_{i,j}$ represents the average received signal noise ratio of $SS_{i,j}$ from the BS.

Thus, the p.d.f. of $\gamma_i$ is given by

$$f(\gamma_i) = (\sum_{j=1}^{N_i} 1/\overline{\gamma}_{i,j})\ e^{-\gamma_i\ (\sum_{j=1}^{N_i} 1/\overline{\gamma}_{i,j})}. \tag{24}$$

$$Th_{i,j}^W = \pi_i \alpha \int_0^{\infty} Blog_2(1+\gamma_i) f(\gamma_i) d\gamma_i = \pi_i \alpha B (\sum_{j=1}^{N_i} 1/\overline{\gamma}_{i,j}) \int_0^{\infty} log_2(1+\gamma_i) e^{-\gamma_i (\sum_{j=1}^{N_i} 1/\overline{\gamma}_{i,j})} d\gamma_i$$
$$= \pi_i \alpha B \frac{e^{(\sum_{j=1}^{N_i} 1/\overline{\gamma}_{i,j})}}{ln2} \Psi(\sum_{j=1}^{N_i} 1/\overline{\gamma}_{i,j}) \quad (25)$$

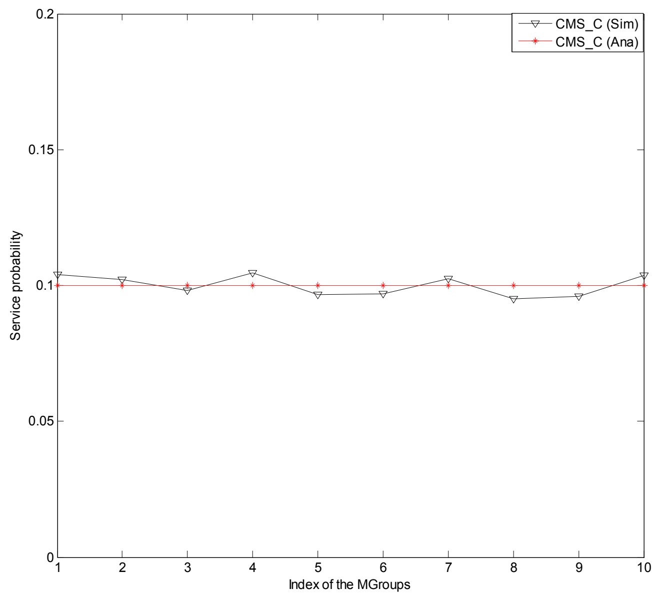



Fig. 7. Service probability of each $MGroup$.

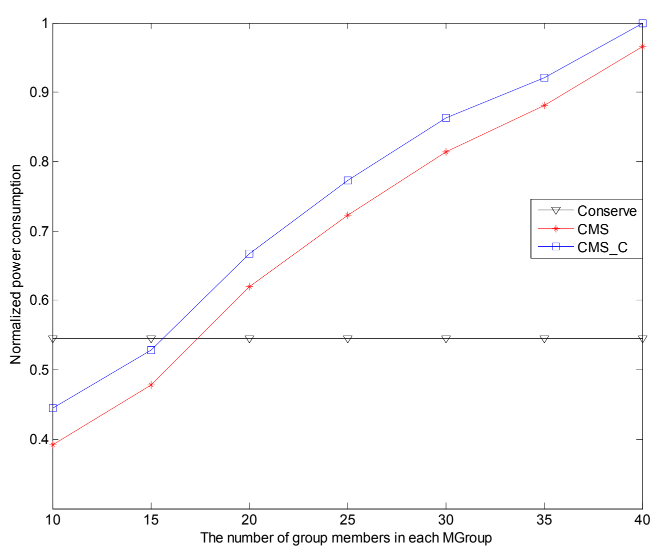



Fig. 8. Power consumption versus the total number of group members in each MGroup.

The average throughput of group member $SS_{i,j}$ is given by (25), where $B$ is channel bandwidth, and $\Psi(x)$ is defined as $\Psi(x) = \int_x^{\infty} e^{-t} \frac{1}{t} dt$.

Thus, the group throughput achieved by MGroup $i$ for the

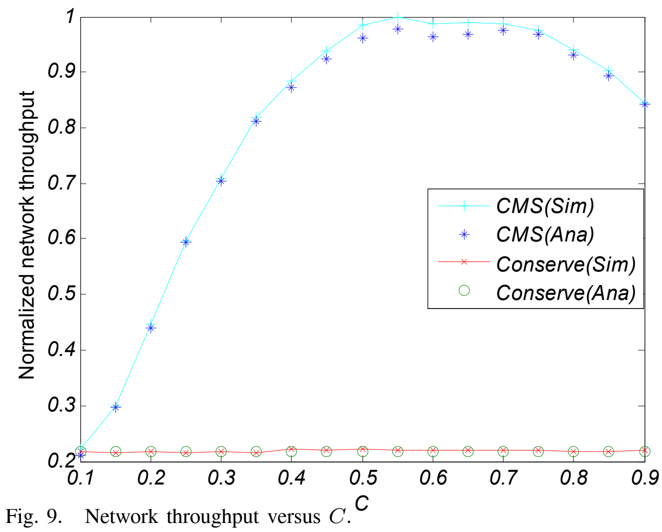



Fig. 9. Network throughput versus $C$.

scheme $Conserve$ is given by

$$Th_i^W = \sum_{j=1}^{N_i} Th_{i,j}^W. \quad (26)$$

## ACKNOWLEDGMENT

The authors would like to thank Dr. G. K. Karagiannidia and Dr. T. A. Tsiftsis for their helpful discussions. This work is partially supported by a Strategic Research Grant from the National Sciences and Engineering Research Council of Canada (NSERC).

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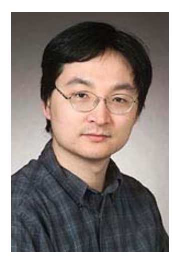

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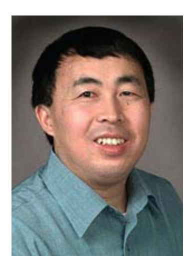

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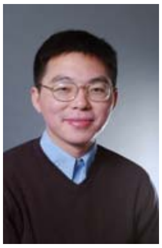

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