OLM: Opportunistic Layered Multicasting for Scalable IPTV over Mobile WiMAX

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Abstract—We propose Opportunistic Layered Multicasting (OLM), a joint user scheduling and resource allocation algorithm that provides enhanced quality and efficiency for layered video multicast over Mobile WiMAX. This work is a lead off and complete synergy of layered video multicasting with opportunistic concept. The target application is characterized by groups of users acquiring popular video programs over a fading channel. To accommodate various bandwidth requirements and device capability, video streams are coded into base and enhancement layers using scalable video coding technology. Correspondingly, the optimization problems, which select the best subset of users to receive a specific video layer and assign the most appropriate modulation and coding scheme for this video layer, are specifically formulated for both video layer types. We also design fast and effective algorithms to bridge the gap between theoretical throughput capacity and implementation concerns. Thus, the basic video quality can be efficiently guaranteed to all subscribers while creating most utility out of limited resources on enhancement information. To overcome the inevitable packet loss in a multicast session, an FEC rate adaptation scheme to approach theoretical performance is also presented. Favorable performance of the proposed algorithms is demonstrated by simulations utilizing realistic Mobile WiMAX parameters.

Index Terms—Resource allocation, scalable video, multicasting, OFDMA, mobile WiMAX.

1 Introduction

With the gradual paradigm shift from analog-to-digital media, from push-based media broadcasting to pull-based media streaming, and from wired interconnectivity to wireless interconnectivity, wireless broadband access with provisioned quality of service (QoS) for digital multimedia applications to mobile end users over a wide area is the new frontier of telecommunications industry [1]. Thanks to the new generation of wireless technology, and cost-effective chipset designs based on volume, a new scalable wireless distribution system architecture without large investment is envisaged. Worldwide Interoperability for Microwave Access (WiMAX) technology, based on current IEEE 802.16-2009, and IEEE 802.16m in the future, for mobile wireless access in metropolitan area networks (MAN), is thus introduced as one of the most competitive solutions for the all-IP-based fourth generation (4G) wireless technology [2], [3].

The emerging deployment of Internet protocol TV (IPTV), which will provide a more function-rich and user-interaction form of TV to the consumers, over the existing IP infrastructure calls for sufficient bandwidth and QoS. Real-time IPTV multicast, characterized by groups of users acquiring popular video programs over a wireless fading channel, is rapidly emerging on the broadband platform. QoS constraints in terms of bandwidth and packet loss are stringent for this class of applications. Mobile WiMAX supports multicast and broadcast service (MBS) while utilizing orthogonal frequency division multiple access (OFDMA) with adaptive modulation and coding scheme (MCS) capability, which enables a better throughput-delay tradeoff by changing the targeted/scheduled users in every transmission [4]. To ensure efficient use of the WiMAX resources and for QoS assurance, effective subscribers' scheduling and radio resource allocation mechanisms are critically needed to deal with the very heterogeneous and dynamic channel conditions of various users who are subscribing to the same video through MBS of WiMAX. However, these mechanisms are not specified in the WiMAX standard, and therefore service providers should have their scheduling and allocation designs. A better design would jointly integrate the scheduling and resource allocation tasks to achieve superior multicast performance and is the key to ensure effective dissemination to users.

Channel conditions of mobile stations (MSs) are time varying and location dependent due to fading and shadowing, the so-called multiuser diversity effect. Since many users fade independently, at any given time some subset of users will likely have strong channel conditions. The opportunistic scheduling takes advantage of the instantaneous channel conditions to derive the instantaneous data rates of each MS [5]. More specifically, each MS periodically measures and reports the channel quality indicators (CQIs)

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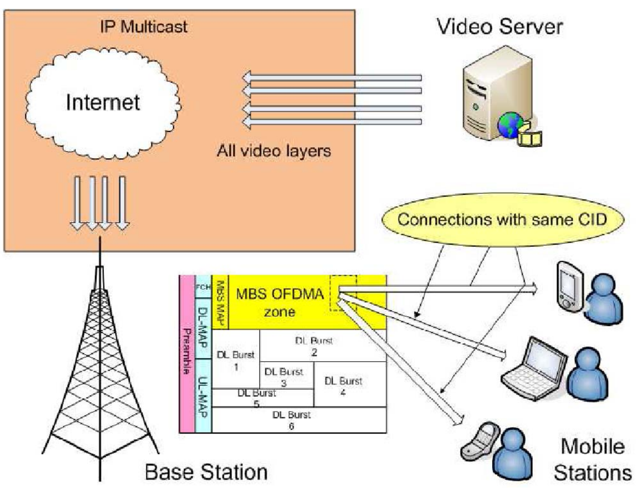


Fig. 1. An end-to-end layered multicast architecture for WiMAX.

to the base station (BS). An opportunistic scheduler at a BS selects a user (or a subset of users) with a relatively good channel condition to transmit while maintaining predefined QoS or fairness constraints. Thus, opportunistic schedulers often achieve higher network performance than schedulers that do not take into account channel conditions, such as round robin ones. For example, if a BS attempts to multicast a stream of bits to two MSs, A and B. In an extreme case, channel qualities of A and B are alternatively fluctuating between binary conditions of good or bad in equal chance and always in opposite state with each other. To guarantee correct receiving of packets, transmission over bad channel requires a more robust modulation and coding scheme carrying 1 bit per resource unit (bpru) comparing to 5 bpru over good channel. Obviously, if we schedule both A and B on every transmission to ensure reliable reception on both MSs, only 1 bpru can be used. However, if we schedule one good MS on each transmission alternatively with 5 bpru, each station can receive 2.5 bpru on average and result in higher throughput. This concept is called opportunistic multicasting [4]. In contrast to opportunistic unicasting, which schedules the best subset of users in each transmission to receive different content separately, opportunistic multicasting schedules the best subset of users in each transmission to receive the same content.

To support high-quality media over heterogeneous wireless medium, the scalability of video streams is another key factor [6]. Conventionally, source rate adaptation is realized through end-to-end (client to server) message exchange based on receiver side real-time bandwidth inference feedback. Scalable bit streams, in contrast, enable the capability of adaptation not only at end nodes, but in intermediate entities. More robust rate adaptation corresponding to rapid fluctuating wireless channel condition can therefore be achieved. The scalable video coding extension of the H.264/AVC standard [7] provides not only the desired scalability but good coding efficiency. Fig. 1 shows an end-to-end layered multicast architecture, which takes advantage of layered video, IP multicast, and MBS in WiMAX. When a video is subscribed at the first time by any user in a WiMAX cell, all video layers will be first sent to the BS, where each layer is sent as a multicast group. Then, for each video layer, the BS determines the set of users to schedule and the modulation and coding scheme used to transmit the data.

Multicast scheduling and resource allocation has attracted growing attention in the literatures. More specifically, resource optimization for layer encoded video over WiMAX using adaptive MCS has been shown in [8], [9]. In [8], the authors propose a resource allocation scheme that first serves all mandatory layers and then offers additional enhancement layers to some scheduled users by optimizing the total utility, which is commonly defined to be proportional to the amount of quality of experience (QoE) of users, within a scheduled frame. Similarly, [9] maximizes total utility in every scheduled frame, where a greedy algorithm is specifically applied to find the best MCS for each layer. Nonetheless, we argue that the throughput can be further improved when temporal optimization across scheduled frames is conducted. The throughput capacity of opportunistic multicasting can be further improved by collaborating with forward error correction (FEC) codes [10], [11]. Authors in [12] further propose an opportunistic scheduling algorithm based on fixed rate of FEC code and throughput requirement per resource unit. Our design leads off the synergy of this concept with layer encoded video and adaptive FEC. Practical scenarios such as resource consumption of OFDMA slots, realistic channel modeling, long-term throughput, are all taken into account for a novel formulation and better system performance of layered video over Mobile WiMAX.

Based on preliminary results in [13], we propose Opportunistic Layered Multicasting (OLM), a complete joint user scheduling and resource allocation algorithm that provides enhanced QoS and efficiency for layered video multicast over Mobile WiMAX based on an opportunistic multicasting optimization formulation. We minimize resource usage across all users for mandatory (base) video layer delivery through adapting MCS. At the same time, the MCS for the optional (enhancement) video layers and the scheduled users are determined to maximize total utility. Thus, the basic video quality can be efficiently guaranteed to all subscribers while creating most utilities out of limited resource on enhancement layers information. An indispensable FEC rate adaptation scheme is developed to provide reliable delivery. To complete the work, heuristic algorithms which bridges the gap between theoretical throughput capacity and implementation concerns are also created and detailed. To the best of our knowledge, OLM is the first joint user scheduling and resource allocation proposal exploiting opportunistic multicasting on layered video. Advantage of our proposed algorithm is demonstrated by simulations utilizing realistic Mobile WiMAX parameters. Moreover, this OFDMA-based opportunistic layered multicast can also be easily applicable to other 4G technology, i.e., Long-Term Evolution (LTE), which is also based on OFDMA technology in the downlink distribution.

The paper is organized as follows: Section 2 addresses related IEEE 802.16 Mobile WiMAX specification. The optimization formulations of the intended problems are addressed in Section 3. We then discuss the proposed joint scheduling and resource allocation algorithms in Section 4.

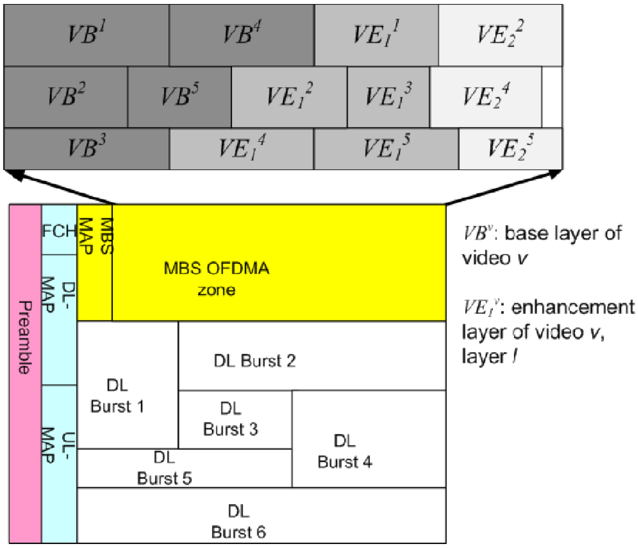


Fig. 2. OFDMA downlink subframe with MBS region in Mobile WiMAX. The MBS region can be further arranged for multiple video layers.

In Section 5, simulation results are presented and discussed, followed by a conclusion in Section 6.

2 Video over Multicast and Broadcast Service in WiMAX

Orthogonal frequency division multiplexing (OFDM) uses a large number of evenly spaced subcarriers for modulation to increase the efficiency of data communications by increasing data throughput. OFDM allows only one user on the channel at any given time. To accommodate multiple users simultaneously, the OFDMA is introduced to allow more flexible multiple access. Like OFDM, which employs multiple closely spaced subcarriers, OFDMA further divides subcarriers into groups, with each group being named a subchannel. In Mobile WiMAX, which uses OFDMA technologies, there are two commonly used subcarrier grouping rules for subchannelization: one is based on diversity permutation and the other is contiguous permutation. The diversity permutation draws subcarriers pseudorandomly to form a subchannel. Due to the frequency diversity and intercell interference averaging provided, the diversity permutation has been recommended for mobile users' scenarios, which calls for the use of partially used subcarrier (PUSC) mode in the resource allocation.

By appropriately adapting the MCS for each video layer in OFDMA frames, a BS decides if an MS can correctly decode transmitted bits given its link quality, so the subset of MSs to be scheduled is determined. This is the typical technique used to execute opportunistic concept, control resource usage, and admit subscribers throughout in our system design.

Multicast and Broadcast Service in Mobile WiMAX is supported by either constructing a separate MBS region in the downlink frame along with unicast service or the whole frame can be dedicated to MBS [3]. Combining with PUCS mode, an OFDMA downlink subframe is illustrated in Fig. 2, where a preallocated MBS region can be further allocated to base layers VB^v and enhancement layers $\{VE_1^v, VE_2^v, \ldots\}$ of the vth video channel.

TABLE 1
List of Notations

Notation	Description
v	Index of a video program
l	Index of a video layer
$\mathbf{N}_v$	The set of subscribe users $\{1, 2, \ldots, N_v\}$ to v
$\mathbf{N}_{v,l}$	The set of admitted users $\in \mathbf{N}_v$ to (v, l)
U	Total amount of resource for the service in slots
m	Index of an MCS $\{1, 2, \ldots, M\}$
c	Slot capacity in bit per second (b/s)
n_{cpsl}	Number of carrier symbols per slot
$n_{bpsy}(m)$	Number of bits per carrier symbol to m
$r_{PHY}(m)$	PHY layer code rate to m
$r_{v,l}$	APP layer FEC code rate to (v, l)
(N, K)	FEC block parameter set
f_m	FEC error margin factor
t_{fr}	Frame duration
t_c	Average window size
T	Throughput b/s
k	Time index of an OFDMA frame
q	Channel quality
$R_{v,l}$	Source data rate of (v, l)
S	Number of slots consumed in a frame
Q	Average OFDMA frame receiving rate
$u_{v,l}$	Utility function of (v, l)

3 Resource Optimization Using Opportunistic Multicasting

The combination of layered video and opportunistic multicasting results in new formulation. Two optimization problems are formulated to solve the joint scheduling and resource allocation problem of layered video. They both exploit the throughput-delay trade-off by selecting MCSs per *OFDMA* frame to opportunistically schedule a subset of admitted users according to some objective functions. As the *video* frame structure is not our optimization focus in the rest of paper, the term *frame* in later discussions strictly refers to *OFDMA* frame. Notations used in the optimization formulations are defined in Table 1.

The whole set of users (or MSs) that subscribe video v is defined as $\mathbf{N}_v$, and those MSs get scheduled to receive the content at any specific time form the subset $\mathbf{N}_{v,l}$. A user is admitted to (v, l), i.e., cumulatively up to the lth layer ($l = 0$ denotes the base layer, and $l > 0$ denotes the enhancement layers) of the vth video if the MCS adaptation attempts to fulfill its channel requirement (in terms of signal-to-noise ratio (SNR)) during scheduling.

For each frame, WiMAX needs to define several MCSs for all bursts according to the continuously feedback SNR values, CQIs. We consider ideal CQI feedback from MSs for analysis. Based on the SNR requirement table (for bit error rate $< 10^-6$) to each MCS, allocated data are assumed to be successfully decoded if users' current SNR is higher than the required SNR of the MCS applied. Based on the assumption of quasi-static fading channel with coherence time t_{fr}, the channel conditions can: 1) remain the same during an OFDMA frame, 2) vary independently frame-by-frame, or 3) vary nonuniformly across the users.

3.1 Theoretical Advantage of Opportunistic Multicasting

In this section, we first demonstrate the advantage of opportunistic multicasting over nonopportunistic scheduling in terms of the long-term slot throughput. With higher slot throughput, fewer number of slots (resource) are required to transmit the same amount of data. In the derivations below, without loss of generality, only G numbers of nodes near the WiMAX cell edge with similar average signal quality are considered since they dominate the system performance in multicasting. Thus, the analyses can be carried out under i.i.d. Rayleigh channel conditions. We model the nonopportunistic throughput by applying MCSs to always meet the channel quality requirement of the worst user, so all users are able to successfully decode data in *every* OFDMA frame. For opportunistic case modeling, we set MCSs to target on the optimal number of users L^* out of G in each OFDMA frame and maximize the throughput. Due to the fact that any user is equally likely to be among the best ones in terms of channel quality, each user can successfully decode data in L^* out of G frames in average.

According to Mobile WiMAX specification, amount of data $c(m)$ (in bit/s) a slot can carry in a scheduled OFDMA frame given a specific MCS choice m is

$$c(m) = \frac{1}{t_{fr}} \cdot n_{cpsl} \cdot n_{bpsy}(m) \cdot r_{PHY}(m), \tag{1}$$

where a slot is the minimal possible data allocation unit, which is defined to be a collection of subchannels along contiguous OFDM symbols of time duration; the code rate $r_{PHY}(m)$ denotes the rate of effective data rate for a given m, due to the choice of the specific channel coding in physical layer.

To get ready for the formulation of the optimization problems, the average capacity of a slot is defined as

$$\overline{C}^{slot} \triangleq \lim_{k\to\infty} \frac{1}{k} \sum_{j=0}^{k} c(m^j), \tag{2}$$

where $\mathbf{m} = \{m^1, m^2, \ldots, m^k\}$ denotes the MCS set. Since not all the transmission slots can be successfully received and decoded due to the potentially noisy channels, effective average slot throughput of user i is

$$\overline{T}_i^{slot} \triangleq \lim_{k\to\infty} \frac{1}{k} \sum_{j=0}^{k} I\left(m^j, q_i^j\right) c(m^j), \tag{3}$$

where $\mathbf{q}_i = \{q_i^1, q_i^2, \ldots, q_i^k\}$ denotes the feedback CQI set and $I(m^j, q_i^j)$ is an indicator function that equals 1 if user i can correctly decode transmitted data and 0 otherwise, given current channel quality q_i^j and the corresponding choice of MCS m^j.

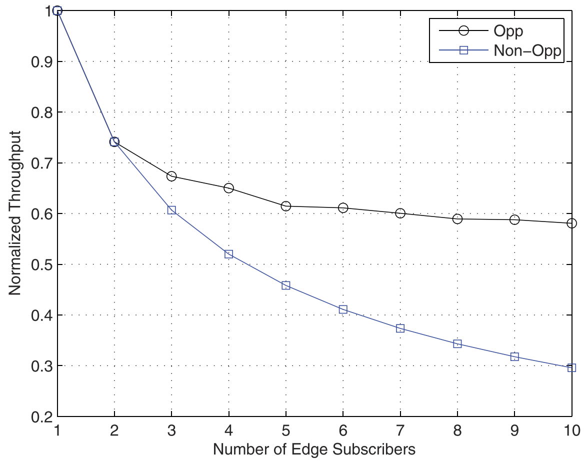


Fig. 3. Normalized throughput versus number of edge subscribers, G. Opportunistic multicasting demonstrates clear advantage when there are more nodes to exploit user diversity.

Under the i.i.d. Rayleigh channel assumption, the signal is exponentially fade in power. So, we let average receiving SNR of user i to be random variable X_i with the cumulative density function (CDF) $F_{\mathbf{x}}(x) = P\{X_i \le x\} = 1 - e^{-\lambda x}$ where X_i is exponentially distributed with mean $1/\lambda$. When the BS determines a specific MCS m to transmit, the SNR requirement is denoted as $X(m)$. To generalize the derivation, the long-term channel capacity in (2) can be modeled as [14]

$$\overline{C}(X(m)) = \log_2(1 + X(m)), \tag{4}$$

in bits/Hz/second. Therefore, theoretical capacity in (4) can be plugged into long-term multicast session throughput in (3) for

$$\overline{T}_i(X(m)) = E[I(X(m), X_i)]E\left[\,\overline{C}(X(m))\right]. \tag{5}$$

We also define random variable $X_{(L)}$ for the Lth largest value of X_i, i.e., $X_{(1)} = \max\{X_1, \ldots, X_G\}$ and $X_{(G)} = \min\{X_1, \ldots, X_G\}$. Thus, we can assign MCSs to meet one of the ordered channel quality anytime, $X(m) = X_{(L)}$, and derive the throughput as in [11]

$$\begin{aligned}\overline{T}_i(X_{(L)}) &= \frac{L}{G} E\left[\log_2\left(1 + X_{(L)}\right)\right] \\ &= \frac{L}{G \ln 2} \int_0^\infty \frac{1 - F_{\mathbf{X}_{(L)}}(x)}{1 + x} dx \\ &= \frac{L}{G \ln 2} \sum_{j=L}^{G} \binom{G}{j} \int_0^\infty \frac{e^{-\lambda x \cdot j} \cdot \left(1 - e^{-\lambda x}\right)^{G-j}}{1 + x} dx.\end{aligned} \tag{6}$$

To model the nonopportunistic scheduling, we have $L = G$ to serve anyone any frame. For opportunistic case modeling, we have $L^* = \arg\max_L \overline{T}_i(X_{(L)})$ to serve optimized subset of users in each frame. As shown in Fig. 3, normalized throughputs of opportunistic and nonopportunistic scheduling are compared side-by-side with various values of G. Generally, the system throughput decreases as there are more nodes around the cell edge and the opportunistic multicasting shows clear advantage over the nonopportunistic scheduling due to user diversity.

3.2 Analytical Formulation of Resource Consumption

We then formulate resource consumption, which is our optimization target, of video layers under opportunistic multicasting scheduling. To take full advantage of the throughput gain shown in Section 3.1 while ensuring received bits are useful for the subscriber set $\mathbf{N}_{v,l}$, the original video stream (v, l) is expanded from video source data rate $R_{v,l}$ to $D_{v,l}$ using application level FEC at optimized code rate r (to be addressed later). In a scalable video system with constant-bit-rate individual layers, the average number of slots consumed S^k at the kth frame for (v, l) can be evaluated given MCS deciding slot capacity $c(m)$

$$S^k = \left\lceil \frac{D_{v,l}}{c(m^k)} \right\rceil. \tag{7}$$

The average throughput $\overline{T}_i$ successfully decoded for user i is subject to the channel quality dependent indicator function

$$\overline{T}_i = \lim_{k\to\infty} \frac{1}{k} \sum_{j=1}^{k} I\left(m^j, q_i^j\right) \cdot D_{v,l}. \tag{8}$$

From (8), we define $\overline{Q}_i$ as average OFDMA frame receiving rate

$$\overline{Q}_i = \lim_{k\to\infty} \frac{1}{k} \sum_{j=1}^{k} I\left(m^j, q_i^j\right), \tag{9}$$

representing the percentage of frames user i receiving given the MCS set. If we apply maximum distance separable (MDS) codes (such as Reed-Solomon codes) or rateless codes (such as Raptor codes), the *ideal code rate* to serve all subscribers $\mathbf{N}_{v,l}$ is the minimum $\overline{Q}_i$ among them, i.e., $\min_{i\in\mathbf{N}_{v,l}} \overline{Q}_i$. This derived amount of FEC can support data rate at $\min_{i\in\mathbf{N}_{v,l}} \overline{T}_i$ to be correctly decoded with high probability [11].

Thus, in order to deliver a video layer, the system requires to spend resource at least maintaining $\min_{i\in\mathbf{N}_{v,l}} \overline{Q}_i \cdot D_{v,l} = R_{v,l}$ to serve a user set $\mathbf{N}_{v,l}$. The average number of slots (amount of resource), $\overline{S}_{v,l}$, in a frame consumed by this layer for an admitted user set can be further formulated by substitute $D_{v,l}$ in (7) using the aforementioned criterion resulting

$$\overline{S}_{v,l} \triangleq S(\mathbf{N}_{v,l}) = \lim_{k\to\infty} \frac{1}{k} \sum_{j=1}^{k} \left\lceil \frac{R_{v,l}}{c(m^j) \cdot \min_{i\in\mathbf{N}_{v,l}} \overline{Q}_i} \right\rceil. \tag{10}$$

However, the ideal code rate can always be achieved only if FEC block size is infinite. In practical video over WiMAX scenarios, the block size is subject to a maximum tolerable delay. The application layer FEC block has parameter (N, K) in terms of frames, i.e., at least K out of N transmitted frames need to be successfully decoded so as to fully recover the original K data frames. The practical formulation is detailed in Section 4.

3.3 Optimization on Mandatory Video Base Layers

In the first optimization problem, the objective is to efficiently (i.e., using least amount resource units) multicast mandatory video streams, usually the base layer $(l = 0)$ with basic perceptual quality, to all subscribers. Note that, in this scenario $\mathbf{N}_{v,l} = \mathbf{N}_v$. The amount of resource consumed in (10) can be minimized when we maximize the minimum effective throughput across all users by dynamically adapting MCS set $\widetilde{\mathbf{m}}$ of allocated slots

$$\begin{aligned}\widetilde{\mathbf{m}} &= \arg\min_{\mathbf{m}} S(\mathbf{N}_v) \\ &= \arg\max_{\mathbf{m}} \left\{ c(m) \cdot \min_{i\in\mathbf{N}_{v,l}} \overline{Q}_i \right\},\end{aligned} \tag{11}$$

subject to

$$\sum_v S_{v,l} \leq U.$$

Only the base layers associated with all the videos channels are considered in case when the required number of slots are more than total preallocated number of slots U for the video multicasting service. In this case, to ensure all base layers are allocated, subscribers with worst channel quality can be dropped from $\mathbf{N}_v$ to allow the choices of more efficient MCS indices so that the total resource budget can be within U slots.

3.4 Optimization on Optional Video Enhancement Layers

After the optimization is carried out for multicasting of base layers, the remaining resources are used to allocate optional video enhancement layers, from which only a subset of users are scheduled to receive, subject to the maximization of a system-wide transmission gain constrained by available resources. The transmission gain used in our formulation is represented by utility functions, $u_{v,l}$, corresponding to subjective video quality gain of user experiences when up to the lth enhancement layer of the vth video are successfully received and decoded. In consequences, the optimization problem jointly considers scheduling (i.e., determine video layers to transmit to a subset of scheduled users) and the resource allocation (i.e., adapting $\mathbf{m}$) can thus be formulated as

$$\max \sum_{v=1} \sum_{l=0} u_{v,l} \cdot \left|\mathbf{N}_{v,l}\right|, \tag{12}$$

subject to

$$\sum_{v=1} \sum_{l=0} S_{v,l} \leq U,$$

where $|\mathbf{N}_{v,l}|$ denotes number of users in $\mathbf{N}_{v,l}$ and $0 \leq |\mathbf{N}_{v,l}| \leq |\mathbf{N}_v|$. We maximize the total utility gained by all scheduled users given the resource constraint and inherited nature of layer dependency (i.e., a scheduled user is allowed to subscribe the lth video layer only if all the lower layers are also subscribed). Note that $u_{v,0}$ denotes the utility contribution from the base layers of all video channels, and the corresponding set of users is all users $|\mathbf{N}_{v,l}|$; therefore, the inclusion of base layers utility does not affect the optimization outcome since no scheduled users selection has taken place.

We tackle this joint optimization problem by iterating the scheduling and resource allocation tasks. Equation (12) requires that a good scheduling candidate should provide maximum utility gain per unit of resource. In other words, to accomplish (12), it is equivalent to solving the subproblem of maximizing the unit utility gain of a specific pair of (v, l), by searching the best MCS $\widetilde{\mathbf{m}}$ and the admitted set $\widetilde{\mathbf{N}}_{v,l}$

$$\begin{aligned}(\widetilde{\mathbf{m}}, \widetilde{\mathbf{N}}_{v,l}) &= \arg \max_{(\mathbf{m}, \mathbf{N}_{v,l})} \frac{u_{v,l} \cdot |\mathbf{N}_{v,l}|}{\overline{S}_{v,l}} \\ &= \arg \max_{(\mathbf{m}, \mathbf{N}_{v,l})} \left\{ c(m) \cdot \min_{i \in \mathbf{N}_{v,l}} \overline{Q}_i \right\} \cdot |\mathbf{N}_{v,l}|,\end{aligned} \tag{13}$$

where $u_{v,l}$ and $R_{v,l}$ (see (10)) are constant given a specific (v, l), and the process continues for the next pair of (v, l) until no available resources left.

4 OLM Resource Efficient Algorithms

In this section, we detail the algorithms designed to solve the corresponding optimization problems, as shown in (11) and (12), with OFDMA-based specification in mind. Different strategies are conducted to mandatory base and optional enhancement video layers. Besides, FEC is implemented in a cross-OFDMA-frame fashion and finite block size N, i.e., every N OFDMA frames.

4.1 Adaptive FEC Code Rate Determination

To ensure every subscriber in $\mathbf{N}_{v,l}$ can receive the video data while choosing the MCS more aggressively, we propose a dynamically adjustable flow-based block erasure (N, K^b) FEC scheme to protect the multicast data, where the bth FEC block uses K^b frames to carry the original data and $N - K^b$ frames to carry FEC redundancy. In other words, the bth FEC block contains N frames from frame $(b-1)N + 1$ to frame bN, and if an MS can successfully decode the data blocks from at least K^b frames out of the N frames in the bth FEC block, it can fully recover the original data carried in the bth FEC block. We choose to adapt K^b with a prespecified fixed length N when generating MDS FEC code to bound the maximum FEC latency. More specifically, we use $N = 200$ in a $t_{fr} = 5$ ms system, this results in one second of delay. The resource efficient value of K^b is determined by

$$K^b = \begin{cases} \lfloor N \cdot \min_{i \in \mathbf{N}_{v,l}} Q_i^{(b-1)N} \cdot f_m \rfloor, & b > 1 \\ \left\lfloor \dfrac{N}{2} \right\rfloor, & b = 1. \end{cases} \tag{14}$$

The average frame receiving rate Q_i^k, instead of using (9), is updated using exponentially weighted recursion for real-time scheduling

$$Q_i^k = \begin{cases} \left(1 - \dfrac{1}{t_c}\right) Q_i^{k-1} + \dfrac{1}{t_c} I\left(m^{k-1}, q_i^{k-1}\right), & k > 1 \\ 1, & k = 1, \end{cases} \tag{15}$$

where t_c is the window size. Also since finite FEC block length and channel quality fluctuation imply the possibility of high decoding error with tight (close to ideal) coding rates. Thus, we apply an *error margin factor* f_m statistically guaranteeing the performance.

In order to decide proper f_m value, the following equation of average *frame error rate* (FER), p, and FEC decode error rate is used:

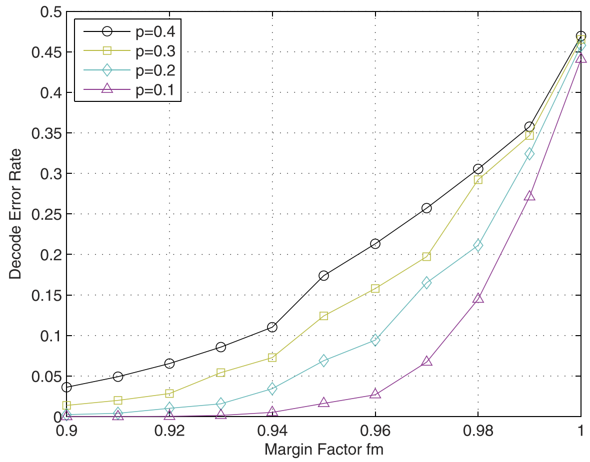


Fig. 4. FEC decode error rate versus margin factor. The best f_m is picked when required error rate is 0.05.

$$\text{Decode Error Rate} = \sum_{a=0}^{K-1} \binom{N}{a} (1-p)^a p^{N-a}. \tag{16}$$

According to the platform detailed later, we set the conservative provisioning FER $p = 0.4$ and target video decode error to be lower than 0.05. As illustrated in Fig. 4, we can search for the largest $f_m (= 0.91)$ to meet the requirements.

For implementation, a BS applies fragmentation/aggregation on the video bit streams to from N equal data blocks given the FEC parameter (N, K^b) at overall data rate $R_{v,l} \cdot (N/K^b)$, i.e., $R_{v,l}/K$ per OFDMA frame. The data block defines the amount of data to be allocated in each OFDMA frame, which must allocate sufficient number of slots (resources) for it. The resource efficient code rate of the bth FEC block, r^b, is thus

$$r^b = \frac{K^b}{N}. \tag{17}$$

4.2 Mandatory Video Base Layer Allocation

To effectively implement the optimization problem of (11), the designed algorithm searches for the best MCS $\widetilde{m}^k$ every OFDMA frame, say the kth, to heuristically approach $\max\{c(\widetilde{\mathbf{m}}) \cdot \min \overline{Q}_i\}$ series as well as least resource consumption. Due to the necessity of real-time scheduling, we design the criterion to be able to evaluate and update progressively for history dependent variable Q. For each frame, the MCS is decided by maximizing the new contributor to the series

$$\widetilde{m}^k = \arg \max_{m \in M} \left\{ c(m) \cdot I\left(m, q_{\widetilde{i}}^{k-1}\right) : \widetilde{i} = \arg \min_{i \in \mathbf{N}_v} Q_i^k \right\}. \tag{18}$$

Intuitively, we jointly consider the maximization of $c(\widetilde{\mathbf{m}})$ and $\min \overline{Q}_i$ by greedily selecting the MCS $\widetilde{m}^k$ for the kth frame based on (18): the BS identifies the subscriber $\widetilde{i}$ with $\min_{i \in \mathbf{N}_v} Q_i^k$ and then selects the best MCS that the subscriber $\widetilde{i}$ can decode.

As shown in Fig. 5, in every frame k, the indicator matrix is evaluated through the most updated CQI feedback and then $\widetilde{\mathbf{m}}^k$ can be found to maximize the target term (18). At the end of an FEC block, its code rate r^b is

1: $b = 1$; $k = 1$; $K^b = \lfloor N/2 \rfloor$; $Q_i^k = 1, \forall i \in \mathbf{N}_v$
2: **repeat**
3: update channel quality q_i^{k-1} and matrix $I(m^{k-1}, q_i^{k-1})$
4: evaluate Q_i^k using (15)
5: find $\widetilde{i} = \arg\min_{i \in \mathbf{N}_v} Q_i^k$
6: find optimized $\widetilde{m}^k = \arg\max_m \left\{ c(m) \cdot I(m, q_{\widetilde{i}}^{k-1}) \right\}$
7: schedule $R_{v,l}/r^b$ of data to be delivered in the k-th frame's OFDMA MBS region using $\widetilde{m}^k$
8: **if** end of the b-th an FEC block **then**
9: $b = b + 1$
10: update K^b using (14)
11: **end if**
12: $k = k + 1$
13: **until** end of video session

Fig. 5. Pseudocode for best $\widetilde{\mathbf{m}}$ series search for mandatory base layer allocation.

updated to ensure efficient usage of resources and keeps up with possible channel quality fluctuation. Given that parameters M, v, and l are fixed and relatively small comparing to potential N_v over service time, complexity of the overall loop is $O(N_v)$.

4.3 Optional Video Enhancement Layer Allocation

For optional video enhancement layers, we execute the optimization formulation of (13) by approaching optimal $\widetilde{m}_{v,l}^k$ every OFDMA frame and updating $\mathbf{N}_{v,l}$ every FEC block. In other words, within an FEC block, a pair of (v, l) is targeted to a fixed set of users, who are dynamically scheduled frame-by-frame within the block. The algorithm in Fig. 6 demonstrates the whole process.

In searching for $\widetilde{m}_{v,l}^k$, operations in Lines 3 to 6 in Fig. 5 are executed first to calculate $\widetilde{m}_{v,l}^k$ and compute the utility function

$$\widetilde{G}_{v,l} \triangleq u_{v,l} \cdot |\mathbf{N}_{v,l}| \cdot \frac{c(\widetilde{m}_{v,l}^k) \cdot r^b}{R_{v,l}} \tag{19}$$

of each (v, l) according to (13). Therefore, we schedule video layers in a descending order of $G_{v,l}$ value until no resource left subject to layer dependency. Note that $\mathbf{N}_{v,l}$ and r^b are fixed during this phase.

At the end of an FEC block, in addition to update K^b, the algorithm searches for the best subset of users to receive this layer of video by picking the bottleneck station $\widetilde{i}$ resulting maximum utility. So, we consider all i dependent terms in (19) to find

$$\widetilde{i} = \arg\max_{i \in \mathbf{N}_v} \left| \{ j : Q_j^k \geq Q_i^k, j \in \mathbf{N}_v \} \right| \cdot Q_i^k, \tag{20}$$

where resulting $\mathbf{N}_{v,l} = \{ j : Q_j^k \geq Q_{\widetilde{i}}^k, j \in \mathbf{N}_v \}$ implies only stations capable of receiving more OFDMA frames than $\widetilde{i}$ are scheduled for this layer. So, the best $\mathbf{N}_{v,l}$ can be continuously updated. The decoupling of $\widetilde{\mathbf{m}}$ (every frame) and $\mathbf{N}_{v,l}$ (end of FEC block) searching results in suboptimal

repeat
for all eligible (v, l) **do**
find $\widetilde{m}_{v,l}^k$ using Fig. 5, Line 3 to Line 6, $\forall i \in \mathbf{N}_{v,l}$
calculate $\widetilde{G}_{v,l}$ using (19)
end for
schedule (v, l) in descending order of $\widetilde{G}_{v,l}$ until no resource left subject to layer dependency
if end of an FEC block **then**
for all eligible (v, l) **do**
find $\widetilde{i} = \arg\max_{i \in \mathbf{N}_v} \left| \{ j : Q_j^k \geq Q_i^k, j \in \mathbf{N}_v \} \right| \cdot Q_i^k$
update $\mathbf{N}_{v,l}$ using $\widetilde{i}$
end for
update K^b using (14)
end if
until end of video session

Fig. 6. Pseudocode for searching $\widetilde{m}_{v,l}^k$ and $\mathbf{N}_{v,l}$ successively for optional enhancement layer allocation.

allocation but makes sure that once a station is chosen to be served, the whole FEC block will not be interrupted. Comparing to the base layer algorithm, the extra loop updating $\mathbf{N}_{v,l}$ has the same search range N_v, so the complexity is still $O(N_v)$.

5 Simulation Results

We introduce simulation platform and comprehensive results in this section. The simulator is built in Matlab with frame-by-frame (OFDMA frame) iteration. In each iteration, the simulator runs the resource allocation algorithm using updated channel quality information. The channel modeling module applies models and parameters described later to update SNR values of each subscriber. In our case, the 95 percent confidence intervals are less than 1 percent in width and are omitted from the results for the sake of clarity.

The preallocated size of the only MBS zone is 25 percent of overall resource to be the limit of the multicasting service can consume. Regarding to overheads, there are 1 MBS_MAP_IE (40 bits), 1 MBS_MAP (28 bits) containing at most $v \cdot l$ number of MBS_DATA_IE (72 bits) [2]. As in Fig. 2, only variable-sized MBS_MAP is located in the MBS zone, so we substract resources for MBS_MAP according to total number of video layered scheduled in this OFDMA frame before video layer allocation. We consider CQI interval to be 1 OFDMA frame in CQICH, while it has been shown that properly reduced frequency on OLM costs little to the performance [15].

5.1 OFDMA Channel Model

In this paper, the configurations of the simulated system are set according to the IEEE 802.16 OFDMA PUSC mode [2]. A cell with three sectors is considered in our simulation,

TABLE 2
System Parameters

Parameters	Value
Operating frequency	2.5 GHz
Duplex	TDD
Channel bandwidth	10 MHz
Cell radius	1.4 km
BS Height	32 m
MS Height	1.5 m
BS Antenna Gain	15 dBi
MS Antenna Gain	-1 dBi
Antenna Pattern	70° (-3 dB) with 20 dB front-to-back ratio
MS Noise Figure	7 dB

TABLE 3
OFDMA Parameters

Parameters	Value
Permutation mode	PUSC
FFT size	1024
Sub-carrier frequency spacing (f)	10.94 kHz
Useful Symbol time $(T_b = 1/f)$	91.4 μs
Guard time $(T_g = T_b/8)$	11.4 μs
OFDMA Symbol Duration $(T_s = T_b + T_g)$	102.9 μs
Frame duration (t_{fr})	5 ms
PUSC Mode	
Null sub-carriers	184
Pilot sub-carriers	120
Data sub-carriers	720
Number of sub-carriers per cluster	24 data+ 4 pilot
Number of clusters per slot	2

where a BS is located in the center and MSs are uniformly distributed within the cell. The system parameters adopted in our simulations are suggested by WiMAX forum as the study case [3]. Table 2 summarizes the system parameters used in the simulations, and the parameters of OFDMA PUSC mode are shown in Table 3. For propagation loss, the COST 231 suburban model with the standard deviation of lognormal shadowing 8 dB is used. Besides, ITU Vehicular A power delay profile [16] is also used in our simulations.

5.2 Performance of Simulation Platform

There are seven MCSs simulated: QPSK 1/2, QPSK 3/4, 16-QAM 1/2, 16-QAM 3/4, 64-QAM 1/2, 64-QAM 2/3, and 64-QAM 3/4. The achievable slot throughput versus distance to BS with fixed MCS is shown in Fig. 7. Based on the given system parameters of the WiMAX with 1.4 Km cell radius, about 20.6 Kb/s can be received at the edge of cells, and, instead of more robust MCSs, 64-QAM 2/3 (with average FER $p = 0.46$) is the favorable MCS. Therefore, the figure confirms possible throughput gain if we can find the best MCS and deal with decoding error.

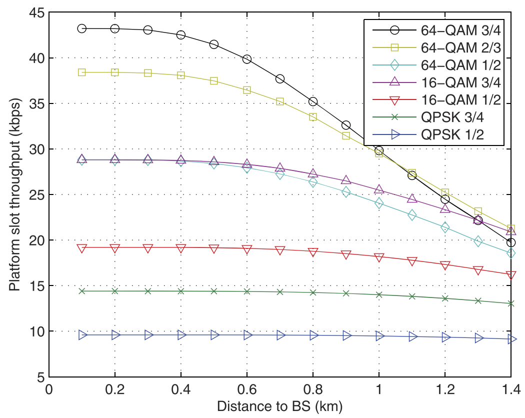
5.3 Mandatory Base Layer Performance

Given $R_{v,l} = 250$ Kbps, several base layer allocation schemes are compared:

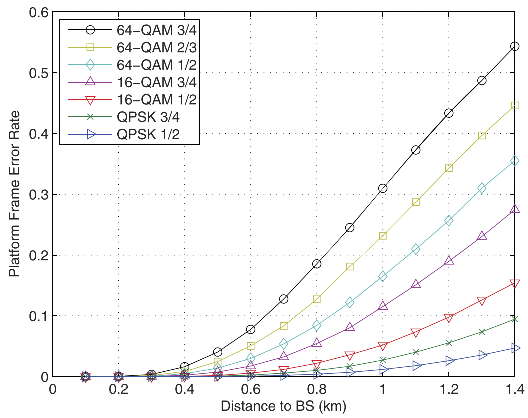
1. proposed OLM method;
2. fixed block length FEC with APP layer code rate $r^b = 0.7$;
3. fixed block length FEC with APP layer code rate $r^b = 0.3$;
4. nonopportunistic schemes in [8], [9].

Note that in all the fixed FEC block length cases, we uses $N = 200$.

Fig. 8 shows the results of average slots throughput versus number of subscribers and decode error rate (after FEC protection) versus number of subscribers. Generally, opportunistic schemes are more favored when the video is more popular. The proposed resource allocation algorithm

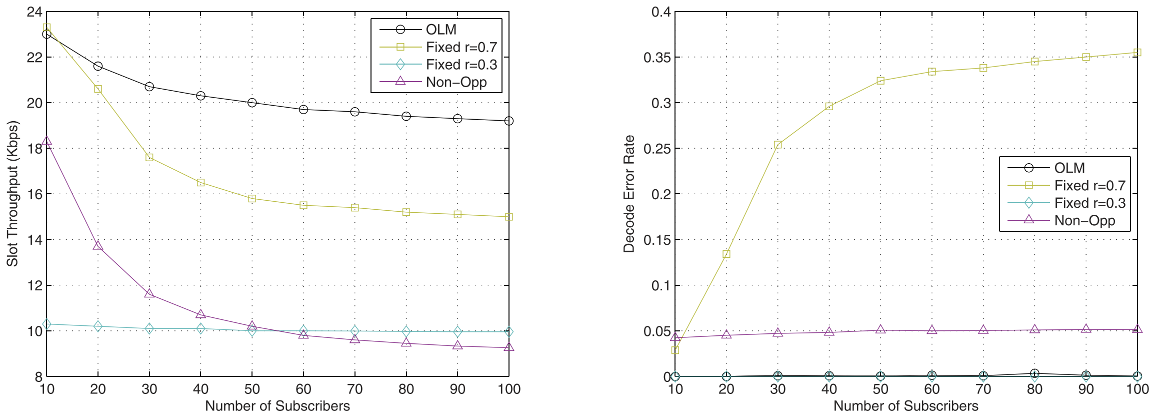


(a) Slot throughput



(b) Frame error rate

Fig. 7. Simulation platform performance. 64-QAM 3/4, or 64-QAM 2/3 actually provide the best throughput at some points. Frame error rates are ranging from 4.7 to 54 percent at the cell edge.



(a) Slot throughput (b) Decode error rate

Fig. 8. Base layer performance. When there are 100 users, the OLM resource allocation algorithm improves nonopportunistic slot throughput 106 percent from 9.3 to 19.2 Kbps while having negligible decode error rates.

find optimal FEC rates frame-by-frame in the range of $r^b = 0.58$ to 0.65. Also, OLM improves slot throughput from 9.3 to 19.2 Kbps (106 percent increase) comparing to nonopportunistic schemes when there are 100 subscribers. The nonopportunistic case also suffers error rate around 5 percent constantly due to deep fading condition of some users. Also, if r^b is fixed and without taking into account the real-time channel condition, either extra resources are consumed ($r^b = 0.3$ too low) or unacceptable error rate is observed ($r^b = 0.7$ too high). OLM with adaptive FEC $f_m = 0.91$ (determined in Section 4.1) provides the best performance where its throughput is optimized while *negligible* loss rate is observed.

If we compare schemes with acceptable receiving quality in terms of decode error rate, they are OLM, $r^b = 0.3$, and nonopportunistic. From Fig. 9, we find that OLM improves average slot consumption against the nonopportunistic one by 58 percent when there are 100 users.

5.4 Overall Performance

We setup a scenario with three videos channels (i.e., $v = 1, 2, 3$) and four layers each (i.e., $l = 0, 1, 2, 3$, three enhancement layers). Specific parameters are overall resource $B = 165$ (1/4 of total channel), $N_v = \{100, 80, 40\}$ subscribers, $R_{v,l} = 250$ Kbps for all (v, l) pair, and $u_{v,l} = \{0.5, 0.25, 0.15, 0.1\}$ for layers 0 to 3 for each v. There are four schemes compared.

The bar plot in Fig. 10 presents the average total utility (by (12)) consumed by each scheme, where normalized base layer and enhancement layer utilities are clearly indicated. We apply an additional criterion that the error rate of (v, l) to an user must be less than 5 percent to support successful video decoding and include in $\mathbf{N}_{v,l}$. For base layer, we notice that not all of subscribers can decode the video correctly if FEC protection is not strong enough (e.g., in the case of $r_{v,l} = 0.7$), resulting in degradation of utility. In the enhancement-layer utility, OLM reserves most resource for optional enhancement layers and further optimized the resource usage for clear advantage.

Besides the total utility, we are also interested in the distribution of top video layer subscribed by each user. Fig. 11 illustrates that OLM make the best quality layer ($l = 3$) successfully decoded by 44 percent of subscribers.

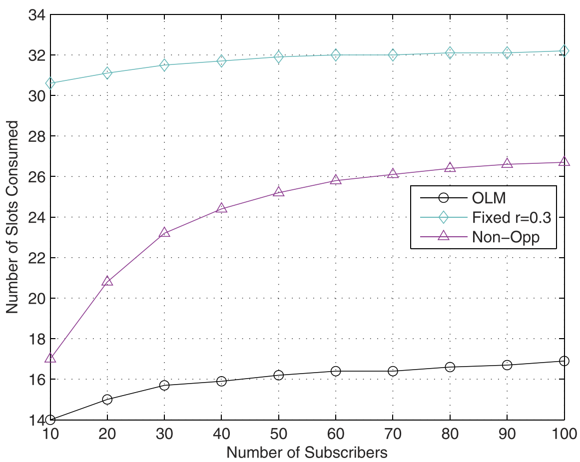


Fig. 9. Number of slots consumed per OFDMA frame. OLM consumes fewer resource to sustain low decode error rate.

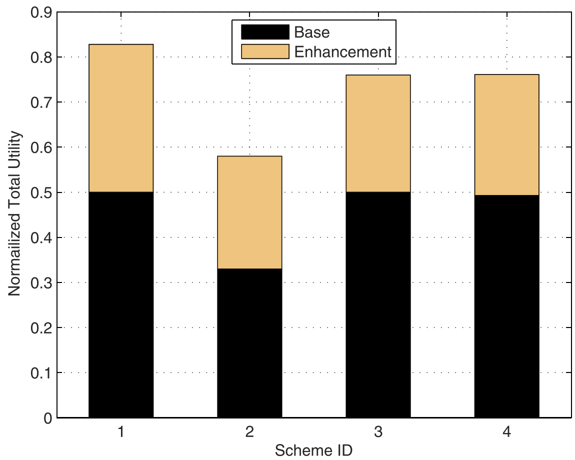


Fig. 10. Normalized total utility under scheme 1) OLM, 2) $r^b = 0.7$, 3) $r^b = 0.3$, and 4) nonopportunistic. Noticeably higher total utility of OLM can be observed.

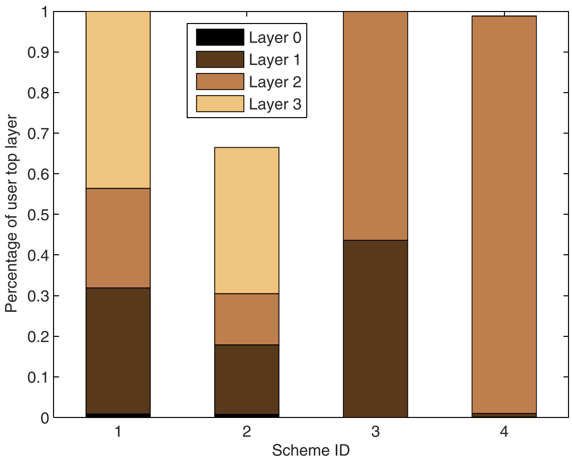


Fig. 11. Top layer distribution among subscribers of $v = 1$ under scheme 1) OLM, 2) $r^b = 0.7$, 3) $r^b = 0.3$, and 4) nonopportunistic. In OLM, 44 percent of subscribers can receive and decode the best quality layer ($l = 3$) video.

Other schemes suffer from either less coverage or failed to push best quality video to users. Overall, OLM utilizing opportunistic adaptive FEC outperforms other schemes.

6 Conclusion

In this work, we contribute the advanced formulation and complete solution for effective multicasting of layered video over Mobile WiMAX. Our simulations show that by incorporating opportunistic concept, the base mandatory video layers can be transmitted using fewer resources while system utility can also be optimized for optional enhancement video layers. The design is not only suitable for Mobile WiMAX systems, but also applicable to all OFDMA systems.

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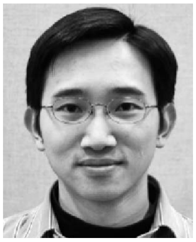

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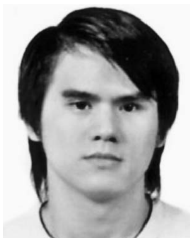

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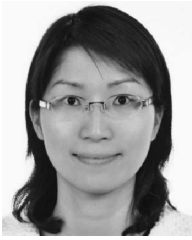

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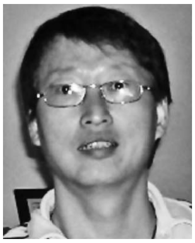

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