System Architecture and Cross-Layer Optimization of Video Broadcast over WiMAX

Jianfeng Wang, Muthaiah Venkatachalam, and Yuguang Fang

***Abstract*— Video broadcast and Mobile TV have received significant interests from both academia and industry recently. The emerging Mobile WiMAX (802.16e) is capable of providing high data rate and flexible Quality of Service (QoS) mechanisms, making the support of Mobile TV very attractive. However, how to efficiently deliver video broadcast over WiMAX is not straightforward, especially in the multi-BS mode. The multi-BS mode requires multiple BSs to be synchronized in the transmission of common multicast/broadcast data. In this paper, we first identify the key design issues for video broadcast over WiMAX in the multi-BS mode. Then, we present an end-to-end solution which fully addresses key issues such as synchronization, energy efficiency and robust video quality. Moreover, we propose a methodology to optimize the coverage, the spectrum efficiency and the video quality. Results show that our proposed scheme can significantly improve the coverage and spectrum efficiency while satisfying video quality requirements.**

***Index Terms*— Mobile TV, WiMAX, macro-diversity, coverage, spectrum efficiency, video quality**

I. Introduction

MOBILE WiMAX has made major strides over the past year and is rapidly proving itself as a leading solution for broadband wireless services. The Mobile WiMAX Air Interface is based on the IEEE 802.16-2004 [1] Air Interface Standard and the IEEE 802.16e Mobile Amendment [2]. Mobile WiMAX Air Interface adopts the Orthogonal Frequency Division Multiple Access (OFDMA) for improved multi-path performance in the non-line-of-sight (NLoS) environments. The inclusion of SIMO/MIMO antenna techniques along with flexible OFDMA sub-channelization schemes, advanced coding and modulation all enable the Mobile WiMAX technology to support high data rates. In addition, OFDMA subchannelization and MAP (a header part of OFDMA frame used to indicate the control information of current frame, like the allocation of subchannel and slot) based signaling schemes provide a flexible mechanism for optimal scheduling of space, frequency and time resources over the air interface on a frame-by-frame basis.

The high data rate and QoS assurance provided by WiMAX make it commercially viable to support multimedia applications, such as video telephony, video gaming, and mobile TV broadcasting. However, to provide mobile TV services over WiMAX, many challenging issues need to be addressed. For example, WiMAX currently defines protocols only in physical layer (PHY) and media access control layer (MAC). Can a simple end-to-end video broadcast solution (such as H.264/RTP/UDP/IP packet transmission over WiMAX MAC/PHY, the so-called IP data cast) work efficiently? Is the video quality smooth during movement and handoff? If the answer is no, what is the best solution? What are the key design issues in such a solution? How many mobile TV channels (e.g., H.264/AVC [14], 320 x 240 pixels, and 30fps) can be supported with the required quality? What about the coverage? How is the energy efficiency? How long does it take to switch video channels? Can we support mobile TV broadcast, two-way voice and data applications simultaneously? To answer all these questions, we need to clearly understand the video traffic (like H.264/AVC), the wireless link budget and wireless channel characteristics. We need to know the packet error rate given packet size, modulation coding scheme and wireless channel condition. We also need to study the relationship between the packet error rate and the effective video frame rate (the average number of video frames per second to be correctly decoded).

The purpose of this paper is to address these questions and design a viable end-to-end solution, which may be the first attempt. We also identify key design parameters and present a methodology to optimize spectrum efficiency (in terms of the number of video channels provided), video quality (in terms of effective frame rate) and coverage area. To the best of our knowledge, such a study has not been thoroughly conducted in the literature [5]–[11].

The rest of this paper is organized as follows. In Section II, we describe the preliminaries of WiMAX multicast/broadcast service (MBS) and the issues in a baseline system. In Section III, we present our proposed end-to-end solution for MBS over multi-BS (Multiple Base Stations). Then, we develop a new methodology to optimize key objectives such as spectrum efficiency, coverage and video quality in Section IV. Section V presents our results to compare the performance of our proposed scheme with that of the baseline schemes. Finally, we conclude the paper in Section VI.

II. WiMAX Basics and MBS Support [1]–[4]

A. OFDMA frame structure

The IEEE 802.16e PHY supports TDD, FDD, and Half-Duplex FDD operation. Fig. 1 illustrates the OFDM frame structure for a Time Division Duplex (TDD) implementation. Each frame is divided into DL and UL sub-frames separated by Transmit/Receive and Receive/Transmit Transition Gaps

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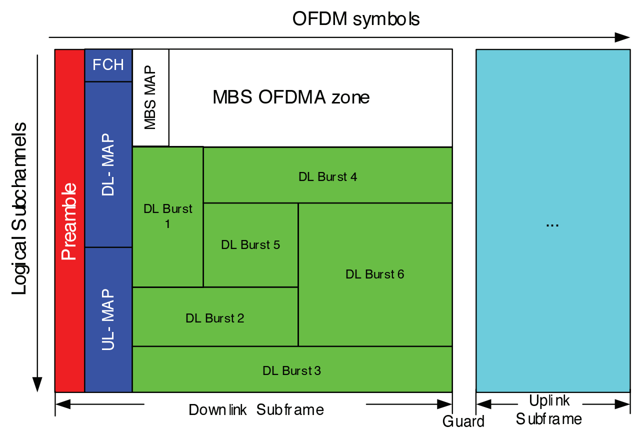

Fig. 1. WiMAX TDD Frame Structure

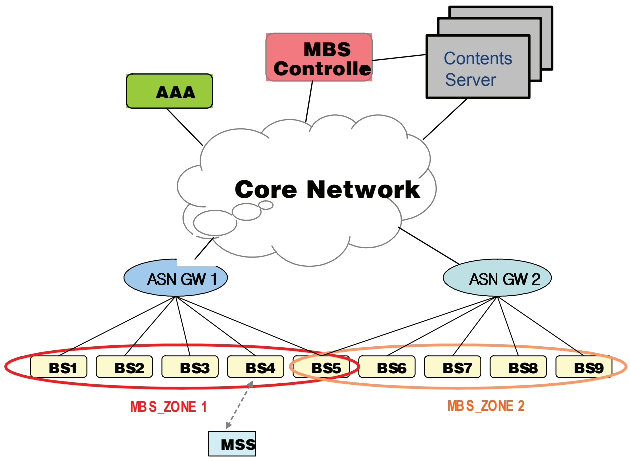

Fig. 2. Network architecture for MBS over multi-BSs

(TTG and RTG, respectively) to prevent DL and UL transmission collisions. In a frame, the following control information is used to ensure optimal system operation:

- Preamble: The preamble, used for synchronization, is the first OFDM symbol of the frame.
- Frame Control Head (FCH): The FCH follows the preamble. It provides the frame configuration information such as MAP message length and coding scheme and usable sub-channels.
- DL-MAP and UL-MAP: The DL-MAP and UL-MAP provide the subchannel and slot allocation and other control information for the DL and UL sub-frames, respectively.

B. PHY/MAC support for MBS

The MBS service can be supported by either constructing a separate MBS OFDMA zone in the DL frame along with unicast service (as shown in Fig. 1) or the whole OFDMA frame can be dedicated to MBS (DL only) for standalone broadcast service. Fig. 1 shows the DL/UL zone construction when a mix of unicast and broadcast service is supported. It may be noted that multiple MBS OFDMA zones are also feasible. There is one MBS MAP IE descriptor per MBS zone to be included in DL-MAP. The MBS MAP IE specifies MBS zone PHY configuration and defines the location of each MBS zone via the OFDMA Symbol Offset parameter. The MBS MAP is located at the 1st sub-channel of the 1st OFDM symbol of the associated MBS zone. One MBS MAP contains multiple MAP_DATA_IEs. One MAP_DATA_IE specifies the connection ID, the location and the PHY configuration (e.g., modulation coding scheme, abbreviated as MCS) of one MBS burst. One MBS burst consists of one or more than one MAC PDU(s).

An MSS (Mobile Subscriber Station) accesses the DL-MAP to initially identify MBS OFDMA zones and locations of the associated MBS MAPs in each zone. Then the MSS can subsequently read the MBS MAPs via MBS MAP redirection without reference to DL-MAP unless synchronization to MBS MAP is lost.

WiMAX supports both single-BS (Base station) mode and multi-BS MBS mode. The multi-BS mode uses Single Frequency Network (SFN) operation. The multi-BS MBS does not require the MSS to be registered to any base station. MBS can be accessed when MSS is in the Idle mode to allow low MSS power consumption. The network architecture of video broadcast over multi-BS is shown in Fig. 2. The flexibility of Mobile WiMAX to support integrated MBS and unicast services enables a broader range of applications.

C. Issues with baseline Multi-BS MBS solution

IEEE 802.16e standard currently only defines the PHY/MAC. One baseline end-to-end multi-BS MBS solution is to use IP data cast of video (e.g., H.264/AVC) over WiMAX (RTP/UDP/IP/WiMAX-PHY/MAC), as shown in Fig. 3. However, such simple IP video data cast does not work well. The following are some key issues.

First of all, synchronization of MBS across multi-BS is hard to achieve. The synchronization here means same video content is transmitted in the same OFDMA frame, the same OFDMA data region by the same channel coding scheme. MBS synchronization is critical not only for achieving macro-diversity and reducing interference, but also for smooth hand-off. The reason why it is hard to achieve synchronization is as follows. As we know, the delay to transmit video data packet copy from MBS Controller to BSs varies over time and varies across BSs. Video data packet copy could also be lost during transmission from MBS Controller to some BS. However, traditionally, each BS makes its own scheduling decision. Therefore, most likely, the same OFDMA region will not transmit the same video data packet.

Second, since the baseline scheme lacks error protection (e.g., Reed-Solomon as the outer coding) beyond PHY/MAC, large-size video frames could be error prone. In order to reduce frame error, strong channel coding should be used in PHY layer. However, this will lead to low spectral efficiency. In addition, if unequal error protection scheme is not available, the video quality will degrade significantly when an MSS experiences shadowing fading, temporal fading or interference. The idea of unequal error protection is to apply more robust channel coding to more important video content. Therefore, the MSS can at least decode some important video frames, e.g., I frame and P frame.

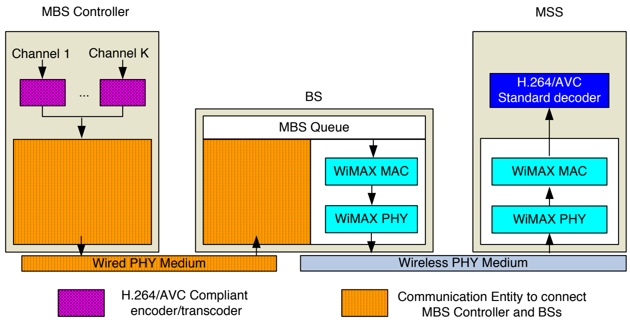

Fig. 3. Baseline MBS system over WiMAX

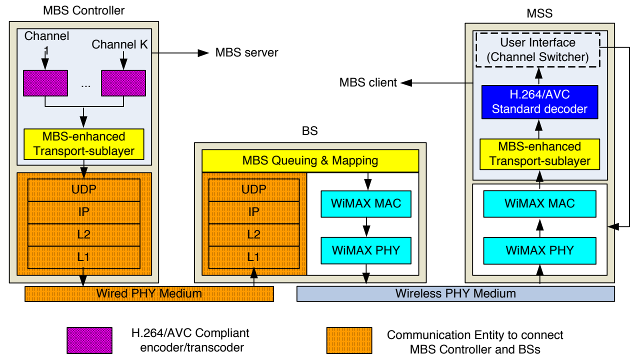

Fig. 4. Proposed end-to-end MBS solution over WiMAX

Third, due to VBR nature of H.264/AVC video traffic, video packets may have to be dropped due to buffer overflow at BS side. Video quality could vary significantly if it is dropped randomly because some important video packets could be dropped.

Fourth, energy efficiency could be low if such simple IP video data cast scheme does not use burst transmission. The burst transmission is a mechanism to allow multiple MAC PDUs belonging to the same video channel to be transmitted/received in an aggregated way. Burst transmission enables MSS to save power by putting transceiver in sleep mode during off-burst interval. However, we need to be cautious when we use burst transmission. If the burst size is too large, video channel switch delay will be too long. In addition, to save power, it is desirable for WiMAX PHY/MAC to decode packets transmitted only on the video channel being currently watched.

Finally, the overhead of RTP/UDP/IP is significant.

All the above issues limit the video broadcast performance over WiMAX. This motivates us to search for a new efficient end-to-end solution. The basic idea is to introduce a MBS-enhanced transport-sublayer into the existing protocol stacks and fully utilize the flexibility of WiMAX PHY/MAC.

III. Proposed End-to-End MBS Solution over WiMAX

A. Overview of the proposed MBS scheme

The proposed end-to-end MBS scheme is shown in Fig. 4. In addition to WiMAX PHY/MAC layers, there are three more functional entities essential to support MBS over WiMAX. These three function entities are MBS server, MBS client, and communication entity between MBS server and BSs.

MBS server consists of H.264/AVC compliant video encoder/transcoder and MBS-enhanced transport-sublayer entity. H.264/AVC compliant video encoder/transcoder conducts video encoding and RTP packetization. MBS-enhanced transport-sublayer entity (at MBS server side) is responsible for mapping video channel ID to multicast connection ID (CID), shaping and multiplexing video traffic, encryption, RS outer coding, constructing MBS_MAC_PDU fitting for transmission over WiMAX PHY/MAC, burst scheduling, and allocating OFDMA data region for each MBS_MAC_PDU.

MBS client consists of video channel switcher, H.264/AVC standard decoder and MBS-enhanced transport-sublayer entity. MSS selects video channel via channel switcher. Channel switcher determines multicast CID according to the selected video channel ID and indicates WiMAX PHY/MAC to decode only those MBS_MAC_PDUs associated with the selected multicast CID. MBS-enhanced transport-sublayer entity (at client side) corrects error of RS sections, decrypts and constructs RTP video packet according to standard H.264/AVC video decoding.

WiMAX PHY/MAC at BS side applies PHY channel coding (specified by MBS server) to each MBS_MAC_PDU and maps each MBS_MAC_PDU to the corresponding OFDMA data region (determined by MBS server) for transmission. One MBS_DATA_IE for each MBS_MAC_PDU will be transmitted in MBS MAP (at the beginning of MBS zone) to indicate the multicast CID and OFDMA data region. At the MSS (Mobile Subscriber Station) side, according to video channel selected by MBS client, WiMAX PHY/MAC decodes only the MBS_MAC_PDUs associated with the corresponding video channel (which translates into multicast CID), thus saving power. Multicast CID and MCS scheme of the targeted MBS_MAC_PDU are retrieved from the received MBS_DATA_IE.

Communication entity between MBS server and BS(s) is provided for transporting video packet from MBS server to multiple BSs, which are physically separated in Multi-BS MBS system. It is worth noting that, in the single-BS MBS system, MBS server and BS may be integrated into one physical entity. In this case, the communication entity linking MBS server and BS is no longer necessary.

Our system has the following salient features. First, we provide broadcast synchronization among multi-BSs through the cooperation between MBS server and BSs. In other words, same video content will be transmitted at the same time and in same frequency subchannel across multi-BSs. In this way, macro-diversity can be achieved and seamless handoff from one cell to another is feasible. Second, we apply RS outer coding and CTC (Convolutional Turbo Code) inner coding to significantly reduce the video frame error rate (FER) without too much overhead. Third, we provide temporal scalability and unequal error protection for H.264/AVC such that the video quality degradation is smooth when users move within and across cells. Fourth, we design a burst-based scheduling/multiplexing scheme whereby a user saves power in decoding what is needed on demand and in burst, without sacrificing channel switch time and multiplexing gain.

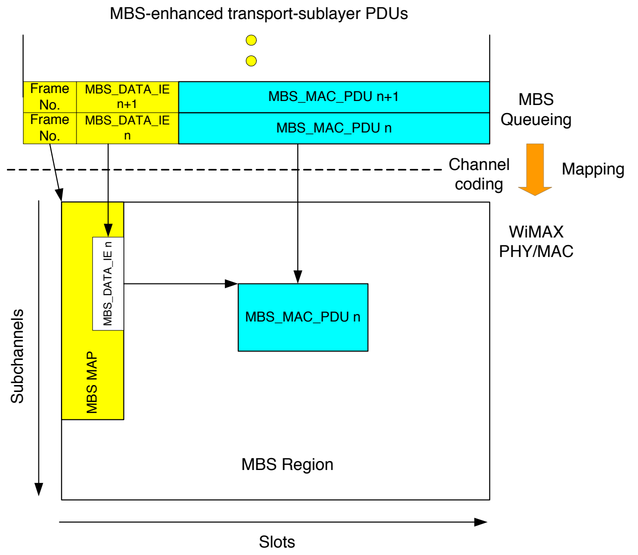

Fig. 5. OFDMA region mapping for MBS_MAC_PDU and MBS_DATA_IE

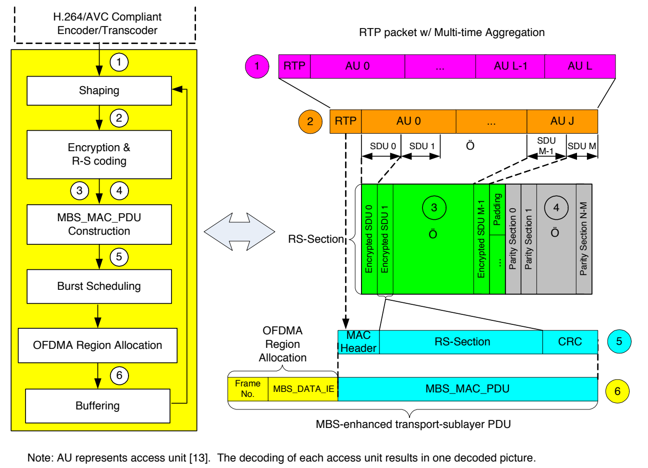

Fig. 6. MBS-enhanced transport-sublayer at server side

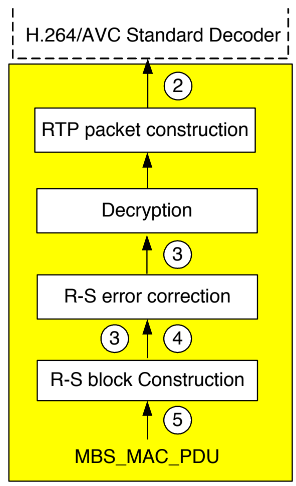

Fig. 7. MBS-enhanced transport-sublayer at client side

Meanwhile, overhead is much reduced by burst transmission and protocol (RTP/UDP/IP) header compression. In addition, security is provided to prevent unauthorized users from accessing the video content. More desirably, we achieve all these features with standard-compliant WiMAX PHY/MAC and H.264/AVC encoder/decoder.

Compared with baseline system (shown in Fig. 3), we add only MBS-enhanced transport-sublayer entity and MBS queuing and mapping entity (shown in Fig. 4). MBS queuing and mapping entity performs operations to buffer MBS-enhanced transport-sublayer PDUs and self-extract them into MBS_DATA_IEs and MBS_MAC_PDUs, as shown in Fig. 5. In the following, we focus on the discussion of MBS-enhanced transport-sublayer.

B. MBS-enhanced transport-sublayer

MBS-enhanced transport-sublayer plays the critical role in video broadcast over WiMAX. The MBS-enhanced transport-sublayer at MBS server side is shown in Fig. 6, the input of which is RTP packet with multi-time aggregation [14], [15] and the output of which is MBS-enhanced transport-sublayer PDUs. The left part of Fig. 6 shows the functional blocks and the right part of Fig. 6 shows the input and output of each functional block.

The MBS-enhanced transport-sublayer at MBS server performs the following functions:

- Map one video channel to one multicast CID
- Shape video traffic according to congestion status
- Add encryption
- Apply Reed-Solomon (RS) outer FEC coding
- Construct MBS_MAC_PDU fit for transmission over WiMAX PHY/MAC
- Choose appropriate inner CTC coding scheme for each MBS_MAC_PDU
- Schedule and multiplex MBS_MAC_PDUs (from multiple video channels) in burst fashion
- Allocate OFDMA data region to each MBS_MAC_PDU
- Construct MBS-enhanced transport-sublayer PDUs

The MBS-enhanced transport-sublayer at MBS client side is shown in Fig. 7, the input of which is MBS_MAC_PDUs and the output of which is RTP multi-time aggregation video packet understood by standard H.264/AVC decoder. Note that WiMAX PHY/MAC at MSS side decodes only those MBS_MAC_PDUs belonging to the multicast CID selected by video channel switcher. Following this, the MBS_MAC_PDUs are passed up to the MBS-enhanced transport-sublayer at client side belonging to the same video channel.

The MBS-enhanced transport-sublayer at MBS client side has the following functions:

- Construct Reed-Solomon block
- Correct Reed-Solomon section error
- Remove encryption
- Construct RTP video packet understood by standard H.264/AVC decoder

As we can see, the MBS client is much simpler than MBS server, which is certainly desirable because MSS has less processing capability and more restricted power-limit.

C. Burst scheduling and OFDMA region allocation

Burst-based transmission is proposed in our system. The scheduling of burst transmission among multiple video channels follows the round-robin algorithm, as shown in Fig. 8. The burst size is chosen to fully utilize frequency diversity and time diversity while balancing energy efficiency and video channel switch delay.

Once a burst is scheduled for transmission, OFDMA frame number and OFDMA data region to transmit each MBS_MAC_PDU is assigned. The OFDMA data region is specified by OFDMA symbol offset, subchannel offset, the number of OFDMA symbols and the number of subchannels.

One MBS_DATA_IE for each MBS_MAC_PDU is constructed to indicate its associated multi-cast CID, selected MCS, and the OFDMA data region. MBS_DATA_IE also includes the redirection to the next MBS MAP which contains MBS_DATA_IE(s) belonging to the same Multicast CID. Via redirection, WiMAX PHY/MAC at MSS side knows the frame number of next OFDMA frame containing MBS_MAC_PDUs which it intends to decode. Since the MBS client knows the end of burst and the beginning of the next burst, MBS can save power significantly by putting transceiver into sleep/idle mode before next burst starts.

D. Channel switching

When MBS client intends to switch to another video channel, it first gets the corresponding new Multicast CID via mapping from video channel to multicast CID. Then WiMAX PHY/MAC checks the MBS MAP in the new OFDMA frame, locates the MBS_DATA_IE containing the new multicast CID and starts decoding the corresponding MBS_MAC_PDU. In the meantime, WiMAX PHY/MAC stops decoding the MBS_MAC_PDUs belonging to the old video channel. Via MBS MAP redirection, WiMAX PHY/MAC knows the frame number of next frame containing interested MBS_MAC_PDUs.

Since MBS client can locate and decode only the packets on the video channel currently being watched, no power will be wasted for decoding unwanted video packets. This is another feature for optimizing energy efficiency in our system.

Define T_i as the transmission time of one GOP sequence for video channel i. The average channel switching time is $T_{cs} \approx \sum_{i=1}^{K} T_i/2$, where K is the total number of supporting video channels.

E. GOP (Group of Pictures) structure and RTP multi-time aggregation

We exploit temporal scalability available in H.264/AVC. We divide each GOP (e.g., $I_0p_1P_2p_3P_4p_5P_6p_7P_8p_9$[1]) into one base-layer GOP sub-sequence (e.g., $I_0P_2P_4P_6P_8$) and one enhanced-layer GOP subsequence (e.g., $p_1p_3p_5p_7p_9$). The encoding of one video picture (or frame) results in one access unit. Correspondingly, the decoding of one access unit results in one complete picture. The decoding sequence is, for instance, ($I_0P_2p_1P_4p_3P_6p_5P_8p_7p_9$). Multiple access units are encapsulated into one RTP packet. By using interleaved mode and multi-time aggregation defined in RFC3984 [15], we allow one RTP packet contains the access units of the whole base-layer GOP subsequence and another RTP packet contains the access units of the enhanced-layer GOP subsequence.

[1]Picture I, i.e., instantaneous decoding refresh (IDR) picture, is coded using intra coding. Pictures P and p are non IDR pictures using inter prediction coding.

To be explained later, the base layer GOP subsequence is applied with more robust FEC coding (RS outer coding and CTC inner coding) than that of the enhanced layer GOP subsequence. In this way, most of users can correctly decode the base-layer all the time. In addition, access units in enhanced-layer may be dropped if the virtual buffer, which contains all the multiplexed MBS-enhanced transport-sublayer PDUs, is larger than certain threshold (in terms of transmission time). The dropping policy is set up in such way that video quality can be kept smooth over time and fair across video channels as much as possible.

In our system, we target H.264/AVC for its technical maturity and commercial availability. However, there is no reason we exclude other video coding schemes in which scalability (temporal scalability, spatial scalability, or SNR scalability) can be exploited. For example, Multiple Description Coding (MDC) scheme could be applied here in a way that one description entity is treated as the base layer and another description entity is treated as the enhanced layer.

F. RS coding and decoding

As we assume, one RTP packet contains multiple access units, i.e., encoding video pictures. After encryption, we apply RS outer coding to each RTP packet to increase the reliability of transmission over WiMAX. More robust RS FEC is used for RTP packet containing base-layer video subsequence than RTP packet containing enhanced-layer video subsequence.

As shown in Fig. 6, each RTP payload is fragmented into fixed-size SDUs. Each SDU is encrypted thereafter. Assume the number of encrypted SDUs is M. N-M parity sections are appended. For convenience, we represent the super RS block as RS(N, M) , where N is RS block size. N and M may vary GOP by GOP. By adjusting N, we can apply unequal protection to base-layer GOP subsequences and enhanced-layer GOP subsequences. (N, M) represents RS code book index, which will be transmitted with RS super block for decoding.

To be discussed next, both SDUs and parity sections are called RS section. Cyclic redundancy check (CRC) is generated for each RS section such that the RS decoder at MBS client can tell whether the RS-section has error, thus increasing error coding efficiency. Note that if $2s+r < N-M$ (s errors, r erasures), then the original transmitted code word will always be recovered. An erasure occurs when the position of an erred symbol is known. A decoder can correct up to $(N-M)/2$ errors or up to $N-M$ erasures.

G. MBS MAC PDU construction

Each MBS_MAC_PDU contains 10-Byte MAC header, L-Byte RS-section and 4-Byte CRC. By checking CRC, the MBS client can determine which RS-section has error. MAC header contains compressed RTP header (which includes RTP

TABLE I
MODULATION CODING SCHEMES AND SPECTRAL EFFICIENCY

Index	MCS	Number of info bits in PUSC Slot
0	QPSK(CTC) 1/2 Rep6	48
1	QPSK(CTC) 1/2 Rep4	48
2	QPSK (CTC) 1/2 Rep2	48
3	QPSK (CTC) 1/2 Rep1	48
4	16QAM (CTC) 1/2 Rep1	96
5	64QAM (CTC) 1/2 Rep1	144
6	64QAM (CTC) 2/3 Rep1	192
7	64QAM (CTC) 3/4 Rep1	216
8	64QAM (CTC) 5/6 Rep1	240

sequence number and RTP timestamp), the type of RS-section (data or parity), the sequence number of RS-section, the size of RS-section and RS code book index.

The modulation coding scheme (MCS) for MBS_MAC_PDU is decided upon its construction. Table I shows some MCSs available in WiMAX (Note PUSC, Fully Used Sub-Carrier, is one of subchannelization schemes). Generally, MBS_MAC_PDUs of base layer use more robust MCS than MBS_MAC_PDUs of enhanced layer.

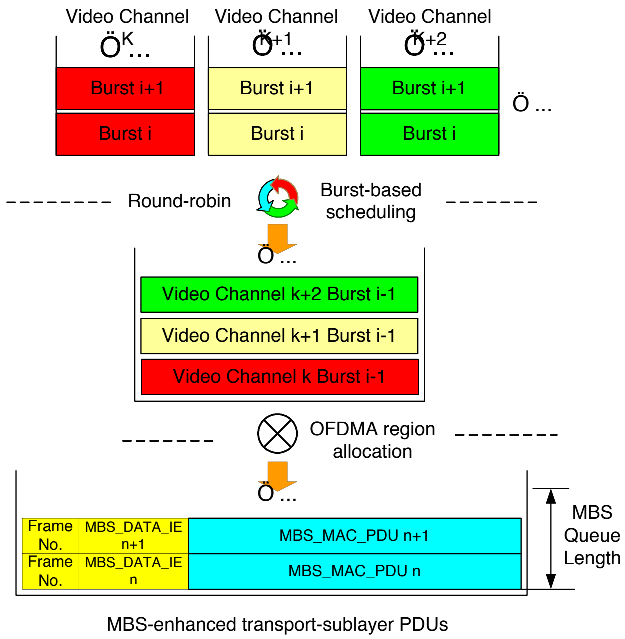

Fig. 8. Round-robin burst-based scheduling

H. Synchronization across multi-BS and macro-diversity

As we have known so far, we allocate schedule-to-transmit OFDMA frame number and OFDMA region to each MBS_MAC_DPU at MBS server side. WiMAX PHY/MAC at BSs side just follows the same schedule made by MBS server and transmits MBS_MAC_DPU copies at pre-determined OFDMA frame and data region with the same PHY channel coding. In other words, same encrypted video content can be transmitted across multiple BSs using the same transmission mechanism (symbol, subchannel, modulation, and etc.) at the same time. In this way, macro-diversity can be achieved and receiving performance can be enhanced.

We notice that the delays to transmit video PDUs from MBS server to BSs can vary from BS to another. So the copies of the same PDU may arrive at BSs in different time. However, this should not be a problem because we allow long enough delay guard such that all the PDU copies can arrive at BSs well before schedule-to-transmit time. In case some PDU copy does not meet the schedule-to-transmit time, it should be dropped at BS.

I. MBS registration, handoff and low-power mode operation

When an MSS is being registered at BS for receiving multicast and broadcast services, it shall initiate dynamic service addition (DSA) procedure with respect to multicast and broadcast connections to inform the BS that the MSS is a consumer of certain multicast/broadcast services. Such knowledge may be used to initiate bi-directional upper layers communication between the MSS and the network for the purpose of configuration of multicast/broadcast service.

Mapping video channels to multicast CIDs shall be known to all BSs belonging to the same MBS geographical zone. In addition, the same security mechanism is applied throughout the same MBS geographical zone. Once an MSS have registered MBS service via one BS in the MBS geographical zone, it should correctly receive video broadcast service throughout the same MBS geographical zone without doing re-configuration and regular handoff when the MSS moves. Moreover, multicast and broadcast service flows are maintained regardless which mode the MSS is operating at. By running idle mode and/or putting MSS into scheduled sleep mode (during off-burst period), MSS can greatly reduce the power consumption by removing unnecessary control signaling and not decoding the unwanted video content.

In case MSS migrates to BS advertising another MBS_ZONE ID, i.e., to another MBS geographical zone, it is expected to register at that BS for further reception of MBS content.

IV. JOINT OPTIMIZATION OF VIDEO QUALITY, COVERAGE AND SPECTRAL EFFICIENCY

In this section, we identify the key design parameters and develop a methodology to jointly optimize video quality, coverage and spectral efficiency, which conflicts with each other in nature.

A. Optimization problem formulation

We use the effective frame rate (EFR) to represent video quality. The effective frame rate is the correctly decoding frame rate per video channel at the application layer. Denote F_b as the base-layer video frame rate and F_e as the enhanced-layer video frame rate (after shaping). F_e is adjusted to meet the total bandwidth requirements. Denote GER_b and GER_e as the base layer GOP subsequence decoding error rate and the enhanced layer GOP subsequence decoding error rate, respectively. The effective frame rate can be lower bounded by

$$EFR \geq F_b\left(1 - GER_b\right) + F_e\left(1 - GER_b\right)\left(1 - GER_e\right). \quad (1)$$

GER_b and GER_e depend on reference distance (d), reference speed (s), channel coding scheme (RS outer coding and CTC inner coding). The channel coding scheme, represented by $\Psi = \{L_b, L_e, \rho_b, \rho_e, MCS_b, MCS_e\}$, is a parameter set which consists of RS section size L, RS coding rate ρ, and MCS scheme for base layer and enhanced layer, respectively. In the following, we use $EFR\,(d, s, \Psi, f_b, f_e)$ to represent the dependence of EFR on various factors.

To meet a certain $EFR\,(d, s, \Psi, f_b, f_e)$, minimal bandwidth (in terms of OFDMA slot rate) per video channel is required. Denote the mean bandwidth requirement (in terms of OFDMA slot rate) for each channel as $R\,(\Psi, f_b, f_e)$. The total bandwidth required to support K video channels can be represented as $K\,(1 + \delta_K)\,R\,(\Psi, f_b, f_e)$, where δ_K is a guard factor (in terms of percentage of mean) provided to absorb video traffic variation. With the consideration of the multiplexing gain, δ_K becomes smaller as K increases.

Since the worst video quality is normally experienced at the cell edge, we can guarantee sufficient video quality throughout the cell if we can satisfy video quality at the cell edge. Let d denote the cell radius. Suppose the effective frame rate requirement throughout the cell is $EFR_{\min}$.

Understanding that the supported number of video channels is a good indicator of the spectral efficiency for video transmission, we formulate the joint optimization of spectral efficiency and video quality as

$$\begin{array}{l} \text{Maximize} K \\ \text{s.t.} \\ EFR\,(d, s, \psi^*, f_b, f_e^*) > EFR_{\min}, \end{array} \tag{2}$$

where ψ^* and f_e^* are derived by

$$\begin{array}{l} \{\Psi^*, f_e^*\} = \underset{\{\Psi, f_e\}}{argmax}\, EFR\,(d, s, \Psi, f_b, f_e) \\ s.t. K\,(1 + \delta_K)\,R\,(\Psi, f_b, f_e) \le \Re, \end{array} \tag{3}$$

where $\Re$ is the total bandwidth (in terms of OFDMA slot rate) available for MBS.

In the following two subsections, we derive the bandwidth requirement $R\,(\Psi, f_b, f_e)$ and RS block decoding error rate GER used for the calculation of $EFR\,(d, s, \Psi, f_b, f_e))$ in detail.

B. Bandwidth requirement ($R\,(\Psi, f_b, f_e)$)

We first calculate the RS block size of one GOP subsequence. Suppose the number of video frame in the base-layer GOP subsequence is Γ_b ($\Gamma_b = F_b/\lambda$, where λ is the GOP arrival rate) and the number of video frame in the enhanced-layer GOP subsequence after shaping is Γ_e ($\Gamma_e = F_e/\lambda$). By following video traffic model (e.g., [12], [13]), we can derive the base-layer GOP subsequence size, represented as $GS_b\,(\Gamma_b)$, and the enhanced-layer GOP subsequence size, represented as $GS_e\,(\Gamma_e)$. Assume β percentage of encryption overhead is added to video traffic. Then we can calculate the number of data RS sections for base layer GOP subsequence, M_b, and the number of data RS sections for enhanced layer GOP subsequence, M_e, as

$$\left\{ \begin{array}{l} M_b = \frac{(1+\beta)GS_b(\Gamma_b)}{L_b} \\ M_e = \frac{(1+\beta)GS_e(\Gamma_e)}{L_e}, \end{array} \right. \tag{4}$$

where L_b and L_e are RS section size for base layer and enhanced layer, respectively. Suppose that the RS coding rate for base layer is ρ_b and the RS coding rate for enhanced layer is ρ_e. Then the number of RS sections for base layer GOP subsequence, N_b, equals M_b/ρ_b. The number of RS sections for enhanced layer GOP subsequence, N_e , equals M_e/ρ_e.

Now we calculate the bandwidth requirement to transmit one GOP subsequence after encryption and RS coding. Denote L_{pdu} as the MAC PDU size and L_{map_ie} as the MAP_DATA_IE size. Denote $BPS\,(MCS)$ as the number of non-duplicate information bytes which can be transmitted in one OFDMA slot under certain MCS. The MCS used to transmit MAP_DATA_IE should be more robust than that for MAC PDU. Then, the total number of OFDMA slots required to transmit one GOP subsequence is

$$\begin{array}{l} S_{GOP-S}\,(N, MCS_{pdu}) = \\ N\left(\frac{L_{pdu}}{BPS(MCS_{pdu})} + \frac{L_{map\_ie}}{BPS(MCS_{map})}\right), \end{array} \tag{5}$$

where the MAC PDU size is calculated by

$$L_{pdu} = MAC\_Header + CRC + L. \tag{6}$$

Note MCS for base layer and MCS for enhanced layer are different, set as MCS_b and MCS_e, respectively. Then the total number of OFDMA slot required to transmit one GOP sequence is

$$S_{GOP} = S_{GOP-S}\,(N_b, MCS_b) + S_{GOP-S}\,(N_e, MCS_e)\,. \tag{7}$$

It can be further represented as

$$\begin{array}{l} S_{GOP}\,(\psi, \Gamma_b, \Gamma_e) = S_{GOP-S}\left(\frac{(1+\beta)GS_b(\Gamma_b)}{\rho_b L_b}, MCS_b\right) \\ \qquad + S_{GOP-S}\left(\frac{(1+\beta)GS_e(\Gamma_e)}{\rho_e L_e}, MCS_e\right). \end{array} \tag{8}$$

Finally, the OFDMA slot rate required to support one video channel can be derived as

$$R\,(\psi, f_b, f_e) = \lambda S_{GOP}\left(\psi, \frac{f_b}{\lambda}, \frac{f_e}{\lambda}\right). \tag{9}$$

C. RS block decoding error rate (GER)

In this subsection, we compute the RS block decoding error rate as a function of such factors as distance d, speed s and channel coding scheme.

For the theoretical analysis, we assume a stationary memoryless channel model. This premise is justified because the shadowing margin and the temporal fading margin are applied and several randomization and interleaving procedures are used.

As we discussed in the previous sections, we use RS outer coding with CRC insertion. Assuming the reliability of CRC for each RS section, the normal RS decoding turns out to be erasure RS decoding. Recall that N is the RS block size and M is the number of data section. The RS block (one GOP subsequence) decoding error probability for erasure RS decoding, denoted as GER, is

$$GER \approx \sum_{i=N-M}^{N} \left(\begin{array}{c} N \\ i \end{array}\right) P_s^i\,(1 - P_s)^{N-i}, \tag{10}$$

TABLE II
TEMPORAL FADING MARGIN (ASSUMING INDEPENDENT RAYLEIGH PATHS AND ITU VEH-A 30KM/H)

MCS	1 RX antenna	2 RX antennas
QPSK (CTC) 1/2 Rep1	9.37	5.84
16QAM (CTC) 1/2 Rep1	9.67	6.22
64QAM (CTC) 1/2 Rep1	9.36	6.54
64QAM (CTC) 2/3 Rep1	11.01	6.43
64QAM (CTC) 3/4 Rep1	11.93	6.81

where P_s is the RS section error rate. Note that, since one RS super block contains several video frames, the RS block decoding error rate represents the upper bound of the derived video frame decoding error rate.

The RS section error rate is

$$P_s \approx 1 - (1 - SLER)^{N_s}, \quad (11)$$

where N_s is the total number of OFDMA slots in an RS section and $SLER$ is OFDMA slot error rate. N_s equals $L/BPS\,(MCS_{pdu})$.

OFDMA slot error rate can be approximated as

$$SLER = 10^{A \cdot C_m + B}, \quad (12)$$

where C_m is the mean capacity and the constants A and B are chosen to fit each MCS curve within the operational range for the given channel model. The mean capacity, C_m, can be calculated by

$$C_m = \log_2\left(1 + SINR_m\right), \quad (13)$$

where $SINR_m$ is the mean SINR (signal-to-interference-noise-ratio) including the shadowing margin and the temporal fading margin. $SINR_m\,(d)$ is calculated by

$$\begin{aligned} SINR_m(dB) &= SNR\,(f, d, H_{BS}, H_{ss}) \\ &+ Md - Sd_m - Fd_m\,(f, s, n_{sc}) - I_m, \end{aligned} \quad (14)$$

where d is the distance, H_{BS} is the BS antenna height above roof-top, H_{SS} is the SS antenna height, f is the carrier frequency, s is the speed, n_{sc} is the number of loaded subcarriers (which represent one RS-section), Md is the macro diversity gain, Sd_m is the shadowing margin, Fd_m is the temporal fading margin (illustrated in Table II), and I_m is the interference margin. SNR, signal-to-noise ratio, takes the relatively static factors such as path loss and cable loss into account. The path loss model for the one applied to non-line-of-sight propagation in urban/suburban macro cellular scenarios, for instance, is represented by

$$\begin{aligned} PL_{ITU-V}(d) &= 80 - 18\log_{10}(\Delta H_{BS}) \\ &+ 40(1 - 4\Delta H_{BS}/1000)\log_{10}(d) + 21\log_{10}(f) \end{aligned} \quad (15)$$

where ΔH_{BS} is the BS antenna height in meters above the average rooftop level, d is the distance between BS and SS in km, and f is the carrier frequency in MHz.

V. RESULTS AND DISCUSSIONS

We set the system parameters as shown in Table III. The total OFDMA slot rate is 144kps. Video traffic follows H.264/AVC QVGA (240*320) with frame rate 30fps, mean data rate 300k bps and peak data rate 384k bps. The GOP structure is IpPpPpPpPp. For simplicity, we assume the mean size of I frame, the mean size of P frame and the mean size of p frame are 2.2K bytes, 1.2K bytes and 1.1K bytes [13], respectively. Guard factor δ_K is set as $0.28\,(1 - K/35)$. Note that we use very robust MCS (QPSK CTC 1/2 Rep 2) to transmit MAP_DATA_IE - this combined with the macro diversity on the MAP_DATA_IE ensures that the error probability of the MAP_DATA_IE is negligible.

We compare our schemes (denoted as Pro-1 and Pro-2) with baseline schemes (denoted as Ref-1 and Ref-2). The characterization of each scheme is shown in Table IV (Note b represents base layer and e represents enhanced layer). The parameters of each scheme are chosen to satisfy our targeted minimal requirements of coverage (d > 2km), mobility (ITU Veh-A 30 km/h) and video quality (EFR > 14.5 fps for case 1; EFR > 28.5 fps for case 2). As shown in Fig. 9, Pro-1 achieves much higher coverage than Ref-1, about 178% higher with EFR > 14.5 fps and 67% higher with EFR > 28.5 fps. Similarly, Pro-2 achieves about 195% higher coverage than Ref-2 with both EFR > 28.5 fps and EFR > 14.5 fps. The gain in coverage is largely due to the increasing macro-diversity gain and frequency-time-diversity gain as well as the reducing interference margin. The macro-diversity gain can be as high

TABLE III
SYSTEM PARAMETER SETTING

Parameter	Value
Frequency Reuse (Cells x Sectors x Frequencies)	1x3x1
Carrier frequency	2.5 GHz
Permutation type	PUSC
BW	10 MHz
FFT size	1024
Cyclic prefix	1/8
OFDMA frame length	5ms
Symbol length	102.86
Data carriers	720
Pilot carriers	120
Cell size	> 2km
Channel model	ITU Veh-A 30 km/h
Path loss model	ITU-R
Shadowing Margin	7.7 dB
Temporal Fading Margin	Lookup (Table II)
Interference Margin	3 dB for baseline scheme 0.5 dB for proposed scheme
BS Height	15 m
BS Rms power/sector	42 dBm
BS Antenna Model	[3GPP]
BS Cable Loss	2 dB
SS Terminal type	handheld
SS Height	1.5 m
SS Antenna	2 omni
SS Noise power	-97.36 dBm
L_{pdu} (bytes)	512

TABLE IV
CHARACTERIZATION OF SCHEMES

	Pro-1	Pro-2	Ref-1	Ref-2
RS coding rate	b=e=5/6	b=4/5, e=5/6	5/6	2/3
MCS: MAC_PDU	b=3, e=4	b=e=4	3	4
MCS: MAP_DATA_IE	2	2	2	2
Multiplexing	Yes	Yes	Yes	Yes
Macro-diversity	Yes	Yes	No	No
Frequency-Time diversity	Yes	Yes	Partial	Partial
Protocol Header Compression	Yes	Yes	No	No

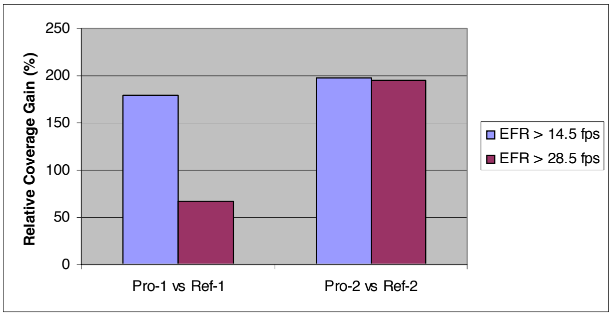

Fig. 9. Relative coverage gain

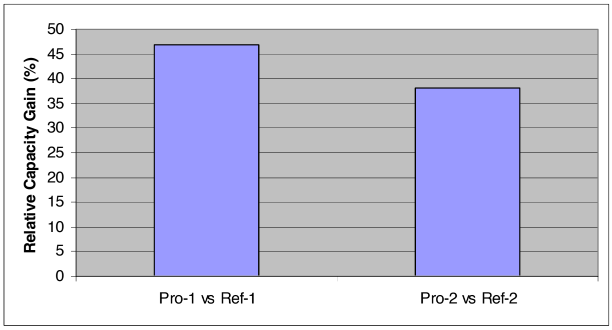

Fig. 10. Relative capacity gain

as 5dB and the frequency-time-diversity can be as high as 3dB. The interference margin can be reduced from 3dB (in baseline scheme) to 0.5dB (in our proposed scheme).

Fig. 10 shows the relative capacity gain (capacity here refers to the number of supporting video channels). Pro-1 supports 47% more video channels than Ref-1 and Pro-2 supports 38% more video channels than Ref-2. There are two folds of reasons. First, our proposed schemes can use higher coding rate to achieve the same EFR, thus reducing channel coding overhead. Second, we apply RTP/UDP/IP compression. For each MAC PDU, we can reduce protocol header size by about 36 bytes.

Fig. 9 together with Fig. 10 shows that we can achieve much higher coverage and support much more number of video channels while maintaining the same video quality.

VI. Conclusion and Future Work

In this paper, we identified the key design issues in video broadcast over WiMAX and proposed an end-to-end solution to support video broadcast over multi-BS with macro-diversity. Some key design problems, e.g., synchronization, have been well addressed in our solution. Moreover, we provide a methodology to optimize the number of supported video channels, video quality and coverage.

The salient features of our system include 1) broadcast synchronization among multi-BSs through the cooperation between MBS controller and BSs, so that macro-diversity can be achieved and seamless handoff from one cell to another is feasible; 2) using Reed-Solomon code as the outer code and Convolutional Turbo Code as the inner code to significantly reduce the video frame error rate (FER) without too much overhead; 3) temporal scalability and unequal error protection for H.264/AVC such that the video quality degradation is smooth when users move within and across cells; 4) a burst-based scheduling/multiplexing scheme whereby a user saves power in decoding what is needed on demand and in burst, without sacrificing channel switch time and multiplexing gain; 5) security mechanisms that prevent unauthorized users from accessing the video content. More desirably, we achieve all these features with standard-compliant WiMAX PHY/MAC and H.264/AVC encoder/decoder.

The simulation results have shown that our proposed solution can significantly improve spectral efficiency and coverage while maintaining satisfactory video quality. In the future work, we will investigate the benefit of MIMO and compressed MBS DATA IE to further improve system performance. We will also study the joint design of video coding (transform-coding) and multiplexing for video broadcast by considering rate-distortion behavior in both time domain and user (video channel) domain. Furthermore, we need to revisit the OFDMA parameter settings such as FFT size, cyclic prefix ratio and OFDMA frame length and find the best setting fit for broadcast service in single-frequency networks.

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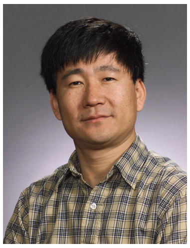

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