Auction based Optimal Subcarrier Allocation for H.264 Scalable Video Transmission in 4G OFDMA Systems

G Chandra Sekhar
Department of Electrical Engineering
Indian Institute of Technology Kanpur
Kanpur, India
Email: gcsekhar@iitk.ac.in

Shreyans Parakh
Department of Electrical Engineering
Indian Institute of Technology Kanpur
Kanpur, India
Email: shreyans@iitk.ac.in

Aditya K. Jagannatham
Department of Electrical Engineering
Indian Institute of Technology Kanpur
Kanpur, India
Email: adityaj@iitk.ac.in

***Abstract*—In this paper, we present a price maximization scheme for optimal OFDMA subcarrier allocation for wireless video unicast/multicast scenarios. We formulate a pricing based video utility function for H.264 based wireless scalable video streaming, thereby achieving a trade-off between price and QoS fairness. These parametric models for scalable video rate and quality characterization are derived form the standard JSVM reference codec for the SVC extension of the H.264/AVC, and hence are directly applicable in practical wireless scenarios. With the aid of these models, we propose a novel auction based framework for revenue maximization of the transmitted video streams in the unicast and multicast 4G scenario. A closed form expression is derived for the optimal scalable video quantization step-size subject to the constraints of the unicast/multicast users in the 4G wireless systems. This yields the optimal OFDMA subcarrier allocation for multi-user scalable video multiplexing. Further, the proposed scheme is cognizant of the user modulation and code rate, and is hence amenable to adaptive modulation and coding(AMC) feature of 4G wireless networks. We simulate a standard WiMAX based 4G video transmission scenario to validate the performance of the proposed optimal 4G scalable video resource allocation schemes.**

I. INTRODUCTION

Orthogonal Frequency Division for Multiple Access (OFDMA) is rapidly emerging as the PHY layer scheme of choice in modern wireless communications and is employed by the dominating 4G wireless standards such as WiMAX and LTE for broadband wireless access. OFDMA enables the transmission of high data rate symbol streams over wideband wireless channels, which would otherwise succumb to the distortion arising out of inter-symbol interference due to the frequency selective nature of such broadband wireless channels. OFDMA is based on Orthogonal Frequency Division Multiplexing (OFDM) which can be implemented by employing low complexity IFFT/ FFT operations. OFDM converts a frequency selective wideband channel into multiple parallel narrowband frequency flat sub-carriers, thereby drastically reducing the complexity of receive processing. These subcarriers are allocated to the users and groups in unicast and multicast scenarios respectively for appropriate periods of time. This process is referred to as time-frequency resource allocation in OFDMA systems and holds key to 4G wireless network performance optimization.

Video based applications such as video conferencing, multimedia streaming, mobile TV and real-time surveillance are emerging as popular 4G applications. Hence, a significant component of the 4G Wireless traffic is expected to comprise of video and multimedia based rich applications. Such video applications require the development of sophisticated multimedia codecs for video transmission in the mobile wireless environment. To ensure video delivery while meeting the video quality guarantees is challenging due to the erratic fading nature of the wideband wireless channel coupled with the disparate device capabilities of the cellular users and QoS requirements. This challenge has led to the development of the Scalable Video Coding (SVC) profile of the H.264/AVC which is attractive specially for video transmission in unicast and multicast wireless scenarios.

Scalable Video Coding (SVC) is a unique paradigm wherein a video is coded as a series of embedded bit streams and is stored at its highest fidelity levels as a combination of several base and enhancement layers [1]. However, a novel feature of such a stream is that partial bit streams can be extracted to fulfill the requirements of the wireless video users depending on the nature of their individual link qualities and device capabilities. SVC enables the filtering and extraction of partial bit streams of diverse spatial, quality and temporal resolutions. The bit-rate and quality of the coded video streams depend intrinsically on the frame rate, spatial resolution and quantization parameters. Hence, these parameters have to be chosen appropriately so as to maximize the net video quality while meeting the end-user Quality of Service (QoS) aspects for video delivery.

Hence, efficient allocation of subcarriers is essential in 4G OFDMA towards meeting the above objective in wireless scalable video transmission. Further, generic subcarrier allocation schemes which are not tailored to the nature of the scalable video streams are not amenable to practical wireless scenarios. Hence, one needs to develop schemes for joint codec-link adaptation in such 4G wireless networks for efficient resource utilization. In this context, we propose a novel revenue maximization [2] framework for optimal H.264 coded video rate based time-frequency resource allocation at the 4G wireless QoS enforcement points such as base stations (BS) and access service network gateways (ASN-GW) in a 4G wireless network. The proposed scheme is based on dynamic subcarrier auctioning which supports pricing based incentives to stimulate users to sell and lease under-utilized sub-carriers, thereby improving the overall efficiency. The users submit their bids for video resource allocation either individually (unicast scenarios) or through content providers (multicast scenarios) which are employed by the QoS enforcer for optimal time/ frequency resource allocation. Since rational users are expected to pay appropriate prices as per allocation of the 4G wireless resources, this naturally leads to revenue maximization towards scalable video transmission in 4G wireless networks. Conventional approaches related to scheduling and resource allocation in 4G wireless systems are not specialized to the context of video and do not consider the scalable nature of video transmission, thereby resulting in suboptimal resource allocation and end-user video quality reduction. The proposed scheme avoids this by direct video codec adaptation, thereby enhancing its appeal for use in practical wireless scenarios.

Towards this end we consider parametric scalable video quality and bit-rate models as functions of the scalable video frame rate and quantization parameter for optimal OFDMA subcarrier allocation. These robust models for H.264 SVC coded streams are computed using the JSVM reference codec and hence are readily applicable in practice. We formulate a constrained convex optimization problem based on the above models for auction based optimal OFDMA resource allocation. We use the robust framework of convex optimization to obtain the closed form expression for computation of the optimal coded video parameters, thus leading to codec adaptation. This results in revenue based end-user video quality maximization and efficient bandwidth utilization in 4G wireless networks. Simulation results demonstrate that the proposed model has a significant performance gain compared to video content agnostic schemes for resource allocation for unicast/ multicast scenarios in OFDMA systems.

The remaining portion of the paper is organized as follows. In section II we explain briefly the scalable video rate, quality and scalable video auction models. In section III we describe the OFDMA paradigm used in this paper. In section IV we present closed form solutions for auction based optimal subcarrier allocation in an OFDMA frame. We illustrate the simulation results in section V. Section VI concludes the paper.

II. SCALABLE VIDEO AUCTION MODEL

The rate and quality of the transmitted scalable video streams are intrinsically related to the quantization parameter and frame rate of the scalable codec and have been derived in [3]. The scalable video rate function $R(q,t)$ in terms of the quantization parameter q and frame rate t is given as,

$$R(q,t) = R_{\max} \underbrace{\left(\frac{1-e^{-ct/t_{\max}}}{1-e^{-c}} \right)}_{R_t(t)} \underbrace{e^{d(1-q/q_{\min})}}_{R_q(q)},$$

where $R_{\max} = R(q_{\min}, t_{\max})$ is the highest bit rate of the highest quality video sequence corresponding to the maximum frame rate $t_{\max}$ and minimum quantization parameter $q_{\min}$, and $R_q(q)$, $R_t(t)$ are the normalized rate function vs quantization parameter and frame rate respectively. Similarly, the scalable video joint Quality function is given as,

$$Q(Q,t) = Q_{\max} \underbrace{\left(\frac{1-e^{-at/t_{\max}}}{1-e^{-a}} \right)}_{Q_t(t)} \underbrace{(\beta q + \gamma)}_{Q_q(q)},$$

where $Q_{\max} = Q(q_{\min}, t_{\max})$ is the hight quality of the video sequence corresponding to the maximum frame rate $t_{\max}$ and minimum quantization parameter $q_{\min}$ and is normalized to 100 i.e. $Q_{\max} \triangleq 100$. The normalized quality functions $Q_t(t)$, $Q_q(q)$ with respect to the frame rate t and quantization parameter q are respectively defined as,

$$Q_t(t) = Q_t(t;q) = \frac{Q(q,t)}{Q(q_{\min}, t_{\max})},$$

$$Q_q(q) = Q_q(q;t_{\max}) = \frac{Q(q,t_{\max})}{Q(q_{\min}, t_{\max})}.$$

The quantities $R_{\max}$, a, c, d, β, γ are the video characteristic parameters and are obtained from the standard JSVM reference codec [4] for the SVC developed jointly by the Joint Video Team (JVT) of the ISO/IEC Moving Pictures Experts Group (MPEG) and the ITU-T Video Coding Experts Group (VCEG). The characteristic video parameter values for standard video sequences are given in [5].

A. Auction Bidding Model

In this section, we present the video auction bidding models employed to derive the optimization framework for revenue maximization subject to the bandwidth constraints and quantization parameter bounds of the video sequence. This is employed to propose a revenue objective function as a function of video quality with the bit-rate constraints for video transmission imposed by the communication system. Naturally, the proposed bid function must be increasing with respect to quality of the video as users are expected to pay higher prices for increased video quality. Several parametric utility functions [2] can be employed as valid bid functions towards revenue maximization. In this context a linear price quality bid function can be presented as,

$$P = eQ + f, \tag{1}$$

where f is the minimum admission price and e is the linear price control factor. Then we consider price as a utility function which is derived from the user requirements. Further, the proposed framework for auction based revenue maximization is general and other allied bid functions such as the logarithmic

Sequence	a_i	c_i	d_i	β_i	γ_i	m_i	r_i	$n_i(multicast)$	$R^i_{\max}$	e_i	f_i	θ_i	b_i
Foreman CIF	7.7000	2.0570	2.2070	-0.0298	1.4475	1	5/6	79	3046.30	6	209	209	410
Akiyo CIF	8.0300	3.4910	2.2520	-0.0316	1.4737	2	2/3	72	612.85	10	185	253	529
Football CIF	5.3800	1.3950	1.4900	-0.0258	1.3872	1	2/3	101	5248.90	6	229	253	488
Crew CIF	7.3400	1.6270	1.8540	-0.0393	1.5898	1	5/6	110	4358.20	9	230	286	532
City CIF	7.3500	2.0440	2.3260	-0.0346	1.5196	1	2/3	116	2775.50	6	236	248	580
Akiyo QCIF	5.5600	4.0190	1.8320	-0.0316	1.4737	4	1/2	48	139.63	6	227	239	592
Foreman QCIF	7.1000	2.5900	1.7850	-0.0298	1.4475	1	3/4	105	641.73	5	289	267	357
City 4CIF	8.4000	1.0960	2.3670	-0.0346	1.5196	4	2/3	102	20899.00	8	141	274	341
Crew 4CIF	7.3400	1.1530	2.4050	-0.0393	1.5898	1	1/2	32	18021.00	9	242	252	509

TABLE I
CHARACTERISTIC VIDEO PARAMETERS OF THE RATE AND QUALITY MODELS FOR THE H.264 SVC STANDARD VIDEO SEQUENCES

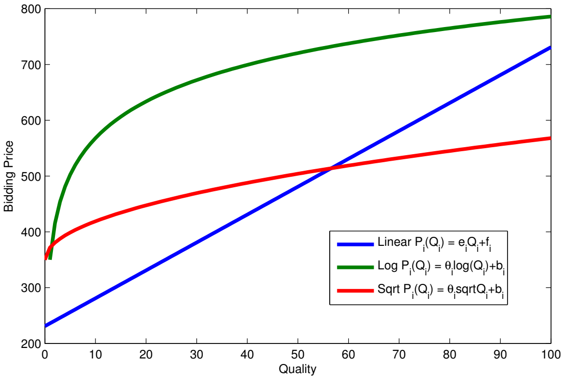

Fig. 1. Comparision of Video Price Bidding Models

and square root functions shown in Fig.1 can be readily incorporated.

III. OFDMA BASED WIMAX WIRELESS NETWORKS

Orthogonal Frequency Division for Multiple Access (OFDMA) is based on the multi-carrier Orthogonal Frequency Division Multiplexing (OFDM) modulation scheme. In OFDM systems the given high bit-rate data stream is divided into lower bit-rate parallel streams, each of which is modulated and transmitted individually over separate orthogonal subcarriers as shown in Fig.2. Hence, In OFDMA systems the available broadband channel is subdivided into different frequency subcarriers which converts the wideband frequency selective channel into parallel narrowband flat fading channels resulting in significantly lower processing complexity. The primary advantage of OFDM is its resilience to delay spread, which arises due to the increased per symbol duration. The presence of the cyclic prefix (CP) greater than the worst-case channel delay spread ensures that the effect of ISI is restricted to the duration of the CP, which can be discarded. The presence of CP converts the linear convolutive channel into a wrapping based circular convolution, which enables low-complexity per-subcarrier frequency domain equalization, thus eliminating the need for complex time-domain equalization [6] [7]. OFDM modulation can be implemented using IFFT/FFT operations at the transmitter and receiver respectively, thereby resulting in a low complexity multi-carrier system even for a large number of subcarriers, which cannot otherwise be implemented employing conventional single carrier modulators. In an OFDM system, OFDM symbols are considered as the time domain resources while the sub-carriers are considered as the frequency domain resources, thereby rendering OFDM suitable for time-frequency resource allocation based optimal transmission. Orthogonal Frequency Division Multiple Access (OFDMA) is a multi-user multiple access scheme in which the data streams of multiple users are multiplexed onto the downlink (DL) and uplink (UL) sub-channels of the OFDM PHY layer. The sub-carrier structure of a typical OFDMA system is shown in Fig.2 and consists of three types of sub-carriers - Data, Pilot and Null sub-carriers. While data sub-carriers are employed for transmission of the modulated user information symbols, the pilot sub-carriers are employed to carry out PHY layer procedures such as jitter, timing delay estimation and frequency synchronization so that the offset errors are minimized. The null or guard sub-carriers avoid overlap with adjacent OFDM bands. Wireless standards such as DSL, WLAN (IEEE 802.11a), WMAN (IEEE 802.16) and fixed WiMAX (IEEE 802.16-2004) employ OFDM as the PHY layer scheme in which a single users uses all the subcarriers at a time. Most of the 4G wireless standards such as LTE, Mobile WiMAX (IEEE 802.16e-2005) employ OFDMA as the PHY layer scheme in which subcarriers and time slots are shared among the users. Multiuser diversity and adaptive modulation makes OFDMA a flexible multiple access technique that allocates subcarriers to the many users with broadly varying applications, data rates and QoS requirements. In our simulations we use the mobile profile of the Worldwide Interoperability for Microwave Access (WiMAX) standard, which is based on the wireless metropolitan area networking (WMAN) standards developed by the IEEE 802.16 group and adopted by both IEEE and ETSI HIPERMAN groups. WiMAX enables the transmission of very high peak data rates through the use of different modulation rates and error correcting coding schemes. WiMAX based on OFDMA PHY supports scalable bandwidth, data-rates and also flexible, dynamic per user resource allocation. WiMAX MAC is designed to support a large number of users, with multiple connections per terminal, each with its own QoS requirement. WiMAX supports strong encryption using Advance Encryption Standard (AES), and has a robust privacy and key-management protocol. All end-

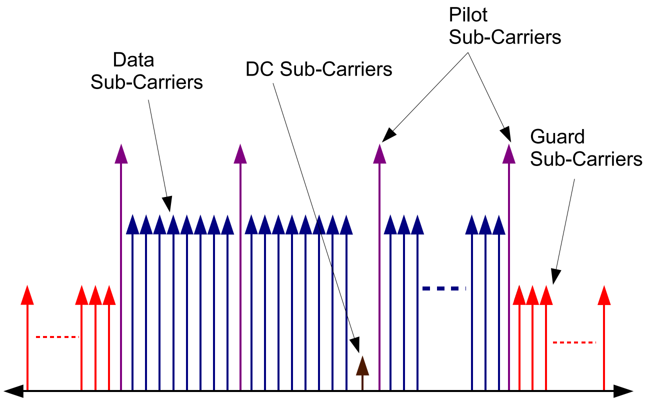

Fig. 2. OFDMA Sub-Carrier Structure

to-end services are delivered over an IP architecture relying on IP-based protocols for end-to-end transport, QoS, session management, security and mobility [8].

IV. OPTIMIZATION FRAMEWORK

The QoS enforcer initially solicits the quality based pricing bids $P_i(Q_i)$ from the users/ content providers in the 4G wireless network. The adaptive modulation coding (AMC) rate aware constrained optimization framework for symbol rate allocation towards auction based revenue maximization in the 4G network can be formulated as,

$$\begin{aligned} \max. \quad & \sum_{i=1}^{N} n_i P_i(Q_i) \\ \text{s.t.} \quad & P_i(Q_i) = e_i Q_i + f_i,\ 1 \le i \le N \\ & \sum_{i=1}^{N} \frac{1}{m_i r_i} R^i(q_i, t_f) \le R_S \\ & q_{\min} \le q_i \le q_{\max} \end{aligned} \tag{2}$$

where R_s denotes the aggregate symbol rate of the OFDMA system and n_i, $1 \le i \le N$ denotes the number of users corresponding to the i^{th} multicast group, where N denotes the total number of groups. The quantities $Q_i = Q^i(q_i, t_f)$ and $R^i(q_i, t_f)$ represent the Quality and Rate of the i^{th} video sequence corresponding to the quantization parameter q_i and fixed frame rate t_f. The adaptive modulation order m_i corresponding to the number of bits per symbol and r_i as code rate of the i^{th} scalable video stream, which is allocated dynamically by the scheduler as per the user DL channel conditions. It can be readily seen that the above problem is convex in nature and the optimization framework can be naturally converted to a standard form convex optimization problem [9] by modifying the optimization objective as,

$$\min. \ -\sum_{i=1}^{N} n_i P_i(Q_i).$$

The above standard form convex optimization problem can be conveniently solved employing standard convex optimization techniques which employ the Karush-Kuhn-Tucker (KKT) framework. The Lagrangian function $L\left(\bar{q}, \lambda, \bar{\mu}, \bar{\delta}\right)$ for the above revenue maximization problem is given as,

$$\begin{aligned} L\left(\bar{q}, \lambda, \bar{\mu}, \bar{\delta}\right) &= -\sum_{i=1}^{N} n_i(\tilde{\beta}_i q_i + \tilde{\gamma}_i) \\ &+ \lambda\left(\sum_{i=1}^{N} k_i e^{d_i(1 - q_i/q_{\min})} - R_S\right) \\ &+ \sum_{i=1}^{N} \mu_i\left(q_i - q_{\max}\right) + \sum_{i=1}^{N} \delta_i\left(q_{\min} - q_i\right) \end{aligned}$$

where $\lambda, \mu_i, \delta_i, 1 \le i \le N$ are Lagrange multipliers, $\tilde{\beta}_i \triangleq e_i Q^i_{\max} Q_t(t_f)\beta_i$, $\tilde{\gamma}_i \triangleq e_i Q^i_{\max} Q_t(t_f)\gamma_i$, and $R^i_{\max}$ is the maximum bitrate corresponding to the i^{th} video stream. The quantity k_i is defined as,

$$k_i \triangleq \frac{R^i_{\max}}{m_i r_i}\left(\frac{1 - e^{-c_i t_f / t_{\max}}}{1 - e^{-c_i}}\right) \tag{3}$$

Applying the KKT conditions for the above Lagrangian optimization criterion and setting $(i.e. \nabla L\left(\bar{q}, \lambda, \bar{\mu}, \bar{\delta}\right) = 0)$ with $\lambda \ge 0, \bar{\mu}_i \succeq 0, \bar{\delta}_i \succeq 0$, we obtain,

$$-n_i\tilde{\beta}_i - \lambda k_i\left(\frac{d_i}{q_{\min}}\right) e^{d_i(1 - q_i/q_{\min})} + \mu_i - \delta_i = 0 \tag{4}$$

From (2), the KKT complementary slackness condition corresponding to the rate inequality constraint is given as,

$$\lambda\left(\sum_{i=1}^{N} k_i e^{d_i(1 - q_i/q_{\min})} - R_S\right) = 0,$$

Therefore, the Lagrangian multiplier λ^* corresponding to the optimal scalable video quantization parameter adaptation obtained by setting $\mu_i = 0$ and $\delta_i = 0$ (corresponding to slack quantization parameter constraints) can be derived as,

$$\lambda^* = -\frac{q_{\min}}{R_S}\left(\sum_{j=1}^{N} \frac{\tilde{\beta}_j n_j}{d_j}\right). \tag{5}$$

We substitute the above expression for λ^* in (4) to derive the closed form expression for the optimal quantization parameter q_i^* as,

$$\begin{aligned} q_i^* &= q_{\min}\left(1 - \frac{1}{d_i}\ln\left(\frac{q_{\min}\tilde{\beta}_i m_i r_i}{\lambda^* k_i d_i}\right)\right) \\ &= q_{\min}\left(1 - \frac{1}{d_i}\ln\left(\frac{R_S}{k_i}\frac{n_i\tilde{\beta}_i\left(d_i\right)^{-1}}{\sum_{j=1}^{N} n_j\tilde{\beta}_j\left(d_j\right)^{-1}}\right)\right) \end{aligned} \tag{6}$$

The above expression yields the optimal quantization parameter q_i^* for the scalable video codec adaptation and time-frequency resource allocation towards video revenue maximization . Thus the above closed form solution provides a fast and low computational complexity scheme for optimal scalable video adaptation compared to employing convex solvers such as CVX and is applicable for both unicast and multicast scenarios.

Further, as described in the section II-A, the proposed optimal framework for the rate constrained time-frequency allocation towards revenue maximization not restricted to linear bidding models and can be readily employed for a large class of utility functions. For instance, consider the general parametric bidding model $P_i(Q_i) \triangleq \theta_i \log_{10}(Q_i)$. The corresponding framework for auction based revenue maximization can be formulated as,

$$\begin{aligned} &\max . \sum_{i=1}^{N} n_i P_i(Q_i) \\ &\text{s.t.} \sum_{i=1}^{N} \frac{1}{m_i r_i} R^i(q_i, t_f) \leq R_S \\ &q_{\min} \leq q_i \leq q_{\max} \end{aligned} \tag{7}$$

Further, another such utility function that can be considered is $P_i(Q_i) \triangleq \delta_i \sqrt{\frac{Q_i}{Q_{\max}}}$. The simulation results below demonstrate the performance of the proposed algorithms for scalable video rate adaptation.

V. SIMULATION RESULTS

In our simulations we consider the streaming of $N = 9$ standard test video sequences [10] and we employ a standard WiMAX profile to illustrate the performance of the proposed optimal OFDMA time-frequency resource allocation schemes. The parameters e_i, f_i, θ_i and b_i corresponding to the bids of the different users are listed in table I. The minimum admission prices f_i and the linear price control factors e_i for the linear price bidding models are chosen randomly in the range 100 to 300 and 5 to 10 respectively. The parameters θ_i and b_i for the non-linear bidding models are chosen randomly in the range 200 to 300 and 300 to 600. The optimal price maximizing bit-rate allocation and the corresponding optimal quantization parameter q_i^* are evaluated by formulating the optimization problem in (2) and computing the optimal solution using the closed form expression in (6). We compare our allocation with the one obtained from the standard CVX based convex solver [11]. The corresponding per video sequence optimal quantization parameter q_i^*, optimal price maximizing bit-rate allocation are listed in table II for the logarithmic bidding model using the WIMAX profile mentioned in [5] with the effective downlink symbol rate $R_s = 6.336$ Msym/s. Further, the corresponding values for the sub-optimal equal bit-rate allocation are also given therein. The associated net revenue comparison for the optimal bit-rate allocation and equal bit-rate allocation for a unicast scenario at various values of symbol rates R_s is given in Fig.3 for the linear bidding function auction. Similarly, Fig.4 demonstrates the comparison for a multicast scenario with the number of multicast subscribers for each group chosen randomly in the range 10 to 150. Form Fig.3 we can observe that the closed form solution allocation from (6) closely agrees with the CVX solver based allocation. We also present the OFDMA multi-user DL-MAP for subcarrier allocation in both equal and optimal bit-rate allocation scenarios in Fig.5 and Fig.6 respectively, for the log pricing based video auction. From the simulation results we can observe that the optimal symbol rate allocation framework yields significant improvement in the net video revenue and can be conveniently employed by the QoS points and Core Network in 4G wireless scenarios.

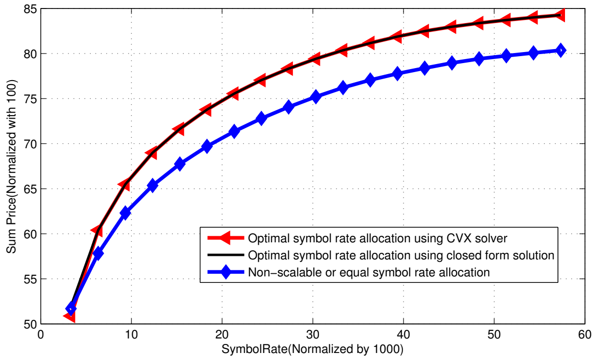

Fig. 3. Symbol rate vs. sum price for unicast scenario at $t = 30$ fps and price as a linear function of quality $(P = eQ + f)$.

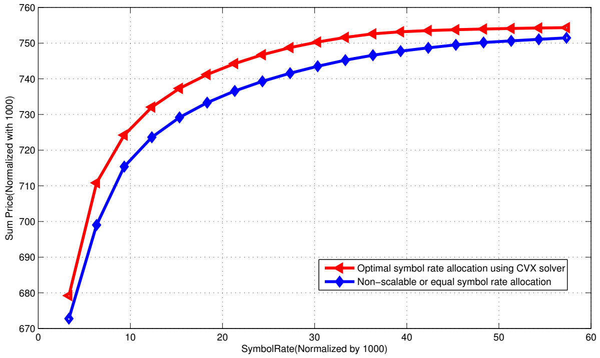

Fig. 4. Symbol rate vs. sum price for multicast scenario at $t = 30$ fps and price as a logarithmic function quality $(P_i(Q_i) = \theta_i \log_{10}(Q_i) + b_i)$.

VI. CONCLUSION

We proposed and presented an auction based scheme for the subcarrier allocation towards revenue maximization in a 4G OFDMA system. The proposed scheme is based on the bidding mechanism, where users of unicast video streams and service providers in multicast scenarios submit their bids to the resource scheduler at the base station. An optimization framework has been proposed for optimal resource allocation with respect to the OFDMA aggregate rate constraints and adaptive modulation and coding paradigm in 4G systems. A closed form solution has been derived for the optimal quantization parameter based link-codec adaptation in OFDMA systems. Further, this framework has been shown to be general in nature and can be readily extended to a variety of suitable utility functions for optimal resource allocation. It has been shown through simulations that the presented optimal subcarrier allocation yields improved performance compared to the

Sequence	Equal Symbol Rate Allocation		Optimal Symbol Rate Allocation					
			Unicast Scenario			Multicast Scenario		
	R^i_{equal}	qp^i_{equal}	R^i_{opt}	q_i^*	$n_iP_i(Q_i)$	R^i_{opt}	q_i^*	$n_iP_i(Q_i)$
Foreman CIF	704	26.195	376.67	29.207	777.96	355.06	29.608	613.08
Akiyo CIF	704	15.000	463.26	16.864	1028.30	402.36	17.809	737.87
Football CIF	704	39.307	611.17	36.648	904.06	679.11	35.587	919.78
Crew CIF	704	31.225	921.64	27.570	1019.30	1078.20	26.301	1134.10
City CIF	704	26.461	400.17	27.489	1015.00	499.05	26.065	1187.80
Akiyo QCIF	704	15.000	139.63	15.000	1070.00	139.63	15.000	513.60
Foreman QCIF	704	16.639	360.62	19.843	872.91	422.78	18.507	922.10
City 4CIF	704	30.272	2023.20	29.797	1433.50	2285.90	29.024	1468.60
Crew 4CIF	704	39.547	802.12	34.410	853.38	528.20	37.016	253.88

TABLE II

SYMBOL ALLOCATION FOR EQUAL AND OPTIMAL SYMBOL RATE USING LOGARITHMIC BIDDING PRICE $P_i(Q_i) = \theta_i \log_{10}(Q_i) + b_i$, IN UNICAST AND MULTICAST SCENARIOS. THE BIDDING PRICE VALUES FOR MULTICAST ARE NORMALIZED BY 100.

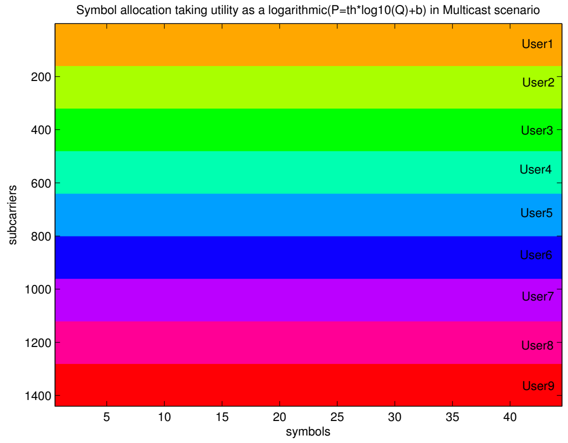

Fig. 5. Allocation of symbols to videos with equal symbol rate allocation.

suboptimal equal subcarrier allocation for the case of DL/UL PUSC WiMAX.

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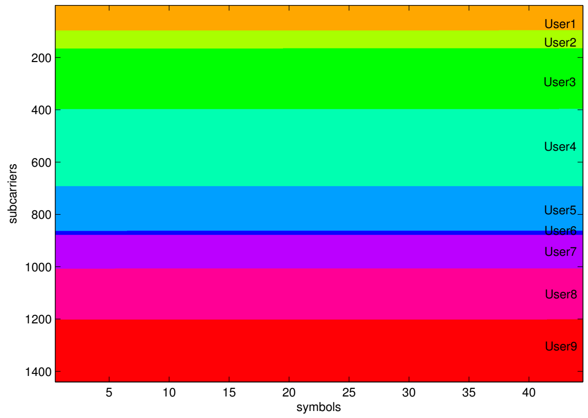

Fig. 6. Allocation of symbols to videos with optimal symbol rate allocation using price as a logarithmic function of quality $(P_i(Q_i) = \theta_i \log_{10}(Q_i) + b_i)$ in multicast scenario.