RESEARCH PROJECT

Final Report on Optimal Game Theoretic Policies for Spectrum Auction and Trading

Submitted to
IIMA-IDEA Telecom Center of Excellence (IITCOE)
on

VCG and Parametric Bidding Auction Based Optimal Resource Allocation for H.264 Scalable Video Transmission In 4G WiMAX

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VCG AND PARAMETRIC BIDDING AUCTION BASED OPTIMAL RESOURCE ALLOCATION FOR H.264 SCALABLE VIDEO TRANSMISSION IN 4G WIMAX

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Executive Summary

In this final project report[1], we present a novel application of the Vickrey-Clarke-Groves (VCG) auction based time-frequency resource allocation for H.264 SVC based scalable video transmission in 4G wireless systems. The net transmitted video quality corresponding to the given bitrate constrained wireless system can be maximized by optimally allocating the OFDMA time-frequency resources amongst the video streams requested by the different unicast/ multicast groups. However, such a centralized allocation is susceptible to subversion resulting from misrepresentation of the characteristic video parameters by malicious users. This, in addition to resulting in a degradation of the net video quality, might also benefit the users reporting incorrect parameter values through disproportionate resource allocation. Our simulation results demonstrate that application of the proposed VCG procedure maximizes the net utility in broadcast/ multicast video streaming when true characteristic parameters are reported, while punishing malicious users when one or more parameters are misreported.

We also 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

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[1] The work presented in this report has been published in the following papers -

Shreyans Parakh, Aditya K. Jagannatham, “VCG Auction Based Optimal Allocation for Scalable Video Communication in 4G WiMAX”, In Proceedings of the Eighteenth National Conference on Communications (NCC 2012) held at the Indian Institute of Technology Kharagpur.

G. Chandra Sekhar, Shreyans Parakh, Aditya K. Jagannatham, “Auction Based Optimal Subcarrier Allocation for Scalable Video Transmission in 4G WiMAX”, submitted to the IEEE India Conference (INDICON 2012).

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.

1 Introduction

Wireless multimedia streaming services have witnessed a tremendous surge in demand with the deployment of 4G broadband wireless cellular networks. Technologies such as WiMAX, LTE provide high data rates and reliable wireless services to the users. Some applications based on video transmission are mobile TV, high speed interactive gaming, video conferencing and multimedia streaming. Modern 4G systems like WiMAX, which incorporate Orthogonal Frequency Division for Multiple Access (OFDMA), necessitate the development of optimal schemes for time-frequency resource allocation and management.

In this context of wireless video transmission, H.264 scalable video coding (SVC) [1] has been proven to be ideally suited for video coding due to its ease of rate adaptability as suited to the wireless link quality. SVC based video transmission ensures fairness in QoS by transmitting the coarse base layer of the scalable video stream to all the end-users subscribing to the video service under consideration. Compared to the spatial and temporal modes of scalability, the quantization parameter of a video stream can be adapted on a much finer scale and allows for greater flexibility towards optimal time-frequency resource allocation. Our previous work in [2] for optimizing the bitrate of a video has addressed the issue of optimal quantization parameter selection for video quality maximization in the context of 4G resource allocation. However, the allocated bitrate and quality of video depends critically on the intrinsic video motion parameters. The optimal solution and the highest video quality is hence obtained only when the parameters are reported accurately by the unicast/ multicast subscribers or service providers. Malicious users can distort the resource allocation scheme at the QoS enforcement points (such as base stations and service gateways in WiMAX) by misreporting the parameter values thereby resulting in suboptimal resource allocation and disproportionate benefits to the malicious users.

Game theory [3]-[4] based resource allocation provides an ideal framework to optimally allocate resources in the presence of such distorting malicious users. Its applications have been recently extended to the field of wireless communication, especially in the context of resource optimization [5]. In the context of 4G wireless video communication, game theory based Vickrey−Clarke−Groves auction procedure can be adapted for time-frequency (TF) resource allocation. The auctioned item in this context is the bitrate corresponding to the allotted TF resources, and the bidders/ decision makers are the service providers or users themselves. The auctioneer is the QoS policy enforcer in the 4G wireless network. This interaction between various decision makers is akin to a strategic game and the decision makers are also termed as players in the nomenclature of game theory. We assume that all the players are rational and are driven towards utility maximization. Each user reports the characteristic video parameter values to the policy enforcer to calculate the sum utility function. Unlike conventional utility based exclusively on video quality, the VCG procedure employs the pricing based net utility function, which prices the TF resources in accordance with the allotment. Hence, users misreporting the parameters are punished by the QoS enforcer through higher resource pricing, in turn resulting in a reduced net utility for the malicious user. Hence, the VCG procedure naturally discourages users' malicious tendency towards misreporting and forces them to report accurate parameter values for maximizing net utility.

Some research regarding the use of game theory with malicious users has been considered in [6] in the context of peer-to-peer live streaming. The research in [7] proposes a Vickrey scheme for computing the shortest path in a decentralized network. The authors in [8] present the application of VCG procedure in mechanism design. In this report we are primarily concerned about the misreporting of the quantizer based rate and quality parameter values. The framework can readily be extended to VCG based optimization for malicious users misreporting other parameter values. The bitrate and quality of video can be modeled as function of the quantization parameter and frame rate. Hence, the VCG based TF bitrate optimization can be performed through the robust framework of convex optimization [9]. Simulation results presented in the end demonstrate the effectiveness of the proposed VCG framework for video pricing based optimal OFDMA resource allocation and malicious user retribution.

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 sub-carriers 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 [10]. 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 [11] 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 rest of the report is organized as follows. Section 2 we explain briefly the scalable video rate, quality and scalable video auction models used in the report. Section 3 describes the VCG procedure based resource allocation. In section 4 we describe the OFDMA paradigm used in this report. In section 5, we present closed form solutions for auction based optimal subcarrier allocation in an OFDMA frame. In section 6, we present the behavior of the net utility function based on the reported video characteristic parameter values. Finally, we conclude the report in section 7.

2 Scalable Video Model

In this section we present the quantization parameter based quality and bitrate models for H.264 scalable video encoding. 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 [12]. The bitrate of the partial video streams can be obtained by encoding the video at various quality levels using the Joint Scalable Video Model (JSVM) reference video codec [13]. It has been demonstrated in literature [12] that the bitrate $R(q, t)$ of a video can be expressed as independent normalized functions of the frame rate t and quantization parameter q. The scalable video rate function $R(q, t)$ in terms of the quantization parameter q and frame rate t [2] is given as,

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

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,

$$Q(Q,t) = Q_{\max} \underbrace{\left(\frac{1 - e^{-at/t_{\max}}}{1 - e^{-a}} \right)}_{Q_t(t)} \underbrace{(\beta q + \gamma)}_{Q_q(q)} \tag{2}$$

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 listed in 1 are the video characteristic parameters and are obtained from the standard JSVM reference codec [13] 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 [2].

Sequence	a_i	c_i	d_i	β_i	γ_i	m_i	r_i	n_i	$R^i_{\max}$
Foreman CIF	7.7000	2.0570	2.2070	-0.0298	1.4475	1	5/6	79	3046.30
Akiyo CIF	8.0300	3.4910	2.2520	-0.0316	1.4737	2	2/3	72	612.85
Football CIF	5.3800	1.3950	1.4900	-0.0258	1.3872	1	2/3	101	5248.90
Crew CIF	7.3400	1.6270	1.8540	-0.0393	1.5898	1	5/6	110	4358.20
City CIF	7.3500	2.0440	2.3260	-0.0346	1.5196	1	2/3	116	2775.50
Akiyo QCIF	5.5600	4.0190	1.8320	-0.0316	1.4737	4	1/2	48	139.63
Foreman QCIF	7.1000	2.5900	1.7850	-0.0298	1.4475	1	3/4	105	641.73
City 4CIF	8.4000	1.0960	2.3670	-0.0346	1.5196	4	2/3	102	20899.00
Crew 4CIF	7.3400	1.1530	2.4050	-0.0393	1.5898	1	1/2	32	18021.00

Table 1: Characteristic video parameters of the rate and quality models for the H.264 SVC standard video sequences. n_i values in the table are number of users in multicast scenario and n_i value is 1 for unicast as one user present in this scenario.

The quality function $Q_t(t)$ describes the variation in quality as a function of the frame rate t and is characterized by the parameter value a. The function $Q_q(q)$ is a decreasing affine function of the quantization parameter, which describes the decrease in quality with increasing quantization parameter q. For a fixed frame rate t_f, the bitrate and quality of video depend exclusively on the quantization parameter. We denote by n_i, m_i and r_i, the number of users in a multicast group, the number of bits in a symbol and the coding rate respectively. The optimal TF resource allocation for sum video quality maximization corresponding to a fixed symbol rate R_S can be computed as the solution of the convex optimization problem,

$$\begin{aligned} \max. \quad & \sum_{i=1}^{N} n_i Q^i(q_i, t_f) \\ \text{s.t.} \quad & \sum_{i=1}^{N} \frac{R^i(q_i, t_f)}{m_i r_i} \leq R_S \\ & q_{\min} \leq q_i \leq q_{\max},\ 1 \leq i \leq N, \end{aligned} \tag{3}$$

where N is the number of unicast users or multicast groups. The functions $R^i(q_i, t_f)$ and $Q^i(q_i, t_f)$ are the bitrate and quality corresponding to the i^{th} video sequence, for the choice of quantization parameter q_i at a fixed frame rate t_f. The optimal solution of the problem stated above has been derived in our previous work [2] using the Lagrange dual variable λ as,

$$\lambda^* = \frac{q_{\min}}{R_S} \left(\sum_{j=1}^{N} n_j Q_{\max} Q_t^j(t_f) \frac{\beta_j}{d_j} \right). \tag{4}$$

The optimal i^{th} quantization parameter is obtained as,

$$q_i{}^* = q_{\min} \left(1 - \frac{1}{d_i} \ln \left(\frac{Q_{\max} Q_t^i(t_f) q_{\min} \beta_i m_i r_i n_i}{R_{\max}^i R_t^i(t_f) \lambda^* d_i} \right) \right) \tag{5}$$

The bitrate and quality of the video sequence can be obtained by substituting q_i in (1) and (2) respectively. Higher quality video requires video to be coded with a lower value of quantization parameter, resulting in higher bitrate. Further, the quantization parameter q can be employed as a convenient handle to adapt the video bitrate as per the constraints imposed by the video streaming scenario. Therefore, knowledge of the characteristic video parameters

a, c, d, β, γ is critical for optimizing the bitrate and quality of the streamed videos. Naturally, such a TF allocation procedure at the QoS enforcement point is subject to manipulation by malicious users who intend to subvert the allocation process, thereby achieving a disproportionate fraction of the resources. The VCG procedure presented below can be employed effectively to mitigate the effect of parameter misreporting through pricing based retribution targeting the dishonest users.

3 VCG based Video Resource Allocation

In this section we present the VCG pricing [4] based TF resource allocation procedure for video quality maximization. We consider the variation of the net VCG allocated utility as a function of the reported parameters d and β and demonstrate that its application in video rate and quality optimization leads to maximization of the net utility function. The utility function in this context of unicast/ multicast video transmission, is the quality of video, which is given as the quality relation as a function of the quantization parameter in (2). The player/ user might misreport the parameter values and subvert the allocation towards achieving disproportionate bitrate and therefore high quality video at the cost of reduced quality to the other users. The overall utility and efficient allocation of bitrate to different videos is thus compromised. Such malicious users are penalized through the VCG auction based TF resource pricing, which automatically leads to higher pricing and net utility reduction for the users misreporting the characteristic video parameter values. Let the actual and the reported utility function of the i^{th} user be denoted by $Q^i\left(q_i, t_f\right)$ and $M^i\left(q_i, t_f\right)$ respectively. The QoS enforcer determines the optimal allocation as per the reported utility functions $M^i\left(q_i, t_f\right)$. Let $\mathbf{q}^*$ denote the optimal quantization parameter allocation determined from the above convex optimization frame work. Also, let the quantity $Y_i\left(M_{-i}\left(\right)\right)$ for the i^{th} user be defined as a function of the $N-1$ utility functions $M^j\left(q_j, t_f\right) \forall j \neq i$ as,

$$Y_i\left(M_{-i}\left(\right)\right) = \max_{\underline{q}} \sum_{\substack{j=1 \\ j \neq i}}^{N} M^j(q_j, t_f).$$

The price p_i of the allocated TF resources for the i^{th} user is given by the relation,

$$p_i = Y_i\left(M_{-i}\left(\right)\right) - L_i(q^*), \tag{6}$$

where the quantity $L_i(q^*) \triangleq \sum_{\substack{j=1 \\ j\neq i}}^{N} M^j(q_j^*, t_f)$. It can be readily demonstrated that such a VCG auction based pricing scheme results in serving appropriate retribution to the dishonest subscribers and service providers. Consider the net utility Z_i of the i^{th} player given as,

$$Z_i \triangleq Q^i({q_i}^*, t_f) - p_i, \tag{7}$$

which is essentially the raw video quality adjusted for the price paid towards experiencing it. The above net utility Z_i can be expressed in terms of the true utility function $Q^i\left(q_i, t_f\right)$ and the reported utility function $M^i\left(q_i, t_f\right)$ as,

$$Z_i = \underbrace{Q^i({q_i}^*, t_f) + \sum_{\substack{j=1 \\ j\neq i}}^{N} M^j(q_j^*, t_f)}_{U_i(\mathbf{q}^*)} - \max_{\underline{q}} \sum_{\substack{j=1 \\ j\neq i}}^{N} M^j(q_j, t_f) \tag{8}$$

The last term $\max_{\underline{q}} \sum_{\substack{j=1 \\ j\neq i}}^{N} M^j(q_j, t_f)$ in the above expression is independent of the reported utility function of the i^{th} user. Hence, it can be observed that $U_i\left(\mathbf{q}^*\right)$ for player i is maximum for the allocated resource $\mathbf{q}^*$, calculated as per the optimization framework, only when the reported utility function $M^i({q_i}^*, t_f)$ coincides with the true utility function $Q^i({q_i}^*, t_f)$. Thus, the VCG procedure effectively punishes malicious users who deliberately misrepresent their video parameters. This TF resource allocation based on the VCG procedure is applied to all the N players/ service providers participating in the given scenario [14]. We now present the algorithm for computing Z_i below.

4 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

```
Suppose $k$ is the indice of video sequence applying VCG procedure.
for $d_l/\beta_l$ do
    {
    for $i = 1 \to N$ do
            • Compute $\lambda^*$ using $R_S$ in (4) with $j$ initialized to $i$.
            • Compute quantization parameter ${q_i}^*$ using (5).
        if ${q_i}^* < q_{\min}$ then
                • set ${q_i}^* = q_{\min}$
                  else if ${q_i}^* > q_{\max}$
                • set ${q_i}^* = q_{\max}$
        end
            • Compute $R^i({q_i}^*, t_f)$ using ${q_i}^*$ and (1).
            • $R_S : R_S - R^i({q_i}^*, t_f)$.
    end
    if ${q_i}^* = q_{\min}$ then
            • $R_S : R_S - \sum \left(R^i({q_{\min}}^*, t_f)\right)$.
            • Repeat for loop for remaining sequences for optimal solution.
    end
    }
        • Compute $\hat{q}_k$ from $R_k/\ Q_k$ using $d_t/\beta_t$ to avoid violation of constraints.
        • Excluding the $k^{th}$ sequence, repeat OPTIMAL to obtain $Y_k(M_k())$.
        • Compute $Z_k$ for every $d_l/\beta_l$.
end
Select maximum $Z_k$.
```

Algorithm 1: Algorithm for VCG procedure of which is modulated and transmitted individually over separate orthogonal subcarriers as shown in Fig.1. 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 [15] [16]. 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.1 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 tech-

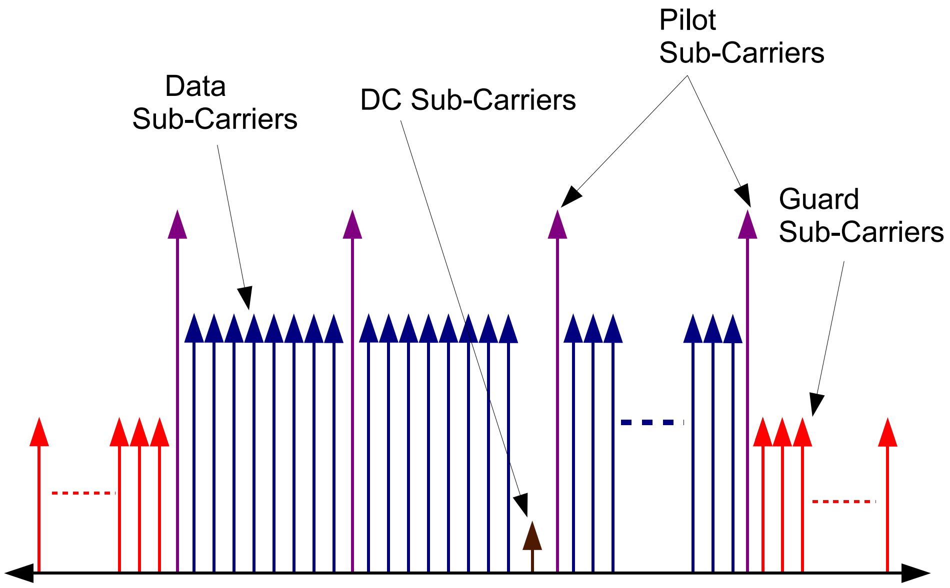

Figure 1: OFDMA Sub-Carrier Structure

nique 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-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 [17].

5 Optimization framework for Auction based Subcarrier Allocation

5.1 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 [11] can be employed as valid bid functions towards revenue maximization. In this context a linear price quality bid function can be presented as,

$$P = eQ + f, \tag{9}$$

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 and square root functions shown in Fig.2 can be readily incorporated.

Sequence	e_i	f_i	θ_i	b_i
Foreman CIF	6	209	209	410
Akiyo CIF	10	185	253	529
Football CIF	6	229	253	488
Crew CIF	9	230	286	532
City CIF	6	236	248	580
Akiyo QCIF	6	227	239	592
Foreman QCIF	5	289	267	357
City 4CIF	8	141	274	341
Crew 4CIF	9	242	252	509

Table 2: Characteristic Auction parameter values for the H.264 SVC standard video sequences

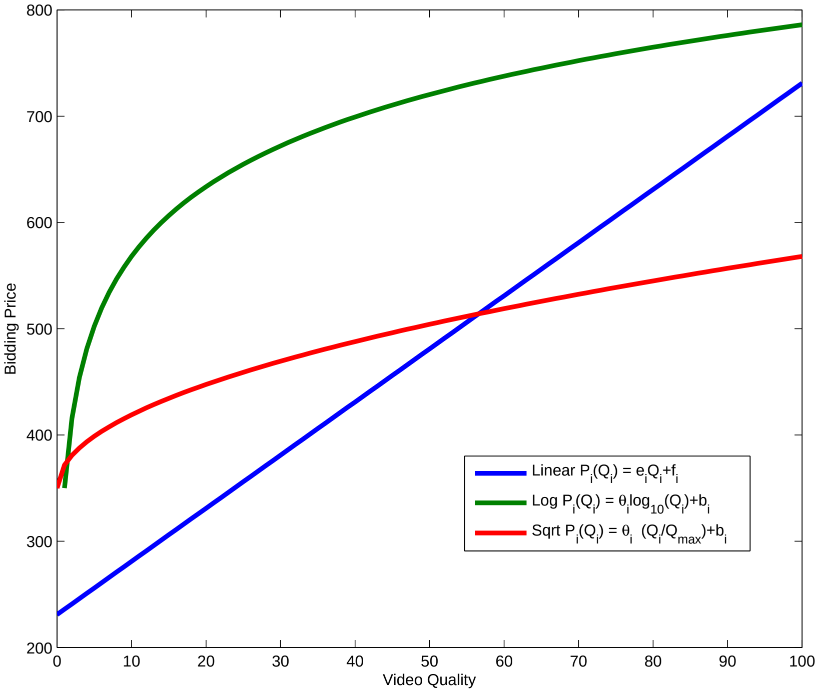

Figure 2: Comparision of Video Price Bidding Models

5.2 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,

$$\begin{aligned} \max. \quad & \sum_{i=1}^{N} n_i P_i(Q_i) \\ \text{s.t.} \quad & P_i(Q_i) = e_i Q_i + f_i,\ 1 \leq i \leq N \\ & \sum_{i=1}^{N} \frac{1}{m_i r_i} R^i(q_i, t_f) \leq R_S \\ & q_{\min} \leq q_i \leq q_{\max} \end{aligned} \tag{10}$$

where R_s denotes the aggregate symbol rate of the OFDMA system and n_i, $1 \leq i \leq N$ 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 $\lambda, \mu_i, \delta_i, 1 \leq i \leq N$ 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,

$$k_i \triangleq \frac{R^i_{\max}}{m_i r_i}\left(\frac{1 - e^{-c_i t_f / t_{\max}}}{1 - e^{-c_i}}\right) \tag{11}$$

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 $\lambda \geq 0, \bar{\mu_i} \succeq 0, \bar{\delta_i} \succeq 0$, we obtain,

$$-n_i\tilde{\beta}_i - \lambda k_i \left(\frac{d_i}{q_{\min}}\right) e^{d_i(1-q_i/q_{\min})} + \mu_i - \delta_i = 0 \tag{12}$$

From (10), 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,

$$\lambda^* = -\frac{q_{\min}}{R_S}\left(\sum_{j=1}^{N} \frac{\tilde{\beta}_j n_j}{d_j}\right). \tag{13}$$

We substitute the above expression for λ^* in (12) to derive the closed form expression for the optimal quantization parameter q_i^* as,

$$\begin{aligned} q_i^* &= q_{\min}\left(1 - \frac{1}{d_i}\ln\left(\frac{q_{\min}\tilde{\beta}_i m_i r_i}{\lambda^* k_i d_i}\right)\right) \\ &= q_{\min}\left(1 - \frac{1}{d_i}\ln\left(\frac{R_S}{k_i}\frac{n_i\tilde{\beta}_i\left(d_i\right)^{-1}}{\sum_{j=1}^{N} n_j\tilde{\beta}_j\left(d_j\right)^{-1}}\right)\right) \end{aligned} \tag{14}$$

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 [18].

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,

$$\begin{aligned}
&\max. \sum_{i=1}^{N} n_i P_i(Q_i) \\
&\text{s.t.} \sum_{i=1}^{N} \frac{1}{m_i r_i} R^i(q_i, t_f) \leq R_S \\
&q_{\min} \leq q_i \leq q_{\max}
\end{aligned} \tag{15}$$

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.

6 Simulation Results

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As in our previous work [2], we consider the WiMAX profile with OFDMA symbol duration of 5 ms each for UL and DL, with 2048 subcarriers, corresponding to 1440 data subcarriers and an effective downlink symbol rate of $R_S = 6.336$ Msps. For analyzing the behavior with respect to the parameters, we consider a scenario, where N=9 video sequences of different resolutions (QCIF, CIF, 4CIF) are being streamed with $n_i = 1$, coding rate of the i^{th} group $r_i = \frac{5}{6}$ and modulation order $m_i = 2$ corresponding to QPSK modulation and frame rate $t_f = 30$ fps. The values of the video characteristic parameters a, c, d, β, γ corresponding to these video sequences are specified in [2]. We consider the optimal allocation of TF resources in this scenario to the different groups and the net utility corresponding to accurate and misreporting of d, β parameters. We begin by specifically considering two separate cases in which a single subscriber of the standard test video sequence football CIF [19] misreports the parameter values d (rate parameter) and β (quality parameter). The scenario with multiple users misreporting multiple parameters is considered in the later simulations.

Case	I	II	III
d_3	1.49	0.4	3.4
q_3	27.82	24.48	23.36
R^3	1621.9	4076.6	789

Table 3: *Quantization parameter and Bitrate for sequence football Case I:*$d = d_t$*, Case II:*$d < d_t$*, Case III:*$d > d_t$

Case	I	II	III
β_3	-0.0258	-0.03	-0.02
q_3	27.82	25.6	28.98
R^3	1621.9	1832.2	1308.5

Table 4: *Quantization parameter and Bitrate for football Case I:*$\beta = \beta_t$*, Case II:*$\beta_m < \beta_t$*, Case III:*$\beta_m > \beta_t$

6.1 Behavior Corresponding to Misreporting d

In this section we illustrate the effect of false reporting of parameter d for the standard football video sequence on the overall bitrate allocation. Case I, II and III in table 3 demonstrate the allotted quantization parameter and corresponding bitrate when $d_m = d_t$, $d_m < d_t$ and $d_m > d_t$ respectively at $R_S = 6.336$ Msps for the standard football CIF sequence. Consider the adverse scenarios, where the user/ service provider reports $d_m = 0.4 < d_t$ shown in case II. This results in suboptimal allocation of TF resources, with a disporportionate alloation of $R^3(q_3, t_f) = 4076.6$ Kbps. This is at the cost of decrease in video quality of the rest of the users. In the later simulations it is shown that the application of the VCG procedure ensures that such malicious users are punished through a reduction in the net utility resulting from the VCG allocation. When $d_m = 3.4 > d_t$ as considered in case III, the alloted bitrate $R^3(q_3, t_f) = 789$ Kbps is much less than the rate 1621.9 Kbps (corresponding to case I). Hence, there is no incentive for the malicious user to misreport a lower value of the parameter d. However, the actual video encoded with this lower value of the allocated quantization paramter $q = 23.36$ will have bitrate $R^3(q_3, t_f) > 1621.9$ Kbps (corresponding to case I) and thus results in violating the overall bitrate constraint. Hence, the malicious user in this scenario is forced to compute the quantization parameter $\hat{q}_3$ corresponding to the allocated bitrate of 789 Kbps to ensure that the rate constraints are not violated. This results in lower quality $Q^3(\hat{q}_3, t_f)$.

6.2 Behavior Corresponding to Misreporting β

We now consider the effect of misreporting of the parameter β of a video sequence on the overall TF resource allocation. Case I, II and III in table 4 shows the computed quantization parameter and allotted bitrate of video sequences when $\beta = \beta_t$, $\beta_m = -0.03 < \beta_t$ and $\beta_m = -0.02 > \beta_t$ respectively at $R_S = 6.336$ Msps for sequence football CIF. When the misreported $\beta_m = -0.030 < -0.0258$ as in case II, the optimal bitrate allocation results in $R^3(q_3, t_f) = 1832.2 > 1621.9$ Kbps and the difference $1832.2 - 1621.9 = 210.3$ Kbps is obtained from taking the share of bits from other videos. Hence, similar to reporting a lower value of d as seen above, the malicious user has an incentive to report a lower value of the parameter β. For case III, corresponding to $\beta > -0.0258$, the bitrate obtained $R^3(q_3, t_f) = 1308.5 < 1621.9$ Kbps, as shown in table 4. The quality $Q^3(q_3, t_f)$ is less compared to the case when β_t is reported. Hence, there is no incentive for the malicious user to report higher values of the quality parameter β.

6.3 VCG Procedure based TF Resource Allocation

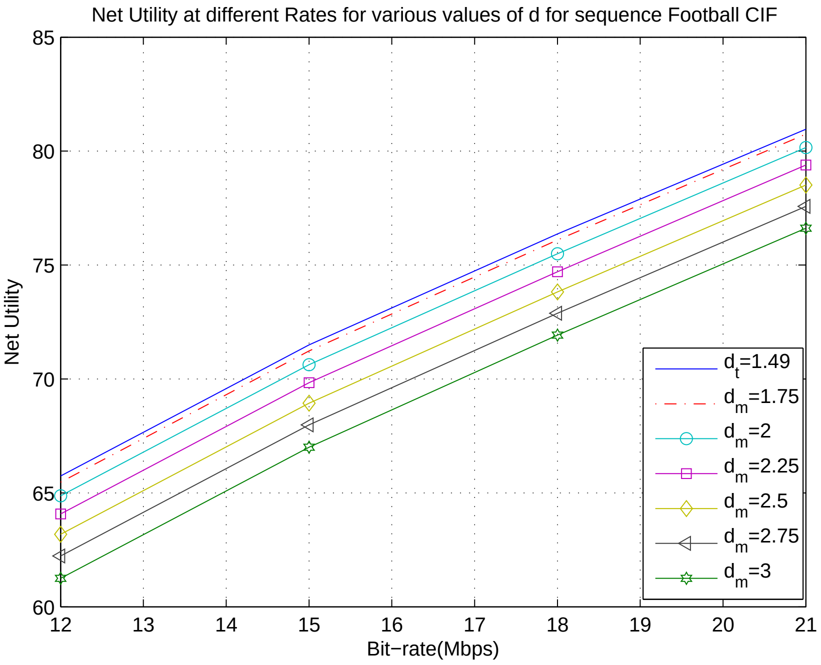

Figure 3: Net utility function vs. Rate at various values of parameter d for sequence football CIF :d_t=true value, d_m=misreprted value

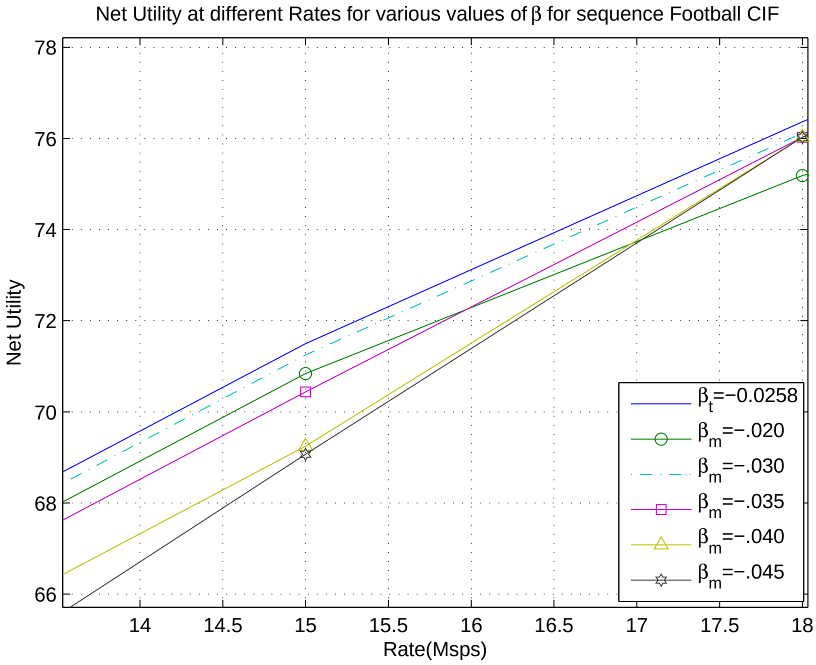

Figure 4: Net utility function vs. Rate at various values of parameter β for sequence football CIF :β_t=true value, β_m=misreprted value

In this section we illustrate the efficacy of the VCG procedure based resource allocation described in section 3 towards punishing such malicious users and reducing their net utility, thereby discouraging false reporting of the video parameters. Similar to the scenarios considered above, we consider the video streaming of $N = 9$ video sequences with $m_i \in \{1, 2, 4, 6\}$ and $r_i \in \{\frac{1}{2}, \frac{2}{3}, \frac{3}{4}, \frac{5}{6}\}$. The TF resources are allocated as per the optimal solution corresponding to the reported utility function maximization in (3) at the VCG price p_i computed in (6). Fig.3 and Fig.4 show the net utility function as a function of the symbol-rate R corresponding to the VCG procedure based TF resource allocation for the video sequence football. It can be seen therein that the net utility function is maximum when the true parameters $d = d_t = 1.49$ and $\beta = \beta_t = -0.0258$. Hence, the VCG procedure penalizes the users misreporting the video characteristic parameters by decreasing their net utility. In these scenarios we only consider false reporting of a single parameter (either d or β, but not both) by a single user. Below, we consider the scenario where multiple users simultaneously misreport one or more characteristic video parameters.

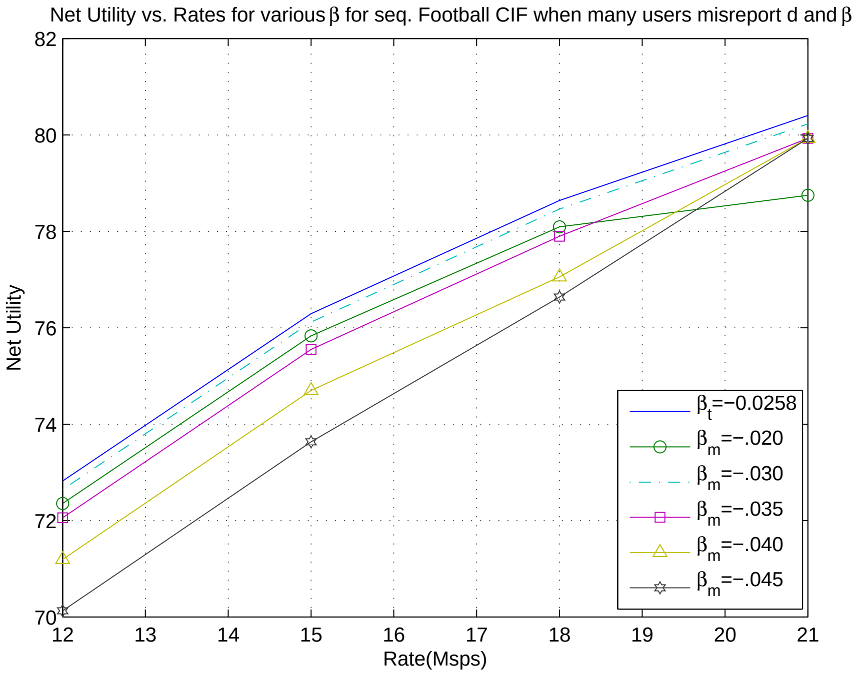

Figure 5: Net utility function vs. Rate at various values of parameter β for sequence football CIF and other misreports :β_t=true value, β_m=misreprted value

We assume the following misreported parameter values $\beta_1 = -0.025, \beta_3 = -0.020, \beta_5 = -0.030, d_3 = 2.2, d_4 = 1.8, d_6 = 2.4$, with user 3 misreporting both d and β considered for simulations in Fig.5 and Fig.6. In Fig. 5 we plot the net utility of user 3 corresponding to misreporting $d_m = 2.2 > d_t = 1.49$ and several possible misreports of $\beta \neq \beta_t$ and $d \neq d_t$. It can be seen that, amongst all the net utility curves, the one corresponding to $\beta = \beta_t = -0.0258$ results in the maximum net utility. Similarly, in fig. 6 we plot the net utility for the false reporting of $\beta_m = -0.020 > \beta_t$ and several possible misreports of the rate parameter d and quality parameter β. Once again, it can be seen that reporting the true value of $d = d_t = 1.49$ results in net utility maximization for user 3. Thus, application of the VCG procedure results in penalizing the parameter misreporting malicious users, thereby encouraging users to report the true characteristic video parameters, thus resulting in optimal TF resource allocation.

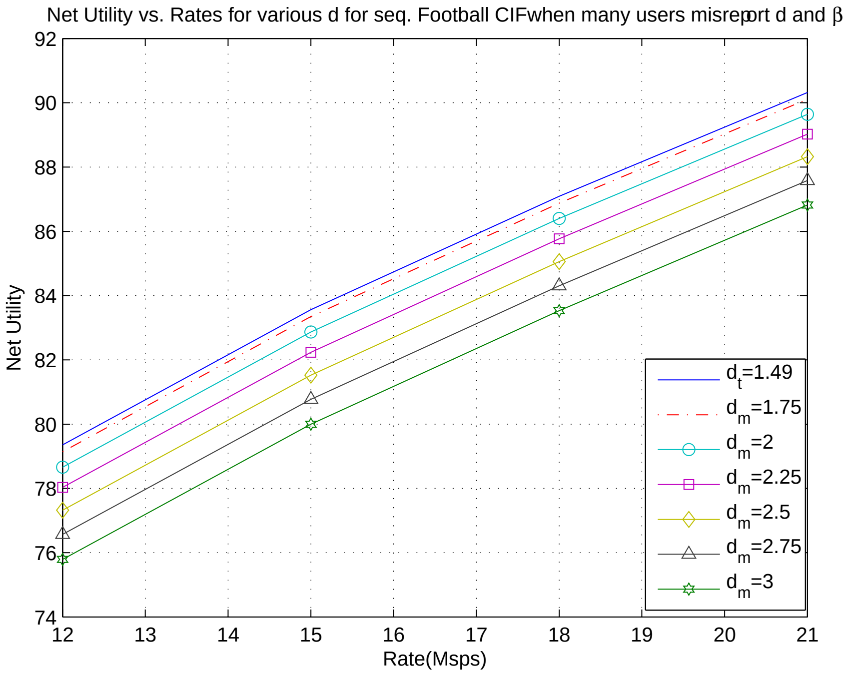

Figure 6: Net utility function vs. Rate at various values of parameter d for sequence football CIF and other misreports :d_t=true value, d_m=misreprted value

6.4 Auction based Optimal Subcarrier Allocation

We also employ the 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 2. 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 (10) and computing the optimal solution using the closed form expression in (14). We compare our allocation with the one obtained from the standard CVX based convex solver [20]. The corresponding per video sequence optimal quantization parameter q_i^*, optimal price maximizing bit-rate allocation are listed in table 5 for the logarithmic bidding model using the WIMAX profile mentioned in [2] with the effective downlink symbol rate $R_s = 6.336$ Msym/s. Further,

Sequence	Equal Symbol Rate Allocation		Optimal Symbol Rate Allocation					
			Unicast Scenario			Multicast Scenario		
	R^i_{equal}	qp^i_{equal}	R^i_{opt}	q^*_i	$n_i P_i(Q_i)$	R^i_{opt}	q^*_i	$n_i P_i(Q_i)$
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 5: 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.

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.7 for the linear bidding function auction. Similarly, Fig.8 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.7 we can observe that the closed form solution allocation from (14) 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.9 and Fig.10 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.

7 Conclusion

In this work we have presented a novel VCG procedure based approach for optimal TF resource allocation towards scalable video transmission. In conventional 4G resource allocation based on sum quality maximization, there is an incentive for malicious users to misreport the

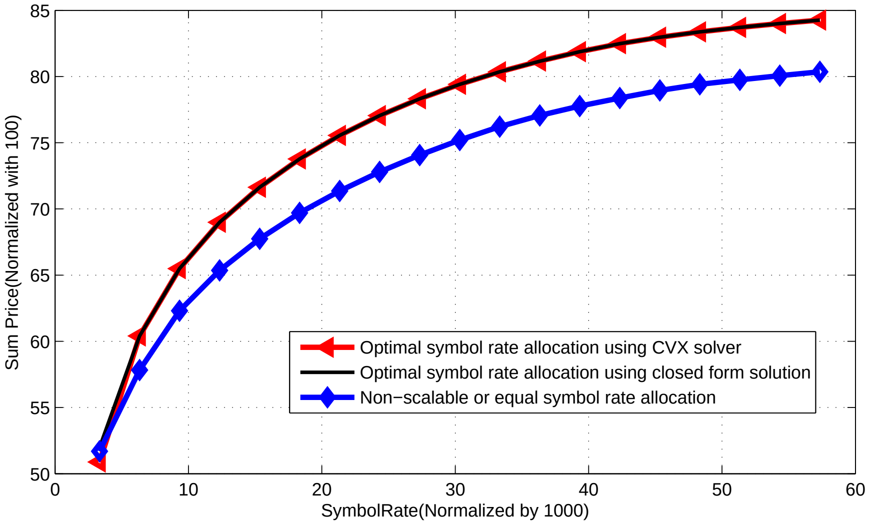

Figure 7: Symbol rate vs. sum price for unicast scenario at $t = 30$ fps and price as a linear function of quality ($P = eQ + f$).

video quality parameters towards disproportionately higher resource allocation, thus leading to suboptimality and subversion of the scheduler operation at the base station. The proposed VCG procedure is effective for resource allocation in such scenarios, since it punishes malicious users through pricing based optimal resource allocation, thereby discouraging false reports. Further, the incidental outcomes of the above VCG based allocation are the price points for the allocated TF resources. Hence, the proposed scheme can also be used as an effective TF resource pricing algorithm for use in the OSS module of the core network, which in turn leads to overall optimal resource allocation.

We also 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

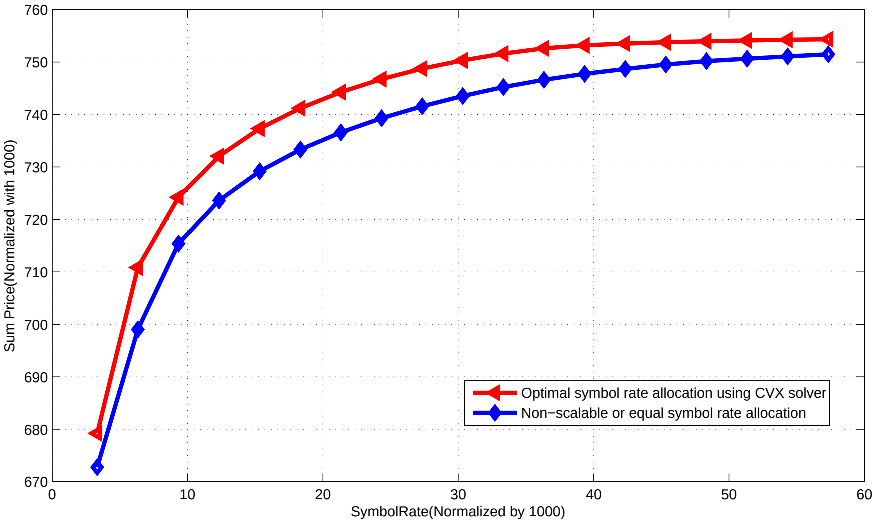

Figure 8: Symbol rate vs. sum price for multicast scenario at $t = 30$ fps and price as a logarithmic function quality $(P_i(Q_i) = \theta_i \log_{10}(Q_i) + b_i)$.

for optimal resource allocation. It has been shown through simulations that the presented optimal subcarrier allocation yields improved performance compared to the suboptimal equal subcarrier allocation for the case of DL/UL PUSC WiMAX.

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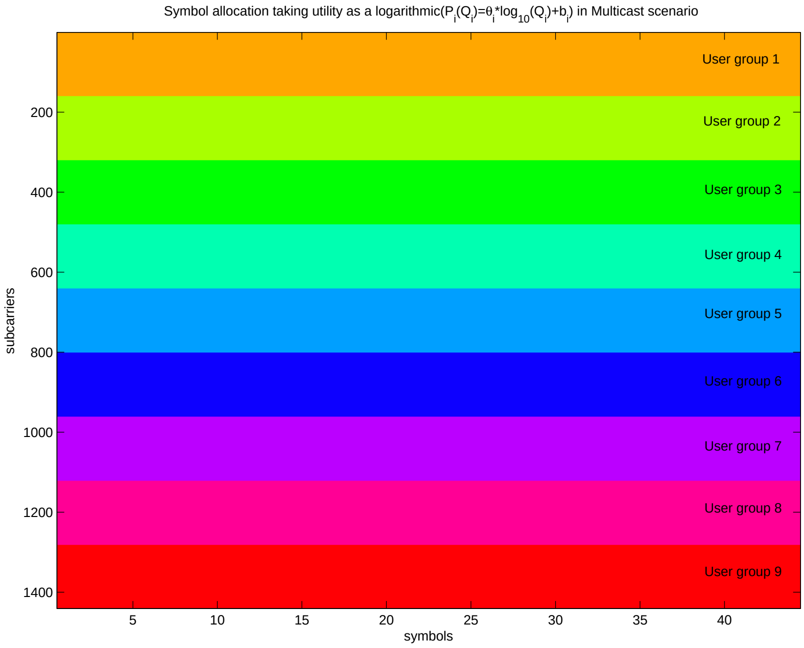

Figure 9: Allocation of symbols to videos with equal symbol rate allocation.

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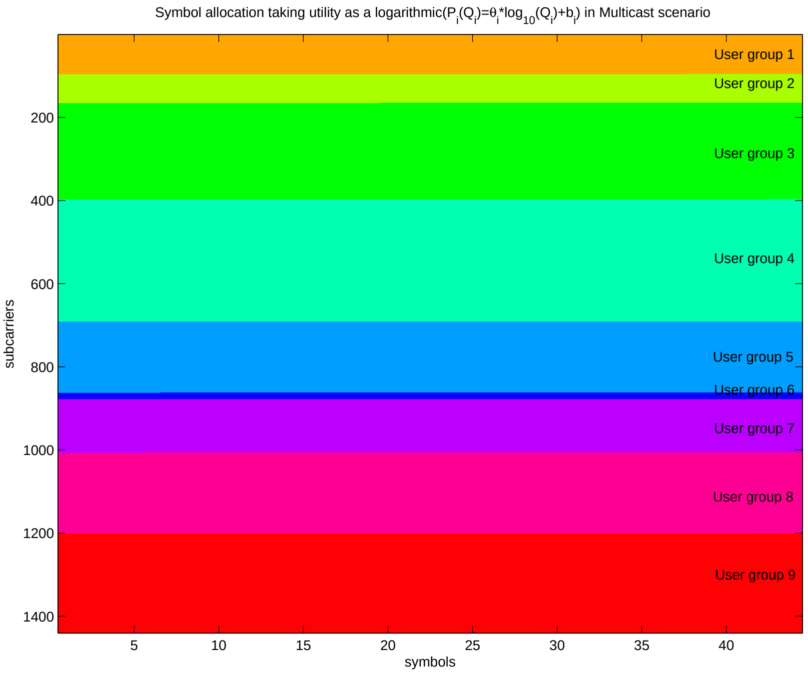

Figure 10: Allocation of symbols to videos with optimal symbol rate allocation using price as a logarithmic function of quality $(P_i(Q_i) = \theta_i \log_{10}(Q_i) + b_i)$ in multicast scenario.

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