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

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***Abstract*—In this paper, we present a novel scheme for optimal OFDMA subcarrier allocation towards video quality maximization employing the paradigm of H.264 based scalable video coding (SVC). We deduce the rate and quality model parameters for video characterization of the SVC extension of the H.264/AVC and propose an optimization framework for sum quality maximization of the transmitted video streams in unicast and multicast 4G scenarios. We derive the closed form solution for optimal quantizer selection towards net video quality maximization subject to rate constraints of the unicast/ multicast users, taking into account the different modulation and coding rates of the multicast groups in the 4G wireless system. This in turn yields the optimal OFDMA time/frequency resource allocation for video multiplexing. In the simulation results section, we specialize our proposed algorithm in the context of WiMAX based 4G video transmission and demonstrate that our algorithm provides significant improvement in video quality over the content agnostic non-scalable equal symbol rate allocation scheme for unicast and multicast scenarios.**

I. Introduction

The rapid rise in the demand for ubiquitous mobile broadband wireless access has spurred the development of 4G wireless standards such as LTE and WiMAX. These technologies enable high data rates to the mobile subscribers. As the bandwidth of the wireless system increases, it is beset by the problem of multipath fading, resulting in intersymbol interference. Hence, Orthogonal Frequency Division Multiplexing (OFDM) which is based on low complexity IFFT/FFT operations and division of the wideband channel into multiple parallel narrowband frequency flat subcarriers has become the most popular physical layer technology for wireless broadband access. Orthogonal Frequency Division for Multiple Access (OFDMA) is the multiple access technology based on OFDM in which different users (unicast) or groups of users (multicast) are allocated a fraction of the total subcarriers over a period of time. This is also known as time-frequency resource allocation in OFDMA systems.

A significant component of the 4G Wireless traffic comprises of video and multimedia based rich applications such as surveillance applications, multimedia streaming, mobile TV, video conferencing etc. A typical wireless communication scenario for the above described applications is shown in Fig.1. To support such video applications on wireless links necessitates the development of sophisticated multimedia codecs tailored for applicability in the erratic mobile wireless environment. A unique challenge for video transmission in 4G wireless systems is to ensure quality of video transmission over the time-varying fading wireless channel to mobile users with devices of disparate capabilities and QoS requirements. This has lead to the development of the Scalable Video Coding(SVC) profile of the H.264/AVC [1],[2] which can be readily adopted for video transmission in unicast and multicast wireless scenarios.

Fig. 1. A Wireless Communication Scenario

Scalable video coding (SVC) enables the video content to be coded and stored at its highest fidelity levels, from which partial bit streams of lower fidelity can be extracted dynamically and adapted to meet the requirements of the users and the wireless links. SVC allows temporal scalability in which the partial video streams can be coded at different frame rates combined with quality scalability, through quantization stepsize selection. Naturally, the bitrate and video quality of the coded video stream depends on the combination of frame rate, spatial resolution and quantization parameter[3]. Hence,

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it is essential to judiciously choose the coded video parameters to maximize the end user video quality and experience. Further, this has a direct impact on the end user Quality of Service(QoS) aspects such as jitter and latency.

In this context, we consider a framework for optimal H.264 coded video rate based time-frequency resource allocation at the 4G wireless Base Station(BS) for video quality maximization. In this paradigm, the users request the videos either individually or in multicast groups and the server allocates time/ frequency resources in the OFDMA system. Previous works such as in [4] consider scheduling and resource allocation based on priority and latency. However, most such previous approaches are not specialized to the context of video and do not take the scalable nature of video transmission into consideration. This leads to suboptimal resource allocation and a net decrease in the video quality delivered to the end users. The authors in [5] allocate the time/ frequency resources for real time layered video transmission in WiMAX assuming fixed bitrate allocation to each multicast group. The utility of each multicast group is assumed to be a concave function of the bitrate allocated. However, the considered rate dependent generic utility function is not an accurate representation of the video quality. In our work, we consider the true perceptual quality based utility functions described in existing literature. Hence, our framework provides a better end user video experience since it optimizes the relevant video quality directly. In [6], a scheme is proposed for allocation of the time resources in a HSDPA cellular network. However, the proposed scheme requires users to request a video quality level, with video quality defined as a function of the number of enhancement layers and the cumulative data rate. However, this framework does not consider the dependence of video quality and bitrate on the quantization and frame rate. Hence, it does not consider a realistic optimization framework as compared to the one illustrated in this work in the context of a practical 4G WiMAX system. Hence, the key to efficient resource allocation in 4G wireless systems lies in the interpretation of the characteristic video rate and quality parameters which lead to optimal bitrate allocation.

Therefore, we consider a framework for optimal OFDMA time-frequency resource allocation based on the characteristic perceptual quality and bitrate models of scalable video bit streams as functions of quantization parameter and frame rate. We compute the bitrate models of the H.264 SVC coded streams using the JSVM reference codec and employ the standard video parameters from works such as [3], [7] to characterize the quality dependence on frame rate, quantization parameter of the coded videos. Based on these models, we formulate a constrained convex optimization problem for optimal OFDMA time-frequency resource allocation. We employ the robust framework of convex optimization [8] to present a closed form expression for computation of the optimal coded video parameters. The server can employ these parameters to compute the optimal resource allocation based on the requirements of the users and availability of the bandwidth. This allocation can then be employed by the base station or subscriber station to extract parts of the coded video streams for transmission on the downlink or uplink respectively. This efficient utilization of the available bandwidth results in maximizing the quality of the transmitted video and end user video experience. Our results demonstrate that optimization using the proposed model yields significant enhancement in the video quality as compared to the video agnostic equal bitrate allocation for unicast/multicast scenarios in the OFDMA system.

The rest of the paper is organized as follows. Section II describes the underlying framework considered in this paper and the rate and quality models for videos. Section III describes the scheme for optimal symbol rate allocation in an OFDM frame. We present the simulation results in section IV. Finally we conclude the paper in section V.

II. System Model and OFDMA Framework

In OFDMA systems [9],[10], the high data rate input stream is divided into a multitude of parallel low data rate streams which are subsequently loaded onto the orthogonal subcarriers. Each symbol in the time domain comprises of several orthogonal subcarriers. A few such subcarriers are designated as pilot and guard subcarriers which comprise an overhead in the OFDMA system. Pilot subcarriers are employed to estimate the timing and frequency synchronization parameters so that the offset errors are minimized, while the guard subcarriers avoid overlap with adjacent OFDM bands. The OFDMA scheduler allocates the time/ frequency resource blocks, which are characterized by the allotted OFDM symbols/ subcarriers respectively, to the users. The bitrate of the OFDMA system depends on the number of symbols in each OFDM frame, the number of subcarriers used in each symbol, the modulation and channel coding formats employed.

In this context, the 4G wireless cellular standard WiMAX [11], which employs OFDMA in the physical layer for transmission of bits was designed to provide a high data rate broadband air interface to its users coupled with seamless data transfer under high speed mobility. WiMAX provides services such as Unsolicited Grants Service (UGS) for constant bitrate VOIP applications, Real Time Polling Service (rtPS) for real time applications such as video transmission, Non Real Time Polling Service for large data transfers and Best Effort service for web applications. Thus, the scheduler present at the base station helps in optimally allocating the bandwidth resources, aimed at avoiding traffic congestion and data starvation. Thus, the DL scheduler has the critical tasks of optimal bandwidth allocation, choosing the modulation and coding schemes and data bursts depending on the service priority and wireless link quality determined from the channel quality indicator (CQICH) feedback channel. It then generates the UL/DL MAP containing the control information for users to access their bursts. Hence, our proposed model aims at optimally allocating the time-frequency resources in the UL and DL scheduler to maximize the net video quality.

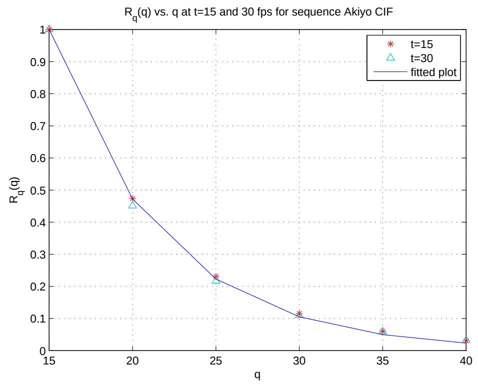

Fig. 2. Normalized rate $R_q(q)$ vs q at t=15,30 fps for sequence Akiyo (CIF)

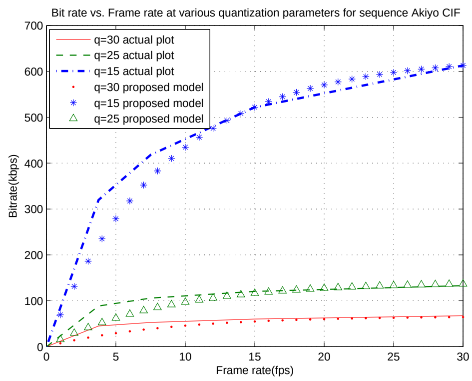

Fig. 3. Plot showing proposed bitrate following actual bitrate at q=15, 25, 30

A. Scalable Video Rate and Quality models

The parametric models given in [3], can be conveniently employed to model the video bitrate. As proved in this work, we model the rate as a product of the normalized functions of the frame rate t and quantization parameter q. We employ the JSVM [12] reference codec to compute the rate parameters for quantization parameter in the range $15 \leq q \leq 40$, and frame rates $t = 15, 30$ fps. Let $R_{\max}$ denote the maximum bitrate corresponding to the coded video at the highest frame rate $t_{\max}$ and finest quantizer resolution $q_{\min}$. The normalized rate functions $R_t(t), R_q(q)$ of the frame rate t and quantization parameter q respectively are given as,

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

The video characteristic parameters c and d model the bitrate variation as a function of the frame rate and quantization parameter respectively. The parameters c and d are obtained by minimizing the mean square error between measured rate using the JSVM codec and modeled data for frame rates 15 fps and 30 fps. Frame rates lower than 15 fps result in noticeable artifacts due to persistence of human visual system. Fig.2 demonstrates the plot of $R_q(q)$ vs. quantization step size q for the standard *Akiyo* test sequence. The normalized rate function $R_q(q)$ above has a more general form compared to the one in [3] since we model a much wider range of the quantization parameter $15 \leq q \leq 40$ compared to the range employed therein. Hence, the resulting joint rate function $R(q, t)$ is given in terms of the normalized rate functions $R_t(t), R_q(q)$ as,

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

where $R_{\max}$ is the bitrate of the highest quality video sequence corresponding to encoding at frame rate $t_{\max}$ and quantization parameter $q_{\min}$. The plot in Fig.3 verifies that our proposed rate model closely follows the observed rate. Videos coded at lower values of quantization parameter $q \in [1, 15]$ result in an exponential increase in bitrate and hence are not suitable for transmission in bandwidth constrained wireless scenarios. Further, we limit the quantization parameter to $q_{\max} = 40$ as higher values lead to significant degradation of quality.

Similarly, the normalized video quality functions $Q_t(t), Q_q(q)$ with respect to the frame rate t and quantization parameter q respectively can be modeled as,

$$Q_t(t) = \frac{1 - e^{-at/t_{\max}}}{1 - e^{-a}}, \, Q_q(q) = \beta q + \gamma.$$

The function $Q_q(q)$ is well approximated as a linear function of the quantization parameter q as demonstrated in Fig.4. The parameters β, γ are derived by fitting a linear model to video quality at the points $q = 15$ and $q = 35$ using the models specified in [3] while parameter values a are given in [3] for CIF resolution and have been linearly extrapolated for the remaining videos of different resolutions with the values given in [7]. The resulting video quality is described by the product function,

$$\begin{aligned} Q(q,t) &= Q_{\max} Q_t(t) Q_q(q) \\ &= Q_{\max}\left(\frac{1 - e^{-at/t_{\max}}}{1 - e^{-a}}\right)(\beta q + \gamma), \quad (2) \end{aligned}$$

The constant $Q_{\max}$ is the quality when the video is coded at $t_{\max}$, $q_{\min}$ and can be normalized as $Q_{\max} \triangleq 100$. For a fixed frame rate t_f fps, the quality depends exclusively on the quantization parameter given by $Q_q(q)$. This function can then be employed as a handle to maximize the video quality.

III. Optimal Bit allocation in OFDM frame

Let R_S denote the total symbol rate corresponding to all the subcarriers of the WiMAX OFDMA frame and $n_i, 1 \leq i \leq N$, the number of users corresponding to the i^{th} multicast group. Let $Q^i(q_i, t_f)$, $R^i(q_i, t_f)$ represent the Quality and Rate of the i^{th} video sequence corresponding to the quantization parameter q_i and fixed frame rate t_f. Let m_i be the number of bits per symbol i.e. modulation order and r_i be the code rate of the i^{th} user in the unicast scenario. The optimization criterion for rate allocation toward video quality maximization can be formulated as,

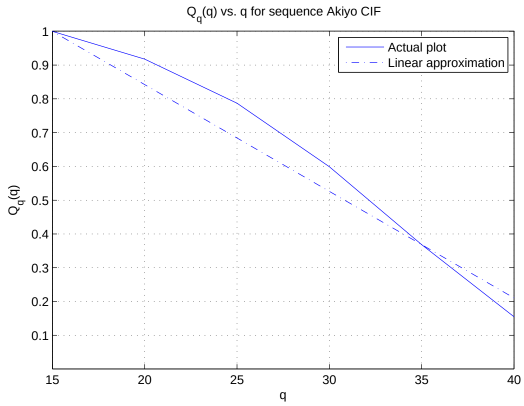

Fig. 4. Video quality $Q_q(q)$ vs q for the video sequence Akiyo (CIF)

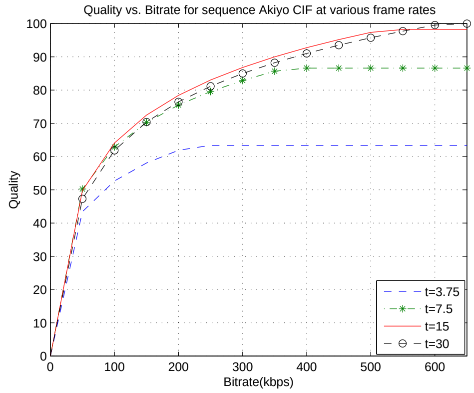

Fig. 5. Quality vs Bitrate for sequence Akiyo CIF at various frame rates

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

The Lagrangian $L\left(\bar{q}, \lambda, \bar{\mu}, \bar{\delta}\right)$ of the above optimization problem can be expressed using the Lagrange multipliers $\lambda, \mu_i, \delta_i, 1 \leq i \leq N$ as,

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

where $k_i \triangleq \frac{R^i_{\max}}{m_i r_i} \left(\frac{1 - e^{-c_i t_f / t_{\max}}}{1 - e^{-c_i}} \right)$ and the quantity $R^i_{\max}$ is the maximum bitrate corresponding to the i^{th} video. The KKT conditions for the above Lagrangian optimization criterion with $\lambda \geq 0, \bar{\mu_i} \succeq 0, \bar{\delta_i} \succeq 0$, can be formulated as follows.

$$
n_i Q_{\max} Q_t^i(t_f) \beta_i - \lambda k_i \left(\frac{d_i}{q_{\min}} \right) e^{d_i(1 - q_i/q_{\min})} + \mu_i - \delta_i = 0
$$

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

where the last condition above follows from the complementary slackness of the inequality constraint. Assuming $\mu_i = 0$ and $\delta_i = 0$, the expression for the optimal Lagrange multiplier λ^* can be derived as,

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

Substituting the value of λ^*, μ_i and γ_i in the first KKT equation yields the closed form expression for the optimal quantization parameter q_i^* given as,

$$
\begin{aligned}
{q_i}^* &= q_{\min} \left(1 - \frac{1}{d_i} \ln \left(\frac{Q_{\max} Q_t^i(t_f) q_{\min} \beta_i m_i r_i}{R^i_{\max} R_t^i(t_f) \lambda^* d_i} \right) \right) \quad (5) \\
&= q_{\min} \left(1 - \frac{1}{d_i} \ln \left(\frac{R_S}{k_i} \frac{n_i Q_t^i(t_f) \beta_i \left(d_i\right)^{-1}}{\sum_{j=1}^{N} n_j Q_t^j(t_f) \beta_j \left(d_j\right)^{-1}} \right) \right)
\end{aligned}
$$

Substituting q_i^* in equations (1) and (2) gives the required bitrate and maximum quality for each video. Fig.5 shows the optimal video quality vs. bitrate plot for the video sequence *Akiyo* (CIF) as a function of the maximum rate R_S at various frame rates. This corresponds to the unicast scenario in the above frame work with $N = 1$. As can be seen, the video quality is near 100% for bitrates in the range of $500 - 600$ Kbps. At lower frame rates t, it can be seen from (2) that the quality Q at higher bitrates is lower than 100% because the normalized quality function $Q_t(t) << 1$ for $t = 3.75, 7.5$ fps.

Based on the above analysis, we present an algorithm for fast computation of the optimal quantization parameters q_i^* employing the closed form expression in (5). This algorithm has a very low computational complexity and hence can be employed for rapid computation of the optimal parameters. The algorithm below is described for the general case of multicast video transmission. This can be readily used for the unicast scenario by substituting $n_i = 1$.

IV. Simulation Results

We present simulation results to illustrate the performance of the optimal scheme for OFDMA video transmission employing the DL/UL PUSC (Partial Usage of Subcarriers) diversity permutation scheme used for subcarrier channelization in WiMAX. We consider the WiMAX profile with bandwidth

Algorithm Calculating quantization parameter

for i=1 to N
  Compute λ^* using R_S in (4) with j initialized to i;
  Compute quantization parameter $q_i{}^*$ using (5) ;
 if $q_i{}^* < q_{\min}$
  set $q_i{}^* = q_{\min}$;
 else if $q_i{}^* > q_{\max}$
  set $q_i{}^* = q_{\max}$;
 end if
  Compute $R^i(q_i{}^*, t_f)$ using $q_i{}^*$ and (1);
  $R_S : R_S - R^i(q_i{}^*, t_f)$;
 end

TABLE I
ALGORITHM FOR COMPUTATION OF THE OPTIMAL QUANTIZATION PARAMETERS q_i^*

B = 20 Mhz, OFDMA frame time T = 10 ms (50% split for UL and DL traffic i.e. 5ms sub-frame for DL and UL) and number of subcarriers $N_S = 2048$ [11]. The number of data subcarriers is $N_d = 1440$ with each DL frame consisting of 44 OFDM symbols for data transmission out of the total available 48 symbols. Hence, the effective downlink symbol rate is $R_S = 44 \times 1440 \times (10 \times 10^{-3})^{-1} = 6.336$ Msym/s.

We consider the optimal time-frequency resource allocation for video transmission in the context of the WiMAX system described above. We begin with a unicast video transmission scenario, where each of the $N(= 9)$ standard video test sequences [13] of various spatial resolutions (QCIF, CIF and 4CIF) listed in table II along with the associated values of the video characteristic parameters $a_i, c_i, d_i, \beta_i, \gamma_i$ are streamed to individual users. The videos under consideration have different resolutions and varying degrees of motion. The values of the modulation index m_i for each user are chosen randomly from the set $\{1, 2, 4, 6\}$ corresponding to the standard WiMAX modulation formats BPSK, QPSK, 16-QAM and 64-QAM respectively. The coding rates r_i are similarly chosen randomly from the set $\{\frac{1}{2}, \frac{2}{3}, \frac{3}{4}, \frac{5}{6}\}$ of standard WiMAX coding rates. The optimal video quality maximizing bitrate allocation and the associated quantization parameters q_i^* are computed by solving the optimization problem in (3) employing the standard CVX based convex solver [14] and the closed form solution based algorithm in table I. The corresponding per video sequence normalized quality is listed in table II for both the optimal and equal symbol rate allocation schemes at $t = 30$ fps from which it can be readily seen that the optimal resource allocation scheme outperforms the suboptimal equal resource allocation scheme. Fig.6 shows the comparison of these schemes for the above unicast scenario at various values of symbol rate R_S, clearly demonstrating the efficiency of the optimal allocation scheme described in section III. Further, the optimal resource allocation computed employing the closed form solution in (5) and the associated fast algorithm described in table I achieves a performance close to that of the CVX solver, thereby verifying the theoretical analysis.

Method	Sum $Q/Q_{\max}$ at 15 fps	Sum $Q/Q_{\max}$ at 30 fps
Optimal symbol rate	395.5	364.9
Equal symbol selection	371.6	342.4

TABLE III
COMPARISON OF QUALITY AT FRAME RATES FOR MULTICAST $t = 15$ AND $t = 30$ FPS

Fig.7 shows the comparison of these schemes for multicast scenarios with the number of multicast subscribers chosen randomly from the set $30 \leq n_i \leq 100$ at frame rates $t = 15$ and $t = 30$ fps. The parameters m_i and r_i for each multicast group are chosen randomly as described in the unicast scenario. Similar to the unicast scenario, it can be observed that optimal resource allocation results in progressively larger gains compared to the suboptimal equal resource allocation. Further, the net normalized video qualities for both the resource allocation schemes in the standard WiMAX multicast scenario described above with rate $R_S = 6.336$ Msym/s are given in table III for each of the frame rates $t = 15$ and $t = 30$ fps. It can be clearly seen that the optimal allocation results

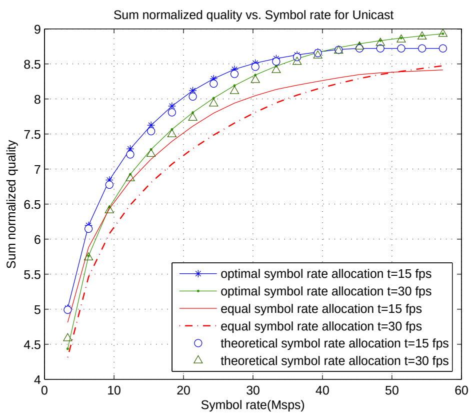

Fig. 6. Unicast:Sum normalized Quality vs. Symbol rate at t=15 and 30 fps

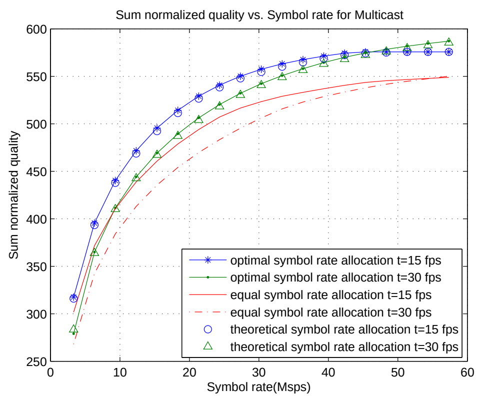

Fig. 7. Multicast:Sum normalized Quality vs. Symbol rate at t=15 and 30 fps

Sequence	a_i	c_i	d_i	β_i	γ_i	m_i	r_i	Equal Symbol rate Selction(ksps)	$Q_i/Q_{\max}$	Optimal Symbol rate Allocation(ksps)	$Q_i/Q_{\max}$
Foreman CIF	7.7000	2.0570	2.2070	-0.0298	1.4475	1	5/6	704	0.666	685	0.660
Akiyo CIF	8.0300	3.4910	2.2520	-0.0316	1.4737	2	2/3	704	1.00	460	1.00
Football CIF	5.3800	1.3950	1.4900	-0.0258	1.3872	1	2/3	704	0.372	877	0.430
Crew CIF	7.3400	1.6270	1.8540	-0.0393	1.5898	1	5/6	704	0.362	1074	0.496
City CIF	7.3500	2.0440	2.3260	-0.0346	1.5196	1	2/3	704	0.602	754	0.618
Akiyo QCIF	5.5600	4.0190	1.8320	-0.0316	1.4737	4	1/2	704	1.00	70	1.00
Foreman QCIF	7.1000	2.5900	1.7850	-0.0298	1.4475	1	3/4	704	0.951	847	0.997
City 4CIF	8.4000	1.0960	2.3670	-0.0346	1.5196	4	2/3	704	0.471	741	0.482
Crew 4CIF	7.3400	1.1530	2.4050	-0.0393	1.5898	1	1/2	704	0.034	828	0.074

TABLE II
ALLOCATION OF SYMBOLS IN AN OFDM FRAME FOR UNICAST AT $t = 30$ FPS

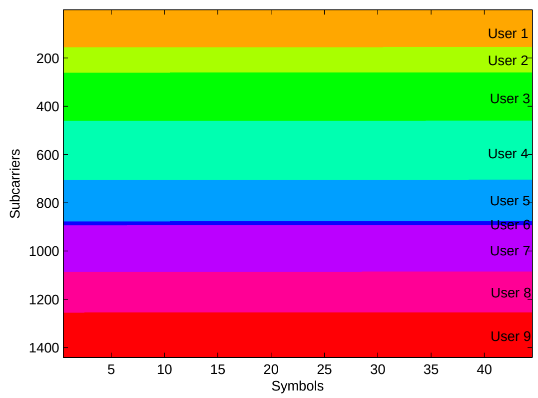

Fig. 8. Allocation of symbols to videos with optimal allocation

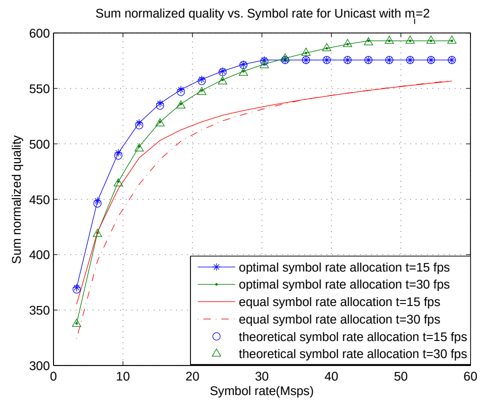

Fig. 10. Unicast: Sum Quality vs Symbol rate at t=15 and 30 fps with $m_i = 2,\ \forall i$ and varying r_i

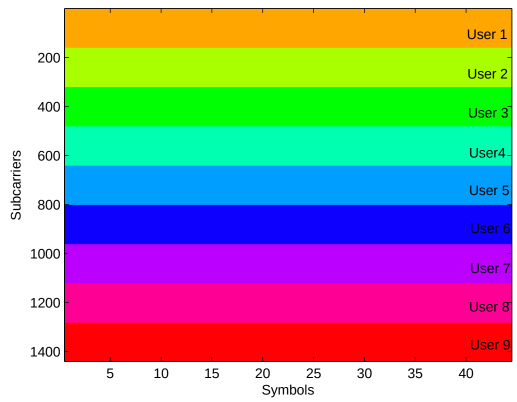

Fig. 9. Allocation of symbols to videos with equal symbol rate allocation

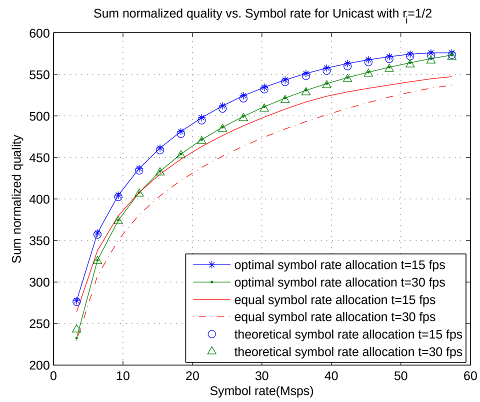

Fig. 11. Unicast: Sum Quality vs Symbol rate at t=15 and 30 fps with $r_i = 1/2,\ \forall i$ and varying m_i

in a significant enhancement of approximately 6.5% in the video quality over equal resource allocation. We schematically represent the optimal and equal allocation of time/frequency resources of the OFDMA symbol for unicast transmission in Fig.8 and Fig.9 respectively with each shade representing the portion of the DL subframe allocated to a particular video sequence belonging to the set under consideration. Finally, we present the comparison of these schemes for unicast video transmission with $m_i = 2,\ \forall i$ at various symbol rates R_S and varying r_i in Fig.10. Similarly, Fig.11 shows the comparison of these schemes for unicast with $r_i = 1/2,\ \forall i$ at various R_S and varying modulation order m_i. We conclude that higher modulation and coding rate provides higher net quality to the users. Overall, the optimal resource allocation algorithm proposed for OFDMA based time-frequency resource allocation results in a significant improvement in the net video quality.

V. Conclusion

We presented a novel scheme for time-frequency resource allocation in OFDMA based 4G wireless systems aimed at video quality maximization. H.264 based scalable video models have been employed to characterize the video bitrate and quality as a function of the quantization parameter q. Based on these models, a constrained convex optimization frame work has been presented for optimal OFDMA based unicast/ multicast resource allocation. A fast algorithm based on the closed form solution of the resource optimization problem has been presented to compute the optimal quantization parameters q_i^* and the associated subcarrier allocation. It has been observed in simulations that the proposed optimal scheme yields a considerable improvement in the video quality. Further, the performance gains increase progressively in multicast scenarios with increasing number of subscribers. For the specific case of PUSC WiMAX with $N_S = 2048$ subcarriers and frame time $T = 10\,\text{ms}$, the proposed optimal scheme obtains a quality gain of about 6.5% over the suboptimal equal symbol rate allocation scheme.

References

[1] H. Schwarz, D. Marpe, and T. Wiegand, "Overview of the scalable video coding extension of the H.264/AVC standard," *Circuits and Systems for Video Technology, IEEE Transactions on*, vol. 17, no. 9, pp. 1103 –1120, Sept. 2007.

[2] Y. Wang, Y.-Q. Zhang, and J. Ostermann, *Video Processing and Communications*, 1st ed. Upper Saddle River, NJ, USA: Prentice Hall PTR, 2001.

[3] Y. Wang, Z. Ma, and Y.-F. Ou, "Modeling rate and perceptual quality of scalable video as functions of quantization and frame rate and its application in scalable video adaptation," in *Packet Video Workshop, 2009. PV 2009. 17th International*, May 2009, pp. 1 –9.

[4] Y.-N. Lin, C.-W. Wu, Y.-D. Lin, and Y.-C. Lai, "A latency and modulation aware bandwidth allocation algorithm for WiMAX base stations," in *Wireless Communications and Networking Conference, 2008. WCNC 2008. IEEE*, 31 2008-April 3 2008, pp. 1408 –1413.

[5] S. Deb, S. Jaiswal, and K. Nagaraj, "Real-time video multicast in WiMAX networks," in *INFOCOM 2008. The 27th Conference on Computer Communications. IEEE*, April 2008, pp. 1579 –1587.

[6] J. Kim, J. Cho, and H. Shin, "Resource allocation for scalable video broadcast in wireless cellular networks," in *Wireless And Mobile Computing, Networking And Communications, 2005. (WiMob'2005), IEEE International Conference on*, vol. 2, Aug. 2005, pp. 174 – 180 Vol. 2.

[7] Y.-F. Ou, T. Liu, Z. Zhao, Z. Ma, and Y. Wang, "Modeling the impact of frame rate on perceptual quality of video," in *Image Processing, 2008. ICIP 2008. 15th IEEE International Conference on*, Oct. 2008, pp. 689 –692.

[8] S. Boyd and L. Vandenberghe, *Convex Optimization*. New York, NY, USA: Cambridge University Press, 2004.

[9] D. Tse and P. Viswanath, *Fundamentals of wireless communication*. New York, NY, USA: Cambridge University Press, 2005.

[10] A. Goldsmith, *Wireless Communications*. New York, NY, USA: Cambridge University Press, 2005.

[11] J. G. Andrews, A. Ghosh, and R. Muhamed, *Fundamentals of WiMAX: Understanding Broadband Wireless Networking (Prentice Hall Communications Engineering and Emerging Technologies Series)*. Upper Saddle River, NJ, USA: Prentice Hall PTR, 2007.

[12] J. Software, "Joint scalable video model, joint video team, version 9.19.7."

[13] "Standard test video sequences," http://media.xiph.org/video/derf/.

[14] M. Grant and S. Boyd, "CVX: Matlab software for disciplined convex programming, version 1.21," http://cvxr.com/cvx, Apr. 2011.