Game Theory Based Dynamic Bit-Rate Adaptation for H.264 Scalable Video Transmission in 4G Wireless Systems

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***Abstract*—In this paper, we propose a game theoretic framework for decentralized H.264 scalable video bitrate adaptation in 4G wireless networks. The framework presented employs a pricing based utility function towards video streaming quality optimization. An algorithm is presented for iterative strategy update of the competing scalable coded video streaming end users towards an equilibrium allocation. In this context we demonstrate the existence of a Nash equilibrium for the proposed video bitrate adaptation game based on the quasi-concavity of the net video utility function. Existence of Nash equilibrium ensures efficient usage of the 3G/4G bandwidth resources towards video quality and revenue maximization. We present simulation results to comprehensively illustrate the performance of the above game theoretic video quality adaptation scheme. We also discuss the behavior of the parameters of the net video utility function, their impact on video bit-rate allocation and overall bandwidth utilization of the wireless network.**

I. INTRODUCTION

Next generation 4G wireless networks such as WiMAX [1], LTE [2] are envisaged to provide a plethora of multimedia content based rich services to the users. The demand for video based services such as video conferencing, interactive gaming and subscription based broadcast/ multicast services is progressively increasing in next generation wireless networks. Thus, reliable video transmission holds the key to efficiency and performance in 4G cellular networks. Towards this end, 4G systems often impose Quality of Service (QoS) restrictions on content delivery to ascertain and satisfy a minimum level of performance for the subscribers. Moreover, the disparate link qualities, display resolutions and device capabilities of the cellular users cannot be handled by conventional static fixed profile video codecs. In this context, H.264 based scalable video transmission provides the flexibility of coded video bit-stream rate adaptation. It is therefore essential to develop an appropriate framework to optimally allocate the scalable video streams to different users/ groups in the wireless network for maximization of bandwidth efficiency. The standard scheduling services such as rtPS and nrtPS available in 4G WiMAX are not targeted towards overall video quality maximization, especially in scalable video scenarios.

In [3] an optimization framework was presented for OFDMA time-frequency resource allocation towards video quality maximization in a 4G network. The bitrate and quality functions of the scalable video stream were described with a minimal number of characteristic parameters to limit the overall complexity of the system. The proposed optimization framework therein was demonstrated to result in a substantial improvement of scalable video streaming quality for a given bitrate R_S. However, the scheme presented therein requires the presence of a central controller such as a base station or QoS enforcement point in the wireless network for optimal video scheduling. Recently, decentralized approaches towards resource allocation have attracted significant research interest especially in the context of dynamic spectrum access (DSA) based cognitive radio networks. Such a framework enhances the flexibility of admission control policies and enables third party vendors to seamlessly integrate their services in future networks.

In this context we propose a game theoretic approach towards decentralized bandwidth allocation for video streaming. The proposed scheme is based on a modified quasi-concave video utility function which incorporates a parametric dynamic video pricing component. This scheme under consideration proportionally prices the users in accordance with the video quality. Hence, it can also be employed to determine the price points for video streaming based subscription services in 4G wireless networks. The video users are initially allocated resources in proportion to the requested bit-rate. We prove the existence of Nash equilibrium for the proposed pricing based utility function. Each player subsequently updates his strategy by selecting the best response to the strategy of other players towards achieving the Nash equilibrium. The bit streams are adapted such that the users achieve a dynamic equilibrium in which there is no incentive to unilaterally deviate from the equilibrium allocation. We describe our work in the context of a 4G WiMAX scenario which is capable of providing services to both fixed and mobile wireless users. However, this proposed approach is general and can be applied to other broadband wireless systems such as HSDPA, LTE in the context of video transmission.

Game theory has been a widely applied in the context of competition based resource allocation in wireless networks. In

[4] we proposed a Vickrey − Clarke − Groves (VCG) auction based procedure for pricing based decentralized optimal video bit-rate allocation which also discourages misreporting of the characteristic video quality parameters through an appropriate malicious user retribution mechanism. The authors in [5], [6] propose a non-cooperative game theory based video coding scheme for multi-object bitrate allocation. However, while their work focuses on codec adaptation, it is not suitable for link adaptation based wireless scenarios. Work on game theory based link rate adaptation and power control in GPRS and UMTS systems is described in [7] and [8] respectively. The authors in [9] also employ a game theoretic approach and introduce a price that is dependent on channel congestion. However, the schemes presented above are generic and do not consider the challenges in joint link-codec optimization for video transmission.

The rest of the paper is organized as follows. Section II describes the wireless network video streaming system model employed in the paper. Section III gives a brief introduction to the key principles of game theory followed by an elaboration of the competition based video bit-rate allocation procedure in section IV. We present simulation results to validate the performance of the proposed algorithm in section V and our conclusions are presented in section VI.

II. SYSTEM MODEL

In this section we describe the standard parametric models to characterize the rate and quality functions of an H.264 coded scalable video stream. The quantization parameter q_i which corresponds to SNR scalability decides the bitrate and the quality of the video sequence. A reduction in q_i will result in higher bitrate/ quality and an increase in q_i will result in lower bitrate/ quality of the video sequence. The bitrate $R_i\left(q_i\right)$ of the scalable video stream of the i^{th} user at a fixed frame rate t and quantization parameter q_i is given from [3], [10] as,

$$\begin{aligned} R_i(q_i) &= R^i_{\max} R^i_t(t) R^i_q(q_i) \\ &= R^i_{\max}\left(\frac{1-e^{-c_i t/t_{\max}}}{1-e^{-c_i}}\right) e^{d_i(1-q_i/q_{\min})}, \end{aligned}$$

where the functions $R^i_t(t)$, $R^i_q(q_i)$ are the normalized rate functions of the frame rate t and quantization parameter q_i of the i^{th} user respectively. The quantity $R^i_{\max}$ denotes the maximum bitrate of the video sequence when coded at minimum quantization parameter $q_{\min}$ and maximum frame rate $t_{\max}$. The value $R^i_{\max}$ is a characteristic of the video sequence and depends on its content. Similarly, the quality $Q_i\left(q_i\right)$ of a scalable video at frame rate t and quantization parameter q_i in [3] is given as,

$$\begin{aligned} Q_i\left(q_i\right) &= Q^i_{\max} Q^i_t\left(t\right) Q^i_q\left(q_i\right) \\ &= Q^i_{\max}\left(\frac{1-e^{-a_i t/t_{\max}}}{1-e^{-a_i}}\right)\left(\beta_i q_i+\gamma_i\right), \end{aligned}$$

where $Q^i_t(t)$, $Q^i_q\left(q_i\right)$ are the normalized quality functions of the frame rate t and quantization parameter q_i respectively of the i^{th} user. The quantity $Q^i_{\max}$ denotes the maximum quality of the video sequence achieved at $q = q_{\min}$ and $t = t_{\max}$. The parameters a_i, β_i, γ_i, c_i and d_i are the characteristic video rate and quality parameters and depend on the nature of the video content. A more elaborate description of the computation of these parameters is given in [3], [10]. Fig.1 demonstrates the quality $Q_i\left(q_i\right)$ of the standard video sequence Football(CIF) as a function of the rate $R_i\left(q_i\right)$ for frame rates $t = 3.75, 7.5, 15, 30$. It can be seen from the figure that the typical video quality function is a concave function of the frame rate. Below we provide a brief introduction to the relevant aspects of game theory which form the basis for the decentralized scalable video rate allocation scheme.

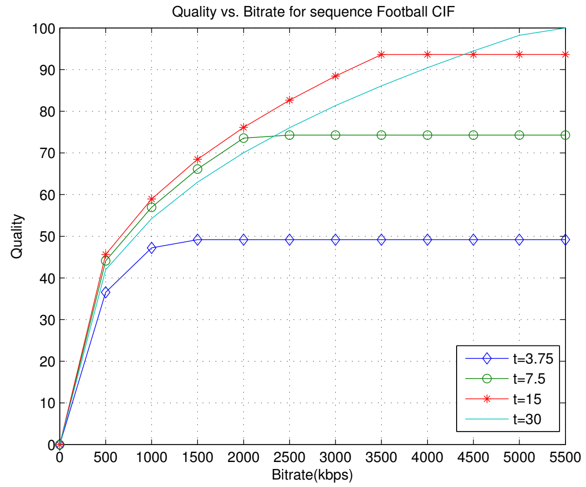

Fig. 1. Quality vs. Bit-rate for the standard video sequence Football (CIF).

III. GAME THEORY FRAMEWORK

We present below a brief overview of the basic concepts and notation employed in the context of game theory [11]. A game is essentially a framework to characterize the competitive interaction between N independent decision making agents termed as players for allocation of a limited set of resources. These interactions are governed by a set of rules. For instance, in the context of a wireless network, the players are the users competing for allocation of time-frequency resources and the governing rules are those dictated by the regulating agencies such as the FCC. Each player i, $1 \leq i \leq N$ in a game has a set of strategies denoted by S_i from which he chooses a strategy $s_i \in S_i$. Let s_{-i} denote the vector of strategies of all the players except the i^{th} player. Each player/ user is associated with a utility function u_i which denotes his reward $u_i\left(s_i, s_{-i}\right)$ corresponding to the outcome of the game. Thus, the utility of the i^{th} user depends not only his chosen strategy, but those chosen by all the other players as well. This can be denoted as,

$$u_i\left(s_i, s_{-i}\right) = u_i\left(s_i, s_1, s_2, ..., s_{i-1}, s_{i+1}, ..., s_N\right).$$

More importantly, it is assumed that all the players are *rational* to mean that they prefer outcomes with higher utility/ payoff and hence try to maximize their utility. The game is considered to be strategic in the sense that every player tries to maximize his utility keeping in view the potential strategies adopted by other users. It is well known that a stable solution of such a strategic game is described by the Nash Equilibrium. A strategy profile $\mathbf{s}^\star$ is a Nash equilibrium of the game if the utility associated with this strategy profile for every player i is such that,

$$u_i\left(s_i^\star, s_{-i}^\star\right) \geq u_i\left(s_i, s_{-i}^\star\right), \forall s_i \in S_i,\, 1 \leq i \leq N. \quad (1)$$

The above definition of the Nash equilibrium essentially implies that none of the $1 \leq i \leq N$ users can benefit by unilaterally deviating from his equilibrium strategy $s_i^\star$ to a different strategy $s_i \in S_i$. The Nash equilibrium of a game is not necessarily unique. The framework developed below is employed to illustrate the condition for existence of the Nash equilibrium. The α upper level set of a function is defined as,

Upper Level Sets. *The α upper level set of a function $f : \mathbf{R}^n \mapsto \mathbf{R}$ is defined as,*

$$C_\alpha = \{\mathbf{x} :\, f(x) \geq \alpha\}. \quad (2)$$

This definition of C_α can be employed to define a quasi-concave utility function f as,

Quasi-Concavity. *A function $f : \mathbf{R}^n \mapsto \mathbf{R}$ is quasi-concave if its domain is convex and the upper level sets C_α are convex for all α.*

In general any *single-peaked* function of one variable is quasi-concave. All concave functions and monotonic transformations of concave functions are quasi-concave. The condition for existence of Nash equilibrium can be stated as follows [12], [13]. There exists at least one Nash equilibrium for a strategic game if $\forall i$ the strategy sets S_i are non-empty, convex and compact subsets of the Euclidean space and each utility function u_i is continuous on the action space $S = \times_{i=1}^{N} S_i$ and quasi-concave on S_i. Thus, employing the results above, one can conveniently characterize the existence of the Nash equilibrium for the game under consideration.

IV. COMPETITIVE 4G VIDEO RATE ALLOCATION

In this section we present the game theoretic framework for H.264 scalable video based 4G video bit-rate allocation. Consider a total available bit-rate of R_S at the QoS enforcement point such as the base-station (BS), application service network gateway (ASN-GW) or core service network (CSN) in a WiMAX network. Let the effective bit-rate corresponding to the time-frequency OFDMA resources allocated to the i^{th} video user be denoted by R_i. We define the pricing function $p_i\left(R_i\right)$ associated with the scalable video bit-rate R_i as,

$$p_i\left(R_i\right) \triangleq \alpha \left(\frac{R_i}{R_S - R_i}\right)^{\theta},$$

where the α and θ are the pricing parameters. It is necessary to select the parameters α and θ judiciously to maximize the net video quality. Hence, the net utility function/ preference relation of the i^{th} video user is given as a function of the video quality $Q_i\left(q_i\right)$ and the allocated bit-rate R_i as,

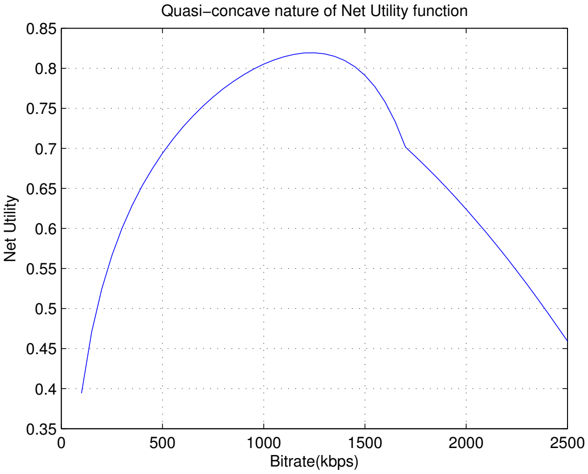

Fig. 2. Net-Utility vs. Bit-Rate function for Football (CIF).

$$u_i(q_i) = Q_i(q_i) - p_i\left(R_i\left(q_i\right)\right),$$

where q_i is the quantization parameter at which the i^{th} scalable video stream is encoded. Substituting the expression for video quality from (1), the utility function above can be simplified as,

$$\left(\frac{1 - e^{-a_i t/t_{max}}}{1 - e^{-a_i}}\right)\left(\beta_i q_i + \gamma_i\right) - \alpha \left(\frac{R_i\left(q_i\right)}{R_S - R_i\left(q_i\right)}\right)^{\theta}. \quad (3)$$

A typical net video utility function as a function of the allocated video rate is shown in Fig.2 for the sequence football CIF with $\alpha = 0.05$ and $\theta = 2$, with a competing allocation of 700 kbps to the standard video sequence Akiyo CIF. The total bit-rate of the corresponding link is assumed to equal 2.5 Mbps. It can be seen therein that the net utility function is quasi-concave in nature. The net utility increases initially as the allocated video bit-rate increases. However, it can be seen from the defined utility function that higher video rate results in higher pricing, forcing the rational users to select the optimal strategy that maximizes the net utility function. Hence, employing the results described in the previous section, the stable video bit-rate allocation corresponds to the Nash equilibrium. The procedure for scalable video bit-rate allocation can be described as follows. Each of the N players requests for an initial bit-rate allocation of $R_i^r(0)$ at iteration $k = 0$, where r denotes a request. The algorithm then proceeds in the following sequence of steps.

1) Once the requested video bit-rates $R_i^r(k)$ at iteration k are received through a MAC based polling mechanism, if the requested bandwidths are such that $\sum_{i=1}^{N} R_i^r\left(k\right) \leq R_S$, the QoS enforcement point allocates the time-frequency resources corresponding to $R_i^a\left(k\right) = R_i^r\left(k\right)$ to the i^{th} user. In case $\sum_{i=1}^{N} R_i^r\left(k\right) > R_S$, the video

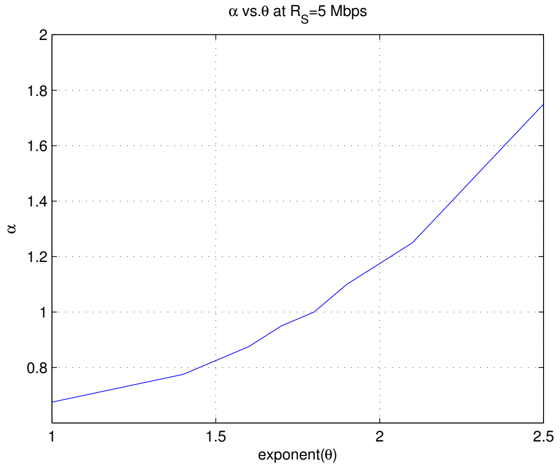

Fig. 3. Plot of optimal pricing parameter α vs. θ at fixed R_S(Mbps)

bit-rates are allocated proportionally such that,

$$R_i^a(k) = R_S \frac{R_i^r(k)}{\sum_{j=1}^{N} R_j^r(k)}.$$

2) The allocated bit-rates $R_i^a(k)$ for the N users are broadcasted in the DL-MAP of the WiMAX frame. Given the bit-rates $R_i^a(k)$ allocated to the video sequences, the video users/ players compute the H.264 scalable video quantization parameter $q_i(k)$ corresponding to the allocated bit-rate. The requested rate $R_i^r(k+1)$ for the next iteration is computed as the regret based strategy update which maximizes $u_i\left(R_i^a(k), R_{-i}^a(k)\right)$ as,

$$q_i^\star(k+1) = \arg\max\{Q_i(q_i(k)) - p_i(R_i(q_i(k)))\}.$$

The underlying strategy set comprising the scalable video bit-rates is non-empty, convex and compact since bit-rates for a given video sequence are limited to the range $[0, R_{\max}^i]$. As seen earlier, the utility function $u_i(R_i, R_{-i})$ is quasi-concave. Hence, the steps above are iteratively repeated to reach the stable Nash equilibrium. The final bit-rates are represented by the stable allocation R_i^a for each user. Further, the incidental outcomes of the above procedure are the price points for scalable video bit-rate allocation. Thus, the proposed competitive framework for video bit-rate allocation can also be employed as a dynamic congestion based pricing procedure at the QoS enforcement points for H.264 video based subscription services. Optimally choosing the values of parameters α and θ helps in efficient utilization of the scarce wireless spectrum. Hence for a fixed exponent θ, one can compute the utilities at various values of the weight parameter α following the above iterative allocation procedure and choose α at which $\sum R_i$ is maximized such that $\sum R_i \leq R_S$. Conversely, one can fix the parameter α, choose the optimal θ such that $\sum R_i$ is maximized corresponding to the Nash equilibrium allocation.

V. SIMULATION RESULTS

We now consider a 4G WiMAX streaming scenario consisting of 5 CIF video sequences (Foreman, Akiyo, Football, City, Crew) with quality and bitrate parameters specified in [3]. The users submit their initial scalable video bit-rate requests to the server through a polling based MAC mechanism. The iterative procedure described in the previous section is employed to compute the video bit-rates corresponding to the stable equilibrium allocation for each video sequence as per the given pricing parameters. In each case the server selects the pricing parameters to maximize the net sum-utility, thus employing the available wireless bandwidth resources efficiently. Fig.3 shows the plot of α vs. θ at typical WiMAX DL data rate $R_S = 5$ Mbps. At a given parameter θ, α is selected such that $\sum R_i \approx R_S$. We observe that the optimal α is exponentially related to the parameter θ for a given bit-rate R_S.

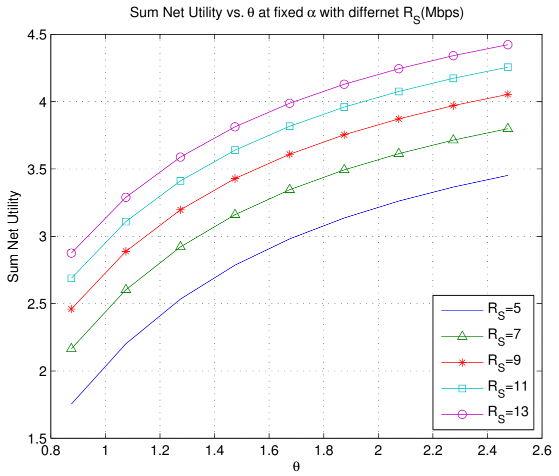

Fig. 4. Sum Net-Utility vs. θ with fixed $\alpha = 1.6$ at different R_S(Mbps)

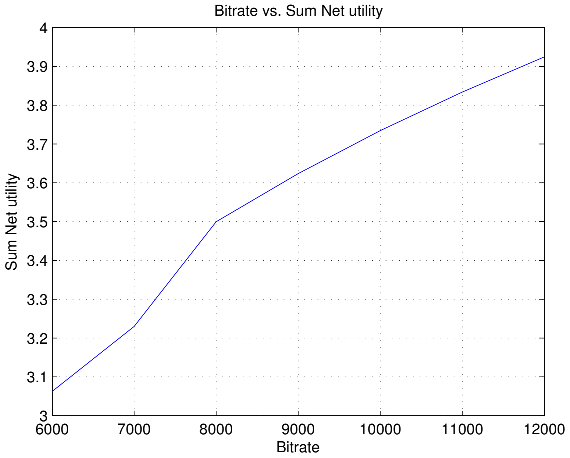

Fig. 5. Sum Net Utility vs. R_S(kbps) with $\theta = 1$

We present the plot sum-utility vs. θ for a fixed weighting parameter $\alpha = 1.6$ with varying R_S in Fig.4. It can be readily seen from (3) that increasing the value of the exponent parameter θ results in decreasing the video price leading to an increase in the overall net-utility. Further, higher values of the

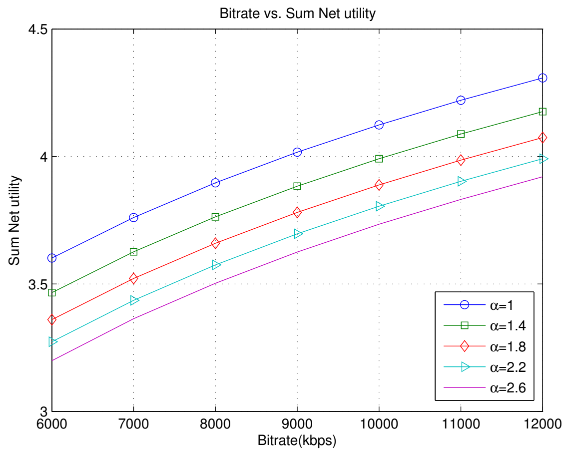

Fig. 6. Sum Net Utility vs. R_S(kbps) with $\theta = 2$ for various α

bit-rate R_S result in higher allocation to the videos streams and increase in the sum net-utility. Similarly, we also plot sum net-utility vs. R_S with the parameter $\theta = 1$ and α computed to maximize the net-utility at every R_S in Fig.5. Finally Fig.6 presents the behavior of net-utility corresponding to the stable allocation for several values of the pricing parameter α and $\theta = 2$. It can be seen that a lower value of α results in a Nash equilibrium bit-rate allocation $\sum_{i=1}^{N} R_i$ closest to R_S, there by leading to efficient bandwidth utilization.

VI. CONCLUSION

In this paper we proposed a pricing based game theoretic scheme for decentralized resource allocation towards H.264 based scalable video transmission in 4G wireless networks. This novel competitive approach for dynamic video resource allocation is based on a joint video quality and parametric pricing based quasi-concave net-utility function for video transmission. Employing the framework of game theory it was demonstrated that such a scheme guarantees the existence of the Nash equilibrium based stable video bit-rate allocation in which no player has an incentive to deviate. A competitive video bit-rate adaptation procedure was proposed based on an iterative strategy update procedure through MAC based polling available in the 4G WiMAX standard. We studied the behavior of the proposed scheme with respect to the video characteristic parameters and simulation results are found to be consistent with the expected behavior of the net-utility. We also demonstrated a paradigm for selection of the optimal pricing parameter values α and θ to efficiently utilize the available wireless bandwidth towards maximizing the net-utility. Thus, Nash equilibrium based scalable video bit-rate adaptation aids in successful design of a decentralized scheme for dynamic resource allocation.

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