QoE-Sensitive Economic Pricing Model for Wireless Multimedia Communications Using Stackelberg Game

Krishna Murthy Kattiyan Ramamoorthy, Wei Wang
Department of Computer Science, San Diego State University
kkattiyanramam8285@sdsu.edu, wwang@mail.sdsu.edu

Abstract— **With the advances in wireless multimedia communication technologies and the rise in end-user experience expectations, meeting the Quality of Experience (QoE) requirements of the mobile multimedia user has become challenging for content providers and wireless carriers. In this research, we chalk up a QoE-sensitive multimedia data pricing economic model, by pricing the quality of the data rather than the quantity of the data. Utility maximization problem between the content provider (sells multimedia content), wireless carrier (provides transmission service) and the mobile user (requests multimedia data) is modeled using the proposed framework. We then formulate the aforementioned problem as a two-stage Stackelberg game and derive the Nash Equilibrium using backward induction method. Simulation study show that each player can obtain optimal strategy where the Stackelberg equilibrium exists stably. Finally, the proposed smart pricing mechanism was tested against the traditional uniform pricing scheme and the results indicate that better utilities can be achieved by leveraging the proposed scheme.**

Index Terms*—*Quality of Experience (QoE), Smart multimedia pricing, Stackelberg game, Wireless multimedia communications.

I. Introduction

The current Cisco Visual Networking Index (VNI) forecast projects global IP traffic to nearly triple from 2017 to 2022. Virtual Reality (VR) and Augmented Reality (AR) traffic are expected to increase 12-fold between 2017 and 2022 globally, a CAGR of 65 percent [1]. With such explosive growth in multimedia traffic, meeting the QoE requirement of the mobile user becomes the biggest concern for content providers due to bandwidth constraints. This is because low multimedia quality leads to poor QoE which in turn leads to reduced usage of the applications/ services and hence reduced revenues [2].

Digital video compression techniques have been predominantly used in multimedia communication. High Efficiency Video Coding (HEVC), also known as H.265 is the state-of-the-art video compression standard in which the video is divided into GOP (Group of Pictures) and encoded. Each encoded video stream contains I (Inter frame), P (forward predicted frames) and B (bi-directional predicted frames). The B frames can be predicted or interpolated from an earlier and/or later P frame while the P frame can be predicted from the I frame [3]. I frames are more important than P frames because the transmission errors of I frames will infect the successful transmission of subsequent P frames. Therefore, the multimedia frames have unequal importance. Different multimedia packets have different bandwidth requirements and different communication energy consumption attain certain QoE for the end user [4].

Recently, Smart Media Pricing (SMP) was conceptualized to price the QoE rather than the binary data traffic in multimedia services [5]. In this research work, we leverage the concept of SMP to chalk up a QoE-sensitive multimedia pricing framework, to allocate price according to the quality of multimedia frames purchased by / transmitted to the mobile user.

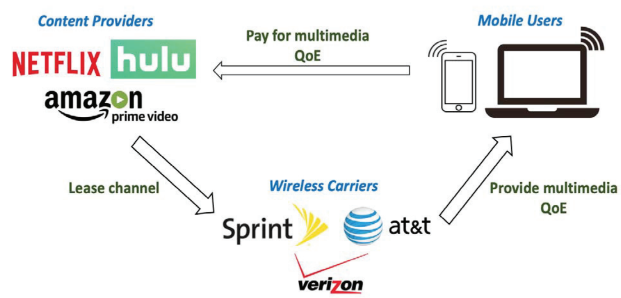

Fig. 1. Three party interaction of economic modeling between content provider, wireless carrier and mobile user.

Fig. 1 shows the typical economic multimedia service model in wireless multimedia communication. The mobile user requests multimedia content with certain QoE requirement and pays the content provider. The content provider leases the channel from wireless carriers to transmit the requested content. The wireless carrier allocates resources to the mobile user to provide the multimedia service at requested QoE level. In this paper, we propose a Stackelberg game based decision-making scheme to determine the equilibrium between the cost paid by mobile user and multimedia quality achieved.

There has been rapid evolution in pricing practices among Internet service providers (ISPs) in the U.S. and other international markets, particularly in moving away from flat-rate

978-1-7281-0962-6/19/$31.00 ©2019 IEEE

pricing to improve their revenue [6]. Several pricing concepts such as priority pricing, Paris-Metro pricing, smart-market pricing, responsive pricing, expected capacity pricing, edge pricing, and effective bandwidth pricing have been proposed to tackle issues of network congestion and profit maximization [7]. These methods, however, do not take into consideration several important parameters such as, multimedia quality achievable under same network condition and users personal preference for a multimedia content.

Smart media pricing for allocating price according to multimedia distortion reduction [4] and wireless multimedia relay communication to provide incentives to devices participating in content forwarding [9] have been investigated. The service model between provider, carrier and mobile users was modeled as a best response game and Nash Equilibrium was derived for the non-concave utility function [8]. In this work, we focus on developing a multimedia quality aware pricing strategy to achieve the pledged QoE for the mobile users.

The rest of the paper is organized as follows. In section II, the interplay between the content provider, wireless carrier and mobile user is mathematically modelled and the utility functions are formulated. The profit maximization problem is then converted to a two-stage Stackelberg game and an algorithm to determine the Nash equilibrium is devised in section III. In section IV, we present the simulation results. Finally, we draw conclusions in section V.

II. System Model

The three-party interaction shown in Fig. 1 is reduced into a two-party game, by integrating the content provider wireless carrier alliance (in short, provider carrier alliance). The provider and carrier typically negotiate a deal behind the scene and form an alliance. Therefore, the interplay between the provider-carrier alliance is not the scope of this paper. The Fig. 2, shows the interaction between the provider carrier and the mobile user. In the proposed model the provider-carrier dynamically decide the cost per bit y_j for requested multimedia data. Since each frame has unequal importance, the mobile user has the flexibility to determine the number of bits y_j to purchase for a given cost.

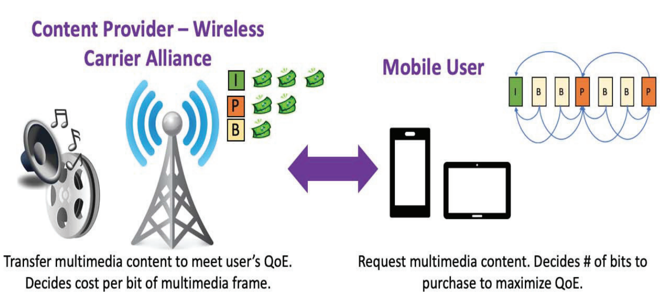

Fig. 2. System model for spectrum allocation in QoE centric wireless multimedia communications

The multimedia QoE achieved by the user is determined by the number of bits purchased. Fig. 2, also shows the relationship between I, P and B frames. Therefore, for a lower cost y_j, the user is willing to purchase the B frames and P frames which maximize their QoE whereas at a higher cost, the user is interested only in purchasing the I frame. In this section, we define the utilities of the provider-carrier alliance and the mobile user. The terminologies packet and frame are used interchangeably in this paper.

A. Utility of mobile user

The mobile user requests a sequence of frames $j = 1, 2, , m$ with unequal importance from the content provider over the wireless channel offered by the wireless carrier. The QoE is defined as a function of multimedia media quality described by Peak Signal to Noise Ratio (PSNR) and the Packet Error Rate (PER). The PER P_k is defined as the number of error packets after forward error correction divided by the total number of received packets. P_k is related to the Bit Error Rate (BER) and the bit length of the corresponding packet l_k.

$$P_k = 1 - (1 - BER)^{l_k} \tag{1}$$

Let q_j and l_j denote the multimedia quality and the bit length of the j^{th} frame. The set of ancestor frames which the j^{th} frame refers to is denoted by π_j. For each frame j, the QoE is related to the multimedia quality, bit length and the successful transmission probabilities of its ancestor frames and can be modeled as a logarithmic function [10]

$$QoE = a_1 \log \left(a_2 \sum_{j=1}^{m} q_j l_j \prod_{k \in \pi_j} (1 - P_k) + a_3 \gamma + a_4 \right) \tag{2}$$

where a_1, a_2, a_3 and a_4 are positive system parameters used to fine-tune the QoE model and γ is the users personal preference of a certain multimedia content. For example, some users could have a greater affinity towards a soccer match video, while some users may not be interested in soccer at all. These users would have different values for γ. The effect of γ on the QoE model is further discussed in the simulation study.

The mobile user pays content provider with ψ_{user} for delivering multimedia QoE. This can be modeled as the product of the cost per bit of data transmitted y_j and the amount of multimedia transaction bits l_j.

$$\psi_{user} = \sum_{j=1}^{m} y_j l_j \tag{3}$$

The optimization on the mobile users is to purchase the right number of packets (bits) that maximizes its utility, subjected to bit length constraint. The utility is defined as the total QoE gain subtracted by the financial cost paid by the user.

$$U_{user} = a_1 \log\left(a_2 \sum_{j=1}^{m} q_j l_j \prod_{k\in\pi_j} (1-P_k) + a_3\gamma + a_4\right) - \sum_{j=1}^{m} y_j l_j \quad (4)$$

$$st.\ U_{user} \geq 0$$

$$l_{min} < l_j < l_{max}$$

where l_{min} and l_{max} represent minimum number of bits to encode the multimedia data and the maximum number of bits that can be supported within a frame.

B. Utility of the provider-carrier allience

The content provider and the wireless carrier will negotiate a commission rate for leasing the wireless channel resource, in order to achieve the pledged QoE for the end user. The utility of the provider-carrier alliance U_{PC} could be estimated as the total revenue charged from the mobile user subtracted by the operational cost of provider and the carrier.

$$U_{PC} = \psi_{user} - \psi_{provider} - \psi_{carrier} \quad (5)$$

The payment received from the user ψ_{user} is modeled in equation (3). The operational cost of the provider $\psi_{provider}$ is a function of source coding control as shown in equation (6), where α is the cost per bit of source coding control.

$$\psi_{provider} = \alpha \sum_{j=1}^{m} q_j l_j \quad (6)$$

The cost on the wireless carrier side can be modeled as logarithmic function of successful transmission probabilities of the ancestor frames

$$\psi_{carrier} = \beta \sum_{j=1}^{m} \log \prod_{k\in\pi_j} (1-P_k) \quad (7)$$

where β denotes the operating cost of the wireless carrier. The optimization problem for the provider-carrier alliance is to set the proper cost per bit of multimedia data that maximizes its utility.

$$U_{PC} = \sum_{j=1}^{m} y_j l_j - \alpha \sum_{j=1}^{m} q_j l_j - \beta \sum_{j=1}^{m} \log \prod_{k\in\pi_j} (1-P_k) \quad (8)$$

$$st.\ U_{PC} \geq 0$$

III. STACKELBERG GAME ANALYSIS

In this section, we first normalize the utility equations (4) and (8) to reduce the number of adjustable parameters. Then the utility maximizing problem between the provider-carrier and the user is be modeled as a two stage Stackelberg game to determine the Nash Equilibrium of the game. Nash equilibrium of the game is defined as the set of strategies, one for client and one for the service provider such that both players have no incentive deviating from that strategy [11].

On the mobile user side, the user controls the number of multimedia frames (bits) to purchase in order to maximize their utility subject to the total multimedia bit constraint $\sum_{j=1}^{m} l_j \leq L$. Optimality can is reached by taking the equality condition as shown below. By choosing a higher value for L, the user can achieve higher multimedia quality at higher financial cost.

$$\sum_{j=1}^{m} l_j = L \quad (9)$$

The per-bit cost y_j for each packet would achieve optimal solution, however, the feasibility of achieving such a global solution would be impractical for a large amount of multimedia packets within a number of user flows. Therefore, instead of finding the Nash Equilibrium per-bit cost y_j for each packet, we can simplify the proposed model to determine the single sub-game perfect Nash Equilibrium base price y_0 that leads to the best utility at provider-carrier alliance side.

We define the normalized base price y_0 as the unit quality gain for each multimedia bit. As shown in Fig. 2, a multimedia frame in a GOP has a dependency on the ancestor frames and the descendent frames to decode their data. The set of frames whose decoding depend upon the successful decoding of packet j, is defined as $\pi_{j'}$. Then the per-bit cost of multimedia packet j can be presented as

$$y_j = y_0 \sum_{k\in\pi_{j'}} q_k \quad (10)$$

The above equations (9) and (10) can be used to simplify the utilities of the user (4) and provider-carrier (8) defined in the previous section as shown below

$$U_{user} = a_1 \log\left(a_2 L \sum_{j=1}^{m} q_j \prod_{k\in\pi_j} (1-P_k) + a_3\gamma + a_4\right) - y_0 L \sum_{k\in\pi_{j'}} q_k \quad (11)$$

$$U_{PC} = y_0 L \sum_{k\in\pi_{j'}} q_k - \alpha L \sum_{j=1}^{m} q_j - \beta \sum_{j=1}^{m} \log \prod_{k\in\pi_j} (1-P_k) \quad (12)$$

The two-stage game is solved using backward induction. We begin by converting the utility functions into the best response functions and then we look for mutual best response $\{L^*, y_0^*\}$. Mutual best response is the set of strategies which produce the most favorable outcome for a player, taking other players' strategies as given [11].

A. Best response of the mobile user

In stage I, as the leader of the Stackelberg game, the provider-carrier offers a real-time cost for multimedia frames y_0 to the users. In stage II, as a follower in Stage I, the user decides the amount of multimedia data L to purchase based on the offer from provider-carrier. It can be proved that utility of the user for downloading the j^{th} packet is concave for given cost y_0 and $L_{min} < L < L_{max}$ by computing the second order derivative of the utility function.

$$\frac{\partial U_{user}}{\partial L} = \frac{a_1 a_2 \sum_{j=1}^{m} q_j \prod_{k\in\pi_j}(1-P_k)}{a_2 L \sum_{j=1}^{m} q_j \prod_{k\in\pi_j}(1-P_k)+a_3\gamma+a_4} - y_0 \sum_{k\in\pi_{j'}} q_k \tag{13}$$

$$\frac{\partial^2 U_{user}}{\partial L^2} = -\frac{a_1 a_2^2 \sum_{j=1}^{m} q_j^2 \prod_{k\in\pi_j}(1-P_k)^2}{\left(a_2 L \sum_{j=1}^{m} q_j \prod_{k\in\pi_j}(1-P_k)+a_3\gamma+a_4\right)^2} \tag{14}$$

Since a_1 is positive system parameters and all the other terms in the equation are squared, we have the second derivative $\frac{\partial^2 U_{user}}{\partial L^2} < 0$. Therefore, the utility function of user is concave and the best response of the user L^* that would maximize their utility can be computed by equating the first derivative $\frac{\partial U_{user}}{\partial L} = 0$

$$\frac{a_1 a_2 \sum_{j=1}^{m} q_j \prod_{k\in\pi_j}(1-P_k)}{a_2 L \sum_{j=1}^{m} q_j \prod_{k\in\pi_j}(1-P_k)+a_3\gamma+a_4} - y_0 \sum_{k\in\pi_j'} q_k = 0 \tag{15}$$

The equation (15) can be solved to derive the fixed relationship between the users multimedia requirement L and the cost charged by the provider-carrier alliance y_0. Therefore, the user always purchases L^* number of frames based on equation (16) in order to achieve maximum utility.

$$L(y_0) = \frac{\frac{a_1 a_2 \sum_{j=1}^{m} q_j}{y_0 \sum_{k\in\pi_j'} q_k} - a_3\gamma - a_4}{a_2 \sum_{j=1}^{m} q_j \prod_{k\in\pi_j}(1-P_k)} \tag{16}$$

B. Best response of the carrier-provider alliance

The carrier-provider being rational knows the amount of multimedia frames the user would purchase L^*, such that their utility is maximized for any given cost y_0. Therefore, the utility of the user shown in equation (12) can be rewritten in terms of y_0 as shown below.

$$U_{PC} = y_0 L(y_0) \sum_{k\in\pi_{j'}} q_k - \alpha L(y_0) \sum_{j=1}^{m} q_j - \beta \sum_{j=1}^{m} \log \prod_{\kappa\in\pi_j} (1-P_k) \tag{17}$$

It is hard to prove the concavity of the second order derivative of the utility equation above. Therefore, we have used Newton method in a way similar to [4] to find the best response ${y_0}^*$.

Lemma 1: A real function which is differentiable must be a continuous function [13].

Lemma 2: A continuous real function on a closed interval must contain a maximum value and a minimum value [13].

Taking the first derivative of the equations (16) and (17) with respect to y_0, it can be observed that the utility function of the provider-carrier is both real and differentiable as illustrated in equation (18) and (19). The result coupled with Lemma 1, proves that the utility function is continuous.

$$\frac{\partial U_{PC}}{\partial y_0} = L(y_0) \sum_{k\in\pi_{j'}} q_k + \frac{\partial L(y_0)}{\partial y_0} \left(y_0 \sum_{k\in\pi_{j'}} q_k - \alpha \sum_{j=1}^{m} q_j \right) \tag{18}$$

$$\frac{\partial L(y_0)}{\partial y_0} = -\frac{a_1}{y_0^2 \sum_{k\in\pi_{j'}} q_k} \tag{19}$$

Since a_1, y_0 and q_k are all positive, the first order derivative of the best response function $\frac{\partial L(y_0)}{\partial y_0} < 0$ at all times. This shows that the function is monotonically decreasing. The multimedia length is constrained as $L_{\min} < L < L_{\max}$.

$$y_{0\,\min} = \frac{a_1 a_2 \sum_{j=1}^{m} q_j \prod_{k\in\pi_j}(1-P_k)}{\left[a_2 L_{\max} \sum_{j=1}^{m} q_j \prod_{k\in\pi_j}(1-P_k)+a_3\gamma+a_4\right] \sum_{k\in\pi_{j'}} q_k} \tag{20}$$

$$y_{0\,\max} = \frac{a_1 a_2 \sum_{j=1}^{m} q_j \prod_{k\in\pi_j}(1-P_k)}{\left[a_2 L_{\min} \sum_{j=1}^{m} q_j \prod_{k\in\pi_j}(1-P_k)+a_3\gamma+a_4\right] \sum_{k\in\pi_{j'}} q_k} \tag{21}$$

Therefore, it can be inferred that the best response for the base cost y_0 is confined within a close interval $\{y_{0\,\min} < y_0^* < y_{0\,\max}\}$. Lemma 2 proves the existence of maximum value which can be determined using a generic global searching algorithm.

C. Stackelberg Game Theoretic Equilibrium Algorithm

Based on the above analysis of the proposed two stage game, we present an iteration based global searching algorithm to implement the smart pricing scheme. The algorithm looks for the mutual best response price and multimedia packet length $\{L^*, {y_0}^*\}$ for the provider-carrier and the mobile user respectively.

The computing complexity of the proposed Stackelberg smart media pricing game algorithm is $O(M)$, which comprises of the maximum iteration steps M to determine the optimal value. Since the best response value for multimedia frame length L^* and the base price ${y_0}^*$, we can make a two-dimensional searching table and update the values in the table during sparse time periods between the multimedia transmission. The computation complexity and the latency between the data transmission can be reduced by determining the mutual best response directly by searching the table whenever the game needs to be performed.

Algorithm 1 QoE Sensitive Pricing - Stackelberg Algorithm

1) **Initialization:**
   1.1. Initialize the system parameters a_1, a_2, a_3 and a_4.
   1.2. Set the user preference value for given multimedia content $\gamma \in [0, 1]$.
   1.3. Define the base cost y_0 and the multimedia quality q_j, $j \in [1, m]$ and q_k, $k \in \pi_j{}'$.
   1.4. Set the physical channel parameters: length of frame L and packet error rate P_k, $k \in \pi_j$.
2) **Iterations:**
   2.1. The algorithms solve for the best responses $\{L^*, {y_0}^*\}$. Thereby, determining the utilities of the provider-carrier alliance and the mobile user $\{U_{PC}, U_{user}\}$.
   2.2. Set the $U_{PC} = U_{user} = L^* = {y_0}^* = 0$.
   2.3. Let $\chi = y_{0\ min} : M : y_{0max}$
   2.4. **For** i=1: M
   2.5. Set $y_0 = \chi$(i)
   2.6. Compute the probable utility for provider-carrier $U_{PC}(y_0)$ according to equation (17)
   2.7. **if** $U_{PC}(y_0) > U_{PC}$
      2.7.1 Update $U_{PC} = U_{PC}(y_0)$
      2.7.2 Set ${y_0}^* = y_0$
      2.7.3 Calculate the optimal frame length to purchase based on equation (16)
      2.7.4 Determine the value of U_{user} according to equation (11)
   2.8. End **if**
   2.9. End **for**
3) **Output:**
   The algorithm searches the closed interval space $[y_{0min}, y_{0max}]$ and determines the Nash equilibrium $\{L^*, {y_0}^*\}$. The corresponding utilities are $\{U_{PC}, U_{user}\}$

IV. Simulation Study

In this section, we evaluate the performance of the proposed QoE - sensitive multimedia pricing framework. The video sequence for simulation is Foreman with H.265 coder. The I-frames successful transmission only relies on itself, while the P-frames refer to the previous I-frame and P-frames. The systems parameters used to fine tune the QoE model $a1 \sim a4$ were chosen as 3.8, 4.9, 3.6 and 3.5 respectively based on the large number of subjective video quality tests conducted by K. Yamagishi, et.al [13]. The bit error rate (BER) was set at 1e-6 and the maximum iteration steps M as 200. The initial values for α and β are 0.1 and 4 respectively.

In the previous section, we have mathematically proved that the utility of the mobile user is concave for any price y_0, declared by the carrier-provider alliance. The Fig. 3, shows that the utility of the user versus the amount of data purchased for base price y_0 = 0.4, 0.5 and 0.6 respectively. The QoE of the mobile user requesting multimedia content is modeled as a function of users personal preference as shown in equation (2). For a fixed base price y_0=0.4, the value of γ is altered to demonstrate the impact of personal preference on the users QoE in Fig. 4. It can be observed that for low data rates, the impact of γ is significant.

Fig. 5 shows the normalized utility of provider-carrier alliance for base price y: y_0 = 0.4, 0.5 and 0.6 respectively. The figure illustrates that the utility is proportional to the

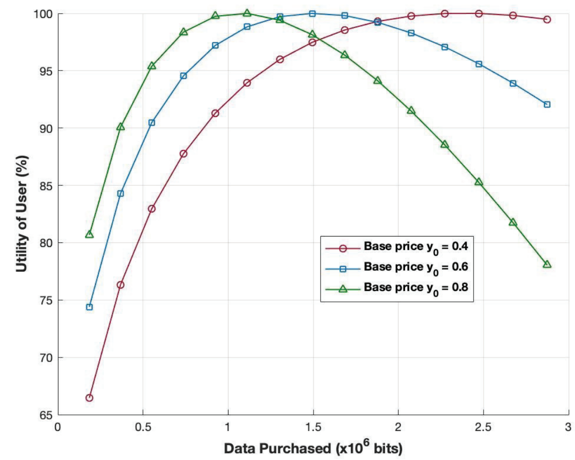

Fig. 3. Utility of user versus multimedia data purchased for various base price y_0.

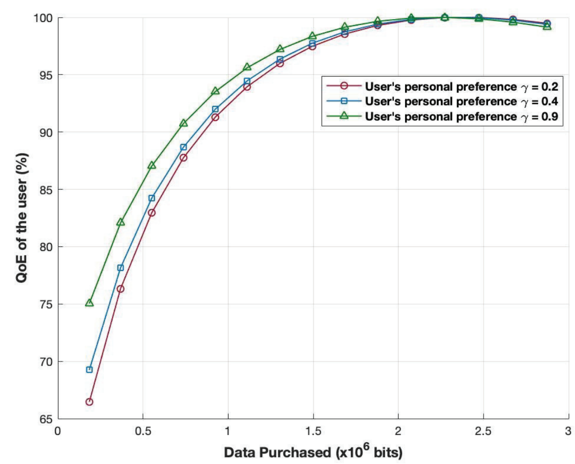

Fig. 4. Effect of users personal preference γ on QoE of the mobile user.

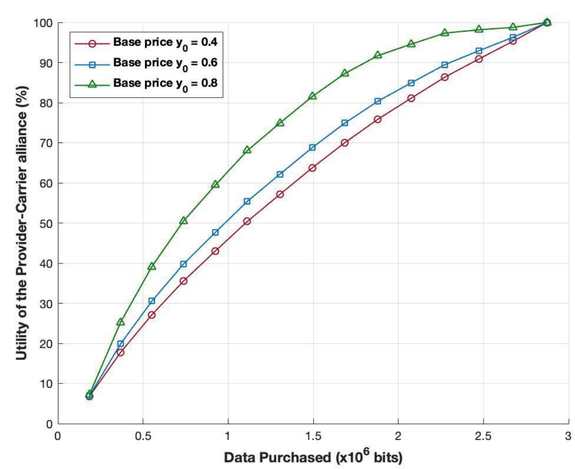

Fig. 5. Utility of provider-carrier versus multimedia data purchased for different base price y_0

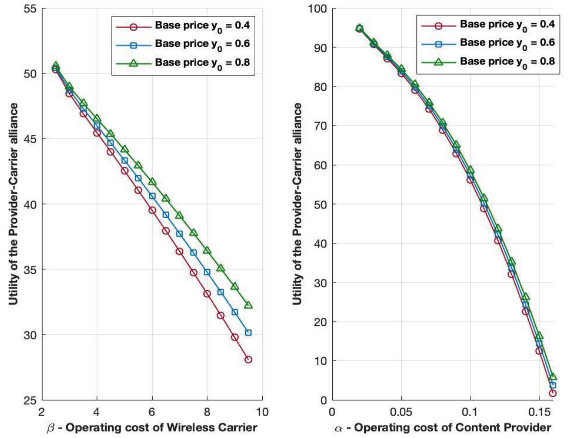

Fig. 6. Utility of provider-carrier versus operation cost of the wireless carrier and the service provider

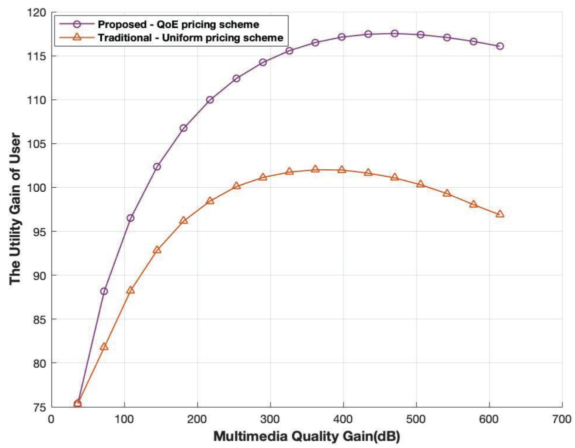

Fig. 7. Utility gain of user versus the multimedia quality gain for uniform pricing and proposed smart pricing schemes

amount of data purchased and how the Nash Equilibrium fails if the provider-carrier deviate from their pledged base price. Fig. 6 shows the utility of the provider-carrier when we change the operation cost of the wireless carrier β and content provider α respectively. It can be observed that for a fixed price y_0, the utility decreases linearly with increasing β and α. Therefore, it can be infered that the different initialization of the constant parameter does not affect the proposed utility equations.

The proposed QoE-sensitive multimedia pricing scheme allocate different prices to frames based on the packet length and PSNR. We compare our scheme with throughput based traditional pricing scheme (equal frame importance). In this scheme, each frame uses the same PSNR and bit length i.e. the resource is sold with a fixed price. The utility gain of the user for both these schemes are shown above in Fig. 7. It can be observed that our scheme outperforms the uniform pricing scheme significantly. This is because the frames are strategically priced (regular packers are incented with lower price while important packets are granted higher price) using Stackelberg game, so as to enhance the overall QoE of user.

V. Conclusion

In this paper, we leverage the Smart Media Pricing (SMP) framework and propose a new QoE-sensitive multimedia economic pricing model solvable by Stackelberg game theory. The contemporary video coding scheme such as H.265 encode video frames with unequal importance. This diversity allows us to price the multimedia frames based on the quality importance rather than the date size. The interactions between wireless carrier content provider alliance and the end user were modeled and solved as a two-stage Stackelberg game. We present an iterative algorithm to determine the Nash Equilibrium of the proposed scheme using backward induction method. Simulation results indicate that higher utilities can be achieved by adopting the proposed QoE-sensitive multimedia economic pricing model.

VI. Acknowledgement

This research was supported in part by National Science Foundation Grant No. 1744182 on Smart Media Pricing research in Wireless Multimedia Resource Allocation.

References

[1] Cisco, Cisco Visual Networking Index: Forecast and Methodology 20172022, Document ID: 1543280537836565, Updated: Nov. 2018.

[2] A. Khan, L. Sun and E. Ifeachor, QoE Prediction Model and its Application in Video Quality Adaptation Over UMTS Networks," in IEEE Transactions on Multimedia, vol. 14, no. 2, pp. 431-442, Apr. 2012.

[3] J. Xu, B. Zhou, C. Zhang, N. Ke, W. Jin and S. Hao, The impact of bitrate and GOP pattern on the video quality of H.265/HEVC compression standard," in IEEE International Conference on Signal Processing, Communications and Computing, Qingdao, 2018, pp. 1-5.

[4] Q. Wang, W. Wang, J. Shi, H. Zhu, N. Zhang, Smart Media Pricing (SMP): Non-Uniform Packet Pricing Game for Wireless Multimedia Communications, in Proc. IEEE INFOCOM SDP Workshop, Apr. 2016.

[5] W. Wang and Q. Wang, "Price the QoE, Not the Data: SMP-Economic Resource Allocation in Wireless Multimedia Internet of Things," in IEEE Communications Magazine, vol. 56, no. 9, pp. 74-79, Sept. 2018.

[6] C. J. Wong, L. Zheng, S. Ha, S. Sen, C.W. Tan, M. Chiang, Smart Data Pricing in 5G Systems, Key Technologies for 5G Wireless Systems, Chap 22, p.478-500, Apr. 2017.

[7] M. Falkner, M. Devetsikiotis and I. Lambadari, An overview of pricing concepts for broadband IP networks, IEEE COMMUNICATIONS SURVEYS, 3(2): 213, 2000.

[8] S. He and W. Wang, A Generalized Best-Response Smart Media Pricing Economic Model for Wireless Multimedia Communications, in Proc. IEEE Consumer Communications and Networking Conference, Jan. 2019.

[9] S. He and W. Wang, Context-Aware QoE-Price Equilibrium for Wireless Multimedia Relay Communications Using Stackelberg Game, in Proc. IEEE INFOCOM SCAN Workshop, May 2017.

[10] Z. Su, Q. Xu, M. Fei and M. Dong, Game Theoretic Resource Allocation in Media Cloud with Mobile Social Users, IEEE Transactions on Multimedia, Vol.18, No. 8, August 2016.

[11] M. J. Osborne, *An Introduction to Game Theory*, Oxford University Press, 2003.

[12] K. G. Binmore, “Mathematical Analysis: a straightforward approach”, Cambridge University Press, 1982.

[13] K. Yamagishi, T. Hayashi, Parametric packet-layer model for monitoring video quality of IPTV services." in Proc. IEEE International Conference on Communications, pp. 110-114, May 2008.