A Generalized Best-Response Smart Media Pricing Economic Model for Wireless Multimedia Communications

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***Abstract*—How to jointly provide Quality of Experience (QoE) to mobile multimedia users and simultaneously address the profit maximization issue of Content Provider (CP) - Wireless Carrier (WC) is a new economic challenge in wireless multimedia communications. In this paper, we consider leveraging the Smart Media Pricing (SMP) concept and develop a generalized best-response game theoretical model to determine the consumed data traffic from users and the media price charged by CP-WC alliance. Based on the SMP utility models of user and CP-WC alliance, a generalized game theoretical best-response game model is proposed to solve the non-cooperative selfish competition between the two players, which does not require concavity of the utility function at all. In the proposed Best Response Nash Equilibrium (BRNE) algorithm, both pure strategy and mixed-strategy schemes are developed for attaining the equilibrium solutions of the CP-WC's data price and user's amount of data consumption. Simulation study demonstrates the efficiency of the proposed BRNE algorithm that both user and CP-WC alliance get better utility when the system takes the Nash Equilibrium solutions.**

***Index Terms*—Quality of Experience, Best Response Game, Smart Media Pricing**

I. INTRODUCTION

The profit maximization of Content Provider (CP) and Wireless Carrier (WC), the Quality of Experience (QoE) improvement of user are two fundamental problems in the 5G wireless multimedia services and multimedia Internet of Things (IoTs). Possible candidate solutions include Smart Data Pricing (SDP) for generic data [1-3], and Smart Media Pricing (SMP) for wireless multimedia services [4]. In SMP, the media price is dynamically decided by the service provider but taking user's response and QoE requirement into consideration at the same time [20]. Unlike SDP, the SMP provides a new service fashion that CP-WC alliance can price the QoE, not the traditional binary data, for mobile users consuming wireless multimedia services.

In Figure 1 we illustrate the new SMP concept that "price the QoE, not the data" to thoroughly investigate the SMP model in the wireless multimedia data services. In the SMP model, various multimedia packets carrying different QoE weights are assigned with different prices. The users pay to the CP to get the multimedia content, and the CP leases wireless channel from the WC. Eventually the WC allocates wireless resources to provide the multimedia service at certain QoE levels.

The idea of allowing customers to join the price determining process has been widely studied in literature. Authors in [5] studied the optimal combination of flat-rate (or static) and usage-based data pricing based on the consumer's data-rate demands. One shortage of the usage-based pricing scheme is that it still requires the wireless ISPs to over-provision capacity for data demands at peak service time. A Time Dependent Pricing (TDP) scheme was provided in [6], where the dynamic pricing benefited both operators and customers by balancing the cost of congestion at peak period and lower price at off-peak time. Authors in [7] proposed a context-aware QoE-driven pricing service paradigm between end user and base station, such that both user and base station (acted as the WC) could obtain desirable utilities.

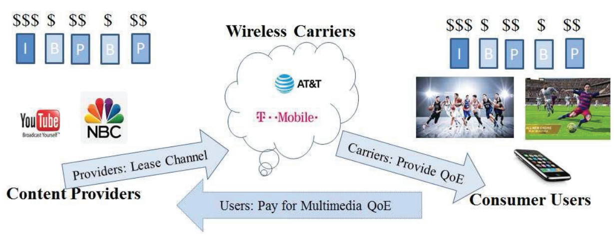

Fig. 1. The illustration of the typical SMP service model: in the network economics model for smart media pricing, users pay to CP, CP leases channel from WC, and WC provide QoE to users.

Aforementioned studies mainly considered the typical two-party game with concave utility functions, where methodologies such as backward induction would be easily applied for seeking the equilibrium SDP/SMP solutions [8]. Authors in [9] provided a price auction game to solve the energy efficiency problem in the typical source-relay cooperative wireless networks. In [10], the base station's price and device's power were considered as two factors operated by these two non-cooperative players respectively. The system could obtain the proper price and power by acquiring the Stackelberg game equilibrium. In [11], authors provided a polymatroidal theoretic framework to maximize the profit through proper bandwidth allocation.

Inspired by above works, we propose a generalized best response SMP game model in this paper to address the issue of profit maximization of CP-WC and QoE improvement of

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users. The major contribution of this paper is two folds. First, the new concept of SMP is proposed to "price the QoE, not the data." Second, the typical assumption of a concave utility function is relaxed in this paper as we develop a best-response pure/mixed strategy game between CP-WC alliance and mobile users.

The rest of the paper is organized as follows. We provide the SMP utility models of CP-WC and mobile user in Section II. The QoE-driven SMP model is fully addressed in Section III. In Section IV the numerical simulations are performed. Finally, we conclude our work in Section V. Key notations and nomenclature of this paper are given in Table I.

TABLE I
SUMMARY OF NOTATIONS

Symbol	Comments
U	Utility function.
q_i	The distortion reduction of the i-th multimedia packet.
C	The cost function.
l_i	The length of the i-th packet.
p_k	The error rate of packet k.
y_i	The data purchase price (per bit) of user.
$a_1 \sim a_4$	Preset parameters of user's QoE model.
∂, β, γ	Preset constant parameters to align object measurements to utility.
N	Number of multimedia flows in the service duration.
M	Number of packets per multimedia flow.
S	Set of all possible combinations of the consumed data length and the corresponding base price.

II. SMP Network Economics Model

A. Interpretation of User's Utility in QoE

The three-party (shown in Fig.1) game can be translated into a two-party game, by unifying the content provider and wireless carrier alliance. Typically the CP and WC could negotiate a deal behind the scene and form an alliance to make the SMP model a two-party game. On the user side, as the QoE-driven player in the game, the proposed utility model of user has to ensure the utility value is positive, i.e., $U_{usr} > 0$. In addition, the Peak Signal-to-Noise-Ratio (PSNR) which is treated as one commonly used objective quality measurement for video streaming services, is used in this work to measure the QoE of user [12] [18] [19]. The utility of user can be expressed as the total QoE gain subtracted by its financial cost for data service:

$$U_{usr} = QoE\left(\sum_{i\in[1...N]}\sum_{j\in[1..M_i]} q_{i,j} * l_{i,j} * \prod_{k\in\pi_{i,j}} (1-p_k)\right) -C_{usr}\left(\sum_i\sum_j y_{i,j} * l_{i,j}\right) \quad (1)$$

where C_{usr} is a monotonically non-decreasing cost function aligning the payment into the user's QoE satisfaction, i.e., if $x \leq y$ then $C_{usr}(x) \leq C_{usr}(y)$. The Packet Error Rate (PER) p_k is related to the channel's Bit Error Rate (BER) and the length of the corresponding packet [21], calculated as $p_k = 1-(1-BER)^{l_k}$. We use the following cost function for user where α is a constant parameter to align price to QoE:

$$C_{usr} = \alpha * \sum_i\sum_j y_{i,j} * l_{i,j} \quad (2)$$

The per-bit price y_i for each packet is determined by the CP-WC alliance and CP-WC would achieve the proper solution by adjusting y_i. Let y_0 denote the normalized base price, i.e., the unit quality gain price for each bit. Let $\pi_j^{'}$ denote the descendant set of packet j, i.e., the set of all the packets whose decoding depend on the successful decoding of packet j [13]. Then the per-bit multimedia price of packet j could be presented as

$$y_j = y_0 * \sum_{k\in\pi_j^{'}} q_k. \quad (3)$$

Instead of finding the optimal price for each packet, we are trying to find the Nash Equilibrium (NE) base price y_0 that leads to the best utility at CP-WC alliance side in our proposed model.

One advantage of the proposed SMP solution is that it is generic and independent to QoE model. Various widely adopted QoE models, such as a parametric packet video QoE model considering packet loss ratio [14], could be seamlessly integrated into the SMP framework. Instead of directly applying these existing QoE models, the packet group quality contribution factor is introduced, and the QoE gain of user is interpreted as:

$$QoE = 1 + \left(a_1 - \frac{a_1}{1+\left(\frac{B_r}{a_2}\right)^{a_3}}\right) * e^{\frac{\sum_{i=1}^{N}\sum_{j=1}^{M_i} q_{i,j} * l_{i,j} * \prod_{k\in\pi_{i,j}}(1-p_k)}{a_4}} \quad (4)$$

where $a_1 \sim a_4$ are pre-set system parameters to fine-tune the QoE model, and B_r is the source coding rate from multimedia compression process. The parameters were chosen as $a_1 = 3.8$, $a_2 = 4.9$, $a_3 = 3.6$ and $a_4 = 3.5$ in research [14] based on large number of subjective video quality tests, and we use them in this study and also investigate other proper values of these parameters to adjust our QoE model in the future. As we can see from Equation 4, the QoE gain of user is a strictly increasing function along with the multimedia quality gain from links. The economical cost on such QoE gain is mainly decided by the CP-WC alliance.

B. Utility Function of CP-WC's Financial Gain

On the other side of the game, the profit-driven CP-WC alliance party, the utility function could be approximated by the total revenue charged from user subtracted by the operational costs of CP and WC respectively:

$$U_{CP-WC} = \alpha * \sum_i\sum_j y_{i,j} * l_{i,j} - C_{CP}\left(\sum_i\sum_j q_{i,j}\right) -C_{WC}\left(\sum_i\sum_j \prod_{k\in\pi_{i,j}} (1-p_k)\right). \quad (5)$$

The cost function of CP (i.e., the C_{CP}) is directly related to its source coding parameter settings, such as the compression ratio, rate-distortion truncation of bit-planes, quantization levels and I-B-P video frame coding mode choice. It is usually an increasing and concave function of the source coding data [15]. We choose a logarithmic function as the cost function of CP:

$$C_{CP} = \beta * \log \left(\sum_i \sum_j q_{i,j} \right) \tag{6}$$

where β is a constant parameter to align data quality to utility. Following the same logic, the cost function of WC can be modeled as

$$C_{WC} = \gamma * \log \left(\sum_i \sum_j \prod_{k \in \pi_{i,j}} (1 - p_k) \right) \tag{7}$$

which implies that WC's cost is directly related to the data transmission quality and channel characteristics between WC and user. The γ is also a preset constant parameter to align PER to utility.

As the profit-driven player in the game, CP-WC wants to specify the per-bit base price y_0 to maximize the alliance utility, where the price rate must also satisfy the constraint that $U_{usr} > 0$. In other words, the data price has to be reasonable that user would like to buy.

C. The Nash Equilibrium of the QoE-Driven SMP Game

The strategy for user to maximize its QoE is to buy more data (i.e., request big $\sum_i \sum_j l_{i,j}$) or to purchase data at low price. Here we assume the PER keeps constant during the service time. On the contrary, CP-WC alliance would like to choose high price rate when providing data service to cover their incurred costs and gain high revenue. The situation between user and CP-WC alliance forms the typical non-cooperative game, which can be modeled as

$$\begin{aligned} \{(L^i, y_0^j) | i, j \in S\} &= \arg\max[U_{usr}, U_{CP-WC}] \\ s.t. \quad U_{usr} &> 0; U_{CP-WC} > 0 \ ; \end{aligned} \tag{8}$$

where S is the set of all possible combinations of the packet groups consumed by user and base price rate that set up by CP-WC. More specifically, the L^i denotes total data length that user consumed during the $i-th$ packet group and the y_o^j implies the $j-th$ base price strategy of CP-WC. The strategy set $\{L^i, y_o^j\}$ is determined by two players with their individual utility maximization purpose. It is necessary to characterize a set of $\{L^i, y_o^j\}$ where both user and CP-WC are satisfied with their utilities.

III. Best Response QoE-driven SMP Game

A. Nash Equilibrium Analysis with Pure Strategy.

Sometime it is hard to prove the utility functions are concave, for example, Equations (1) and (5). Therefore, a generalized best response approach is developed which produces the most favorable outcome for a player when other players' choices of strategies are known. In our case, both CP-WC alliance and user have no wish to deviate from the NE state $\{(L^i, y_o^j)\}$ since neither of them can unilaterally increase their utilities.

Definition 1: When using best response, a strategy set $\{(L^i, y_o^j)\}$ is called the NE of the non-cooperative game if, for every j, $U_{usr}(L^i, y_0^j) \geq U_{usr}(L^*, y_0^j)$ for all $L^* \in S(*, j)$ and for every i, $U_{CP-WC}(L^i, y_0^j) \geq U_{CP-WC}(L^i, y_0^*)$ for all $y_0^* \in S(i, *)$.

To approach the NE, we propose the Best Response Nash Equilibrium (BRNE) algorithm. We first use a simple example to explain how the BRNE algorithm works. We assume the user has two choices of data amount and the CP-WC alliance has two base price options in this simple case. Recall that we have specified the utility functions of user and CP-WC in previous sections. Thus both players' utility values can be numerical computed just like there are shown in the table II. The example's utility value sets (U_{CP-WC}, U_{usr}) of CP-WC and user are listed in the table.

TABLE II
A simple case to find the NE of non-cooperative game with best response method.

L (user) y0 (CP-WC)	$L^1 = 1 \times 10^6$bits	$L^2 = 2 \times 10^6$bits
$y_0^1 = 1$	(20,6)	(22,**<u>10</u>**)
$y_0^2 = 2$	(**<u>24</u>**,4)	(**<u>30</u>**,**<u>8</u>**)

The game NE seeking process is described as follows:

Step 1: The user will choose the best data consumption options according to the base price rates set by CP-WC respectively, in the purpose of choosing the maximum utility. In the case shown in table II, user would like to choose L^2 for the price rate y_0^1 and L^2 for the price rate y_0^2 too. We use the underlines to mark user's corresponding best response utilities.

Step 2: Based on the data consumption options provided by user, the CP-WC alliance will choose the corresponding base price rates that ensuring the maximum utilities for CP-WC. i.e., the CP-WC would choose y_0^2 for both L^1 and L^2 since it gets the best utilities and we mark them with underlines.

Step 3: Determining the NE length-price set(s) $\{(L^i, y_o^j)\}$ of two players based on previous steps' outputs. The $\{(L^2, y_o^2)\}$ is the NE set in table II case, since L^2 and y_0^2 have been both marked as the best response for the user and the CP-WC.

For non-cooperative game it is possible that the system ends up with three scenarios according to the above best response NE definition. 1) There is no NE point for the game, which means there is no commonly best response for two players. 2) There exists only one NE. i.e., the case shown in table II. 3) There exists more than one NE. For the last two scenarios, as long as the players' strategy sets are finite, we would obtain all the NE set(s) based on the aforementioned three steps. It is also known as the best response method with pure strategy, where the solution(s) is(are) the best response(s) for any given set of each player and the opponent's strategy. One the other hand, it is also possible that there is no NE set for two players using pure strategy best response method, such as the classical zero-sum game mentioned in [16]. To handle this particular case, the mixed strategy methodology is introduced to our proposed BRNE algorithm.

B. Mixed Strategy Nash Equilibrium Analysis.

In the example we discussed before, the players will clearly decide one behavior or another (also called pure strategy), especially when there exists the commonly best response for both players. But if the utility value sets fall into the first scenario, which implies there is no exact NE set, the user and the CP-WC can choose to play strategies with some probabilities. The behavior of playing strategies with probabilities is called a mixed strategy and the solution is called mixed-strategy NE [17].

Definition 2: A mixed-strategy NE for user and CP-WC includes two probability distributions over the available action sets: probabilities $\mu_1, \mu_2...$ of the user's data consumption lengths $L^1, L^2, ...$ and probabilities $\sigma_1, \sigma_2...$ of the base price options $y_0^1, y_0^2, ...$ for CP-WC alliance. The CP-WC side must be indifferent (in term of utility gain) between any of the pure strategies played by user with the probability μ_i. The user must get indifferent utilities between any of the pure strategies played by CP-WC with probability σ_j. The probabilities are subject to the constraint of $\mu_i \geq 0, \sigma_j \geq 0, \sum \mu_i = \sum \sigma_j = 1$.

Property 1: There is at least one mixed-strategy NE for user and CP-WC in the proposed SMP game theoretical model.

Validation: According to the mixed-strategy NE definition, to validate property 1 equals to identify that there exists two probability vectors $\vec{\mu} = (\mu_1, \mu_2...)$ and $\vec{\sigma} = (\sigma_1, \sigma_2...)$ for user and CP-WC, such that every option in the strategy's support yields the same expected utility gain [16]. There are in fact two probability vectors that satisfy the three conditions listed in Definition 2.

TABLE III
UTILITY VALUES OF CP-WC AND USER THAT SHOW NO BEST RESPONSE PURE STRATEGY NE FOR TWO PLAYERS.

L (user) y_0 (CP-WC)	$L^1 = 1 \times 10^6$bits	$L^2 = 2 \times 10^6$bits
$y_0^1 = 1$	(**22**,6)	(18,**10**)
$y_0^2 = 2$	(20,**8**)	(**24**,6)

First, we start our analysis with a simple case that can be solved by mixed-strategy NE. The case and its corresponding set up of parameters are shown in Table III (no pure strategy solution). We assume μ_1 and μ_2 are the probabilities that user will choose data consumption options L^1 and L^2. In addition, the σ_1 and σ_2 imply the probabilities that CP-WC will choose base price rates y_0^1 and y_0^2. According to the Definition 2, CP-WC alliance should gain the same utility (regardless of its base price options) when user takes data consumption (L^1, L^2) with probabilities(μ_1, μ_2). We numerically interpret it as

$$22 \times \mu_1 + 18 \times \mu_2 = 20 \times \mu_1 + 24 \times \mu_2 \tag{9}$$

where the left hand side of denotes the utility gain of CP-WC when choosing base price y_0^1, and the right hand side of denotes the CP-WC's utility gain at price rate y_0^2. Recall that we already have

$$\sum_{i=1}^{2} \mu_i = 1, \mu_i \geq 0. \tag{10}$$

It is easily to solve Equations (9) and (10) with substitution method and we obtain the solution $\mu_1 = 3/4, \mu_2 = 1/4$ for user. Based on the same logic, we have the following system of linear equations at CP-WC side

$$\begin{cases} 6 \times \sigma_1 + 8 \times \sigma_2 = 10 \times \sigma_1 + 6 \times \sigma_2 \\ \sigma_1 + \sigma_2 = 1 \end{cases}. \tag{11}$$

We can obtain $\sigma_1 = 1/3, \sigma_2 = 2/3$ by solving (11). Now we declare the profile $(\mu_1, \mu_2; \sigma_1, \sigma_2) = (3/4, 1/4; 1/3, 2/3)$ is a mixed-strategy NE for the case shown in table III since neither player has a profitable deviation from the NE profile.

Algorithm 1 The BRNE Algorithm for finding the Nash Equilibrium

1: **Initialization**: Define the I/O of algorithm. Inputs: (1) The distortion reduction q_i and length l_i of each frame. (2) The reference relationship among frames. (3) Physical channel parameters BER, preset system parameters such as α, β, γ and the QoE adjustment parameters $a_1 \sim a_4$. (4) The maximum values of consumed data $L^{\max}$ and base price rate $y_0^{\max}$.
Outputs: (1) The NE state(s) $\{(L^i, y_o^j)\}$ or the probability vectors $\vec{\mu} = (\mu_1, \mu_2...)$ and $\vec{\sigma} = (\sigma_1, \sigma_2...)$ if there is no pure strategy solutions.
2: **Searching for the NE solutions (pure or mixed-strategy):**
Let $L = linespace[0, L^{\max}, K]$
Let $y = linespace[0, y_0^{\max}, K]$
While $i = 1 : K$ do
  Set $l = L^i$
  For $j = 1 : K$
    Set $y = y^j$
    Calculate the utility set of user and CP-WC $(U_{CP-WC}^{i,j}, U_{usr}^{i,j})$
  End for
  Find the price base y^j which corresponding to the maximum $U_{CP-WC}^{*,i}$, mark it as the best price response for user's L^i strategy
End while
Generate the Utility sets table and pick out the best $U_{CP-WC})$
For $j = 1 : K$
  Find the consumed data length L^i corresponding to the maximum $U_{usr}^{j,*}$, mark it as the best data consumption response for CP-WC's y^j price strategy
End for
Pick out the best U_{usr} for each price strategy)
$RESULT$ = Strategies $\{(L^i, y_o^j)\}$ and their corresponding utility set(s) $(U_{CP-WC}^{i,j}, U_{usr}^{i,j})$ which contain both best price response and best data consumption response.
If $RESULT$ is empty
  Initialize the probability vectors $\vec{\mu} = \vec{0}, \vec{\sigma} = \vec{0}$.
  List the linear system of K equations based on the utility matrix.
  Obtain the $\vec{\mu}, \vec{\sigma}$ by solving the two linear equations respectively.
  $RESULT = \quad \vec{\mu}, \vec{\sigma}$
End if
Return $RESULT$.

We show a generic case in table IV. We assume players CP-WC and user have the same amount of data/price options, i.e., $\{(L^i, y_0^j)|i, j \in [1, K]\}$. This ensures the utility value set $U_{1 \leq i,j \leq K}^{i,j}$ is a square matrix (with size K by K). Referring

TABLE IV

THE GENERAL CASE OF THE DATA CONSUMPTION OPTIONS, BASE PRICE RATES AND THE UTILITY VALUE SETS $U^{i,j} = (U^{i,j}_{CP-WC}, U^{i,j}_{usr})$.

y_0 and L	L^1	L^2	…	L^i	…
y_0^1	$U^{1,1}$	$U^{1,2}$	…	$U^{1,i}$	…
y_0^2	$U^{2,1}$	$U^{2,2}$	…	$U^{2,i}$	…
…	…	…	…	…	…
y_0^j	$U^{j,1}$	$U^{j,2}$		$U^{j,i}$	…
…	…	…	…	…	…

to the validation of case shown in table III and Definition 2, we can obtain the probability vectors $\vec{\mu}/\vec{\sigma}$ (each vector has K unknown variables) for user and CP-WC by solving K linear equations, with *K-1* equations come from the conditions 1 or 2 in Definition 2, and the last equation comes from $\mu_i \geq 0, \sigma_j \geq 0, \sum \mu_i = \sum \sigma_j = 1$.

C. Algorithm and Discussion.

From the above analysis and proofs, we explain our BRNE algorithm (shown in Algorithm 1) in details in this section. The algorithm considers situations of pure strategy and mixed-strategy in sequence. Based on the utility set table, we can determine the existence of pure strategy solutions. The strategy set(s) will be stored in *RESULT* (if there are pure strategies) and returned at the end of the algorithm. Otherwise, the mixed-strategy approach will be triggered (if the *RESULT* is empty). The mixed-strategy solutions (probability vectors $\vec{\mu}, \vec{\sigma}$ for two players) will be stored in *RESULT* and returned by the algorithm at last. The computational complexity of the proposed BRNE algorithm is close to $O(K^2)$, since the NE(s) selection process or linearly system solving process both can be completed in $O(K)$. So the complexity of the BRNE algorithm is mainly determined by the granularity of price rate and data consumption length of two players.

IV. SIMULATION STUDY

In this section, we perform simulations to evaluate the system performance based on the proposed best response solution. For multimedia data, we use the MPEG-4 H.264 codec to compress a "*Foreman*" standard video sequence. Since the values of payment, data quality and PER have big difference in their units, choosing appropriate pre-set system parameters (i.e., α, β and γ) would help us on investigating the inner properties of the proposed method. Thus we first explore the effects of different system parameters on the utility performance of CP-WC. We use the fixed base price rate and consumed data length in the simulation. The parameters sets used in evaluation are listed as follows: Set 1:$\{\alpha = 0.3, \beta = 0.001, \gamma = 0.1\}$; Set 2:$\{\alpha = 0.4, \beta = 0.002, \gamma = 0.2\}$; Set 3: $\{\alpha = 0.5, \beta = 0.001, \gamma = 0.1\}$.

As illustrated in Fig.2 (left) with the CP-WC utility versus PER, the choice of system parameters won't change the trend of utility performance but it affects utility's value range. The rationale behind the increasing CP-WC utility is that the payment from user and WC's transmitting costs both would decrease with increasing PER (according to the utility function 5), but the latter decreases faster.

We choose "Set 2" system parameters in the following simulations as it has the largest value range. Then we evaluate the utilities performance of user and CP-WC in different BER scenarios. As depicted in the Fig.2 (right), the utility of user dramatically decreases along with the increasing of BER while the utility of CP-WC keeps gradually increasing. This result demonstrates that under the fixed price rate and consumed data, the CP-WC gets unilateral benefits from the data service with lower resource leading to higher BER.

The QoE versus BER simulation result is shown in Fig.3, where we can see that the QoE of user and service quality provided by WC have the same trend with increasing BER. From Fig. 2 and 3 we reach the conclusion that fixed price/data service model only benefits the CP-WC. User has to pay extra money to get high data service with increasing BER.

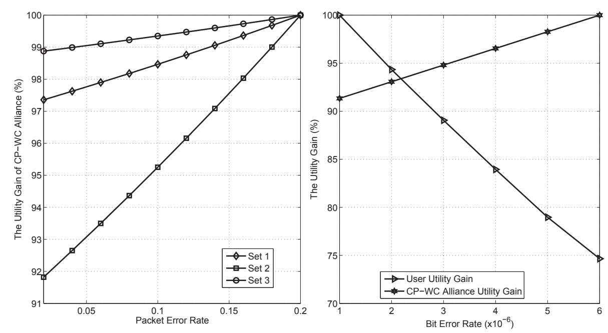

Fig. 2. The effects of different system parameters and PER/BER on the CP-WC and user's utilities.

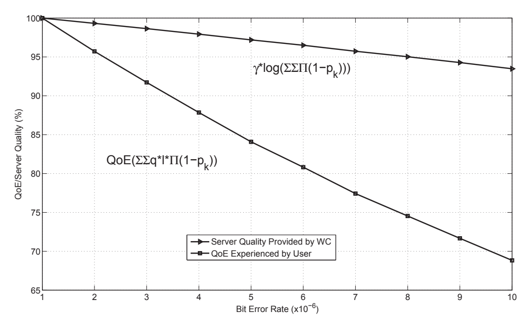

Fig. 3. Service quality provided by wireless carrier and the QoE gain of user, along with the increasing bit error rate.

In Fig.4, we evaluate the utility performance of user and CP-WC in different base price rates. Various bandwidths are considered, so that we can obtain the user's utility in terms of consumed data. The utility of CP-WC has stable trends, and high price rate outperforms all other options. For user, there exists an optimal length-price set that maximize its utility. The optimal length-price point(s) are generated from our best response method and the no players deviate from them.

The overall system performance based on the proposed BRNE algorithm is showed in Fig. 5. The accumulated PSNR

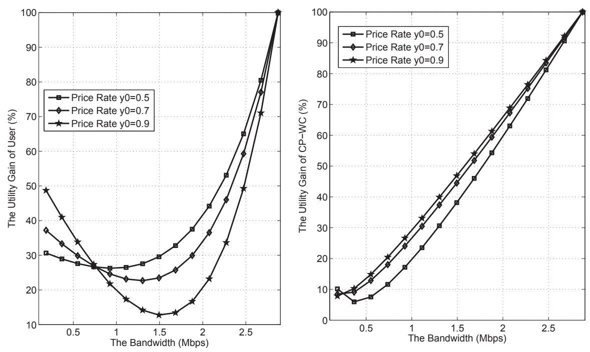

Fig. 4. Illustration of the utility gain trends of user (left) and CP-WC alliance (right) along with the increasing of bandwidth.

acts as the QoE metrics. It is worth noting that in this simulation, the NE solution generated from BRNE algorithm is always pure strategy and the mixed-strategy logic hasn't been triggered. As illustrated in the figure, both user and CP-WC obtain significantly improvements on utility gain when taking the NE solution. The reason behind this is that the price rate and consumed data length are both the best responses for each player according to other's option.

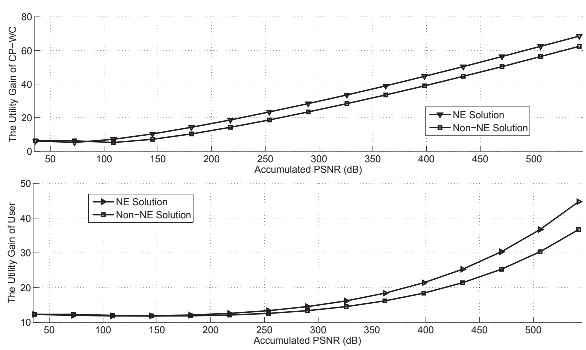

Fig. 5. Illustration of utility gain of CP-WC (up) and user (bottom) under different consumed data lengths and base price rates.

V. Conclusion

In this paper, a generalized best response SMP game theoretical model is developed to address the QoE - profit maximization issue for wireless multimedia communications. The model relaxed traditional assumption that utility functions are concave. Based on the SMP concept to price QoE not the data, we analyze the non-cooperative situation between the two players and develop the BRNE algorithm to acquire the equilibrium solution for both user and CP-WC. Furthermore, both pure strategy and mixed-strategy schemes are analyzed in our analysis, where the corresponding NE solutions from both strategies are addressed. Simulation studies demonstrate the proposed BRNE algorithm works effectively to catch NE solutions by taking players' utility gain in consideration.

VI. Acknowledgement

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References

[1] S. Sen, C. Joe-Wong, S. Ha, M. Chiang, "Smart data pricing (SDP): Economic solutions to network congestion." *Recent Advances in Networking*, vol. 1, pp. 221-274, 2013.

[2] S. Sen, C. Joe-Wong, S. Ha, M. Chiang, "A survey of smart data pricing: Past proposals, current plans, and future trends," *ACM Computing Surveys,* vol. 46, no. 2, 2013.

[3] M. Andrews, U. Ozen, M. Reiman, Q. Wang, "Economic models of sponsored content in wireless networks with uncertain demand," in *Proc. IEEE INFOCOM,* pp. 3213–3218, Apr. 2013.

[4] Q. Wang, W. Wang, S. Jin, H. Zhu, N. Zhang, "Smart Media Pricing (SMP): Non-uniform packet pricing game for wireless multimedia communications." In *Proc. IEEE INFOCOM WKSHPS,* pp. 27-32, Apr. 2016.

[5] P. Hande, M. Chiang, R. Calderbank, J. Zhang, "Pricing under constraints in access networks: Revenue maximization and congestion management." in *Proc. IEEE INFOCOM,* Mar. 2010.

[6] S. Ha, S. Sen, C. Joe-Wong, Y. Im, M. Chiang, "Tube: time dependent pricing for mobile data," *ACM SIGCOMM Computer Communication Review,* vol. 42, no. 4, pp.247-258, 2012.

[7] S. He, W. Wang, "Context-Aware QoE-Price Equilibrium for Wireless Multimedia Relay Communications Using Stackelberg Game," *in Proc. IEEE INFOCOM WKSHPS,* May 2017.

[8] Y. Li, Z. Zhang, W. Wang, H. Wang, "Concurrent Transmission Based Stackelberg Game for D2D Communications in mmWave Networks," in *Proc. IEEE ICC,* May 2017.

[9] X. Zhang, H. Ji, Y. Li, X. Li, "Energy efficient transmission in relay-based cooperative networks using auction game." in *Proc. IEEE WCNC,* Apr. 2013.

[10] Q. Wang, W. Wang, S. Jin, H. Zhu, N. Zhang, "Quality-Optimized Joint Source Selection and Power Control for Wireless Multimedia D2D Communication Using Stackelberg Game," *IEEE Trans. Vehicular Technology*, vol. 64, no. 8, pp.3755-3769, Aug. 2015.

[11] W. Ji, P. Frossard, B. W. Chen, and Y. Chen, "Profit optimization for wireless video broadcasting systems based on polymatroidal analysis," *IEEE Trans. Multimedia*, vol. 17, no. 12, pp. 2310-2327, 2015.

[12] W. Wang, D. Peng, H. Wang, H. Sharif, "An Adaptive Approach for Image Encryption and Secure Transmission over Multirate Wireless Sensor Networks," *Wireless Communications and Mobile Computing,* vol. 9, pp. 383-393, 2009.

[13] S. He, and W. Wang, "User-centric QoE-driven power and rate allocation for multimedia rebroadcasting in 5G wireless systems." in *Proc. VTC WKSHPS,* May 2016.

[14] K. Yamagishi, T. Hayashi, "Parametric packet-layer model for monitoring video quality of IPTV services." in *Proc. IEEE ICC,* pp. 110-114, May 2008.

[15] W. Wang, Q. Wang, K. Sohraby, "Multimedia Sensing as a Service (MSaaS): Exploring Resource Saving Potentials of at Cloud-Edge IoTs and Fogs," *IEEE IoTs Journal*, vol. 4, no. 2, pp.487-495, Apr. 2017.

[16] M. Felegyhazi, J. P. Hubaux, "Game theory in wireless networks: A tutorial," EPFL Tech Report No. LCA-REPORT-2006-002. 2006.

[17] D. Fudenberg, D. K. Levine, "A long-run collaboration on long-run games," World Scientific, 2009.

[18] W. Wang, D. Peng, H. Wang, H. Sharif, H. H. Chen, "Energy-Constrained Quality Optimization for Secure Image Transmission in Wireless Sensor Networks," *Advances in Multimedia*, 2007.

[19] Q. Wang, W. Wang, K. Sohraby, "Multimedia Relay Resource Allocation for Energy Efficient Wireless Networks: High Layer Content Prioritization with Low Layer Diversity Cooperation," *IEEE Trans. Vehicular Technology,* vol. 66, no. 11, pp. 10394-10405, Nov. 2017.

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

[21] P. Mahasukhon, H. Sharif, M. Hempel, T. Zhou, W. Wang, H.H. Chen, "IEEE 802.11 b based ad hoc networking and its performance in mobile channels," *IET Communications,* vol. 3, no. 5, pp.689-699, 2009.