

PRICING GAME AND EVOLUTION DYNAMICS FOR MOBILE VIDEO STREAMING

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ABSTRACT

The recent developments of smart mobile phones and 3G networks enable users to enjoy video programs by subscribing to data plans. Due to phone-to-phone communication technologies and ubiquity of mobile phones, data-plan subscribers are able to redistribute the video content to non-subscribers. Such a redistribution mechanism is a potential competitor for the mobile service provider and is very difficult to trace given users' high mobility. The service provider has to set a reasonable price for the data plan to prevent such unauthorized re-distribution behavior to protect or maximize his/her own profit. In this paper, we investigate the evolutionarily stable ratio of mobile users who decide to subscribe to the data plan. Such an analysis can help the service provider preserve his/her profit under the threat of the redistribution networks and can improve the quality of service for end users.

1. INTRODUCTION

The explosive advance of multimedia processing technologies are creating dramatic shifts in ways that video content is delivered to and consumed by end users. Also, the increased popularity of wireless networks and mobile devices is drawing lots of attentions on ubiquitous multimedia access in the multimedia community in the past decade. Network service providers and researchers are focusing on developing efficient solutions to ubiquitous access of multimedia data, especially videos, from everywhere using mobile devices (laptops, PDAs or smart phones that can access 3G networks) [1]. Mobile-phone users can watch video programs on their devices by subscribing to the data plans from network service providers, and they can easily use their programmable hand devices to retrieve and reproduce the video content [2]. Therefore, it is important to understand end users' possible actions of in order to provide better ubiquitous video access services.

With such a high popularity and the convenient phone-to-phone communication technologies, it is very possible for data-plan subscribers to redistribute the video content without authorization. For example, some users who do not subscribe to the data plan may wish to watch TV programs while waiting for public transportation, and some of them might want to check news from time to time. Hence, these users have incentives to buy the desired video content from neighboring data subscribers if the cost is lower than the subscription fee charged by the service provider. Unlike generic data, multimedia data can be easily retrieved and modified, which facilitates the redistribution of video content.

Nevertheless, the mobile network service provider would like to set the content price to maximize his/her own profit. The service provider's profit can be represented as the total number of subscriptions times content price. If the content price is high, mobile users have less incentive to subscribe to the data plan which might result

in less subscriptions. But on the other hand, the content price in the redistribution network may get higher due to less subscribers and more secondary buyers. In such a case, although a subscriber pays more for the video stream, he/she also gets more compensation by redistributing the data. Hence, setting content price higher does not necessarily reduce the number of subscriptions and it is not trivial to find the optimal price that maximizes the service provider's utility.

The service provider, data-plan subscribers and the secondary buyers who are interested in the video data interact with each other and influence each other's decisions and performance. In such a scenario, game theory is a mathematical tool to model and analyzes the strategic interactions among rational decision makers [3]. In our previous work [4], the equilibrium price of the video stream in the redistribution network was derived. Given the price of the redistributed video streams, the service provider would select the official price to maximize its net profit. Since the mobile users can change their decisions on subscribing or resubscribing, the content owner is interested in the number of subscribers that is stable over the time. Hence, we formulate the video streaming marketing phenomenon as an evolutionary game and derive the evolutionarily stable strategy (ESS) [5] for the mobile users, which is the desired stable equilibrium for the service provider.

The rest of the paper is organized as follows. We formulate the problem in Section 2. In Section 3, the content owner is also considered as a player who sets the price to maximize his/her payoff, but not prevent the video-redistribution among users. Conclusions are drawn in Section 4.

2. PROBLEM FORMULATION

The system diagram is shown in Figure 1. The service provider is responsible of providing video streams with promising quality to the subscribers. The service provider set the content price to be p_o and the mobile users can choose to subscribe to the data plan or not. Suppose there are total N_a mobile users and N_s of them decide to be subscribers and $N_b = N_a - N_s$ of them decide not to subscribe to the data plan. In Figure 1, $N_a = 5$, $N_s = 3$, and $N_b = 2$.

The N_s subscribers would try to set their own price for the video content and sell to the N_b secondary buyers. Each of the N_b secondary buyers will tend to purchase the video content from the subscriber who offers the best price or best transmission quality. In our previous work [4], we have discussed the equilibriums and the optimal pricing in this video redistribution network. Now here comes the service provider's problem: how to set the content price p_o that his/her profit would be optimized.

3. OPTIMAL PRICING FOR THE CONTENT OWNER

Here, we model the video pricing problem for the content owner as a non-cooperative game, which can be played several times. For example, if the total income is not as expected, the service provider can always change the price in practical scenarios. Also, mobile

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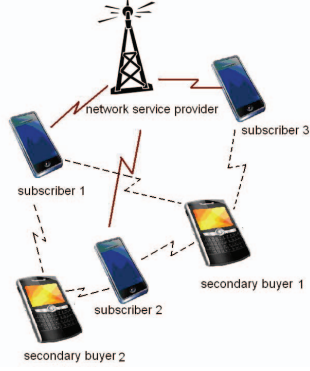


Fig. 1. An example of a mobile video streaming network.

users can try to change their mind on whether to subscribe to the data plan or purchase from other subscribers to see which one is a better choice. Such natural repetitions help all players find the equilibrium.

3.1. Pricing Game Model and Evolution Dynamics

The basic elements of the game are listed as follows.

Game Stages: In the video pricing game, the first mover is the service provider who sets p_o as the price of the video content. Then N_a mobile users who are interested in the video content decide to subscribe to the video streaming service or not. These mobile users also take into consideration the possible payoffs that they can get by reselling the video or purchasing the video from subscribers in the redistribution network when making decisions.

Utility function of the service provider: The content owner's utility equals to price times the number of subscribers,

$$\pi_c = p_o \times N_s, \quad (1)$$

where N_s is the number of subscribers. With a higher price, fewer mobile users would subscribe, especially when it is possible for them to purchase the video content from other subscribers. Therefore, the service provider cannot arbitrarily increase the content price p_o and has to consider mobile users' utilities.

Utility function of the mobile users: Each mobile user has two choices: pay p_o to become a subscriber or pay nothing but purchase the video from other subscribers. Let $\pi_s(N_s, N_b)$ and $\pi_B(N_s, N_b)$ be the utilities that a subscriber and a secondary buyer can get from the redistribution network, respectively.

If user i decides to subscribe to the data plan, then his/her utility contains two parts. The first part is from the subscription to the streaming service, where he/she enjoys the video content with higher quality and shorter delay at a cost of the subscription fee. The second part is from redistributing to the video to secondary buyers. Hence, if user i chooses to become a subscriber, his/her utility is

$$\pi_i(s, N_s, N_b) = \pi_s(N_s, N_b) + g_{Qi} * PSNR_{max} - g_{Di} D_q \left(\frac{K+1}{M} \right) - p_o, \quad (2)$$

where g_{Qi} is user i 's gain per dB improvement in PSNR of the reconstructed video, K is the number of mobile users who are using video streaming service in the network, M is the maximal number of users the network can accommodate, and g_{Di} is user i 's cost per second delay in receiving the bit stream. D_q represents the network delay, which is a function of network occupancy. The first input parameter ' s ' in $\pi_i(s, N_s, N_b)$ denotes the action "subscribe". Note that $\pi_s(N_s, N_b) = 0$ if N_s or N_b equals to 0.

If user i chooses not to subscribe to the data plan, his/her utility only comes from the redistribution network by purchasing the video content from subscribers. Hence,

$$\pi_i(n, N_s, N_b) = \pi_B(N_s, N_b) + g_{Qi} * PSNR_{max} - g_{Di} D_q \left(\frac{K+1}{M} \right) - p_o, \quad (3)$$

where the first input ' n ' in $\pi_i(n, N_s, N_b)$ denotes the action "do not subscribe". Note that $\pi_i(n, N_s, N_b) = 0$ if N_s or N_b equals to 0.

To analyze this game, we first investigate the equilibrium strategy of the mobile users given the content price p_o . As mentioned before, the above pricing game can be played repeatedly and mobile users may use their previous experience to adjust their strategies accordingly. Therefore, a stable strategy for all mobile users that is robust to mutants of users' strategies is preferred in the pricing game. We will use evolutionary game theory to analyze the evolution of the mobile users' behavior and derive the evolutionarily stable equilibrium (ESS). ESS provides guidance for a rational player to approach the best strategy against a small number of players who deviate from the best strategy, and thus achieve stability. The evolutionarily stable equilibrium can be defined as

Definition 1 An evolutionarily stable strategy is the action a^* in the strategy space A such that

- equilibrium condition: $\pi_i(a, a^*) \leq \pi_i(a^*, a^*)$, and
- stability condition: if $\pi_i(a, a^*) = \pi_i(a^*, a^*)$, $\pi_i(a, a) < \pi_i(a^*, a)$ for every best response $a \neq a^* \in A$.

Since each mobile user is not certain of other users' decisions, he/she may try different strategies in every play and learn from the interactions. During such a learning process, the percentage, i.e., the population share, of players using a certain pure strategy ("subscribe" or "do not subscribe") may change. The stable percentage of mobile users that chooses to subscribe to the data plan is what we are interested in.

The population evolution can be characterized by replicator dynamics as follows: at time t , let $N_s(t)$ denotes the number of mobile users that subscribe to the data plan, then the subscribers' population state $x_s(t) = N_s(t)/N_a$, and $x_b(t) = N_b(t)/N_a = 1 - x_s(t)$ is the secondary buyers' population state. By replicator dynamics, the evolution dynamics of $x_s(t)$ at time t is given by the differential equation

$$\dot{x}_s = \eta[\bar{\pi}_s(x_s) - \bar{\pi}(x_s)]x_s, \quad (4)$$

where \dot{x}_s is the first-order derivative of $x_s(t)$ with respect to time t , $\bar{\pi}_s(x_s)$ is the average payoff of mobile users who subscribe to the data plan, and $\bar{\pi}(x_s)$ is the average payoff of all mobile users. η is a positive scale factor. x_s can be viewed as the probability that one mobile user adopts pure strategy "subscribe", and the population state vector $\mathbf{x} = \{x_s(t), x_b(t)\}$ is equivalent to a mixed strategy for that player. If subscribing to the data plan results in a higher payoff than the mixed strategy, then the probability of subscribing to the data plan should be higher and x_s will increase. The rate of the increment is proportional to the difference between the payoff of adopting the pure strategy "subscribe" and the payoff achieved by using the mixed strategy.

3.2. Analysis of Pricing Game with Homogeneous Mobile Users

A strategy is an ESS if and only if it is asymptotically stable to the replicator dynamics. In the pricing game, when time goes to infinity, if (4) equals to zero, then \mathbf{x} is the ESS. In this subsection, we first focus on the scenario where all mobile users value the video equality

in the same way where $g_{Qi} = g_{Qj} = g_Q$ and $g_{Di} = g_{Dj} = g_D$ for all $i, j \in N_a$.

Let $Q = g_Q * PSNR_{max} - g_D D_q \left(\frac{K+1}{M}\right) - p_o$, then in the homogeneous case, the utilities of the subscribers and the secondary buyers are

$$\pi(s, N_s, N_b) = \pi_s(N_s, N_b) + Q, \text{ and } \pi(n, N_s, N_b) = \pi_B(N_s, N_b) + Q, \quad (5)$$

respectively. Note that mobile users are homogeneous and they will have the same evolution dynamics and equilibrium strategy. Given that x_s is the probability that a mobile user decides to subscribe to the data plan, the averaged utilities of the subscribers and the secondary users are

$$\begin{aligned} \bar{\pi}_s(x_s) &= \sum_{i=0}^{N_a} \binom{N_a}{i} x_s^i (1-x_s)^{N_a-i} \pi(s, i, N_a-i), \\ \text{and } \bar{\pi}_b(x_s) &= \sum_{i=0}^{N_a} \binom{N_a}{i} x_s^i (1-x_s)^{N_a-i} \pi(n, i, N_a-i), \end{aligned} \quad (6)$$

respectively. The average utility of all mobile users is $\bar{\pi}(x_s) = x_s \cdot \bar{\pi}_s(x_s) + x_b \cdot \bar{\pi}_b(x_s)$. Then (4) can be rewritten as

$$\dot{x}_s = \eta[\bar{\pi}_s(x_s) - \bar{\pi}_b(x_s)]x_b x_s. \quad (7)$$

In ESS x_s^* , no player will deviate from the optimal strategy, indicating $\dot{x}_s = 0$ in (7). We can then obtain the equilibriums, which are $x_s = 0$, $x_s = 1$ or $x_s = \bar{\pi}_s(x_s) - \bar{\pi}_b(x_s)$. To verify that they are indeed ESS, we will show that these three equilibriums are asymptotically stable, that is, the replicator dynamics (4) converges to these equilibrium points.

The first step is to guarantee that $x_s(t) + x_n(t) = 1$ for all t . We can verify it by summing up(4) with the reciprocal dynamic function of x_n , resulting in

$$\dot{x}_b + \dot{x}_s = \eta[x_s \bar{\pi}_s(x_s) + x_b \bar{\pi}_b(x_b) - (x_s + x_b) \bar{\pi}(x_s)] = 0. \quad (8)$$

Recall that $\bar{\pi}(x_s) = x_s \times \bar{\pi}_s(x_s) + (x_n) \times \bar{\pi}_b(x_s)$, and $x_s(0) + x_n(0) = 1$, the above equation is equivalent to $\dot{x}_n + \dot{x}_s = 0$. As a result, $x_s(t) + x_n(t) = x_s(0) + x_n(0) = 1$ for all t in the evolution process.

Next we need to show that all non-equilibria strategies of the pricing game will be eliminated during the evolution process. If the replicator dynamics is a myopic adjustment dynamic, then all non-equilibria strategies will be eliminated during the process. A dynamic is myopic adjustment if and only if $\sum_{a \in A} x_a \bar{\pi}(x_a, x_{-a}) \geq 0$, where A is the strategy space, x_a is the population of user adopting pure strategy a , and $\bar{\pi}(x_a, x_{-a})$ is the average payoff of users adopting pure strategy a . For our optimal pricing game, the strategy space is $A = \{s, b\}$, where ‘s’ means ‘subscribe’ and ‘b’ means ‘do not subscribe and be a secondary buyer’. Combining (4) with the definition of averaged utility, we have

$$\begin{aligned} \sum_{a \in \{s, b\}} \dot{x}_a \bar{\pi}_a(x_a) &= \sum_{a \in \{s, b\}} \eta[\bar{\pi}_a(x_a) - \bar{\pi}(x_s)]x_a \bar{\pi}_a(x_a) \\ &= \sum_{a \in \{s, b\}} \eta \left(\bar{\pi}_a(x_a) - \sum_{a' \in \{s, b\}} x_{a'} \bar{\pi}_{a'}(x_{a'}) \right) x_a \bar{\pi}_a(x_a) \\ &= \eta \left\{ \sum_{a \in \{s, b\}} x_a \bar{\pi}_a^2(x_a) - \left[\sum_{a \in \{s, b\}} x_a \bar{\pi}_a(x_a) \right]^2 \right\} \geq 0. \end{aligned} \quad (9)$$

Therefore, the reciprocal dynamics of the pricing game in (4) is myopic adjustment and will eliminate all non-equilibria strategies.

	Subscribe	Do not subscribe
Subscribe	(Q_1, Q_2)	$(Q_1 + \pi_{1s}, \pi_{2b})$
Do not subscribe	$(\pi_{1b}, Q_2 + \pi_{2s})$	$(0, 0)$

Table 1. Matrix form of the pricing game with 2 heterogeneous mobile users.

From (7), \dot{x}_s has the same sign as $\bar{\pi}_s(x_s) - \bar{\pi}_b(x_s)$. $\bar{\pi}_s(x_s)$ is a decreasing function of x_s while $\bar{\pi}_b(x_s)$ is an increasing function of x_s since with more subscribers, the redistributed content price will decrease due to higher computation. Therefore, when x_s goes from 0 to 1, the sign of \dot{x}_s either does not change or changes only once.

- When $\bar{\pi}_s(x_s) > \bar{\pi}_b(x_s)$ for all $x_s \in [0, 1]$, in the evolution process, $\dot{x}_s = dx_s(t)/dt > 0$ for all t , and (4) converges to $x_s = 1$, which is an ESS.
- If $\bar{\pi}_s(x_s) < \bar{\pi}_b(x_s)$ for all $x_s \in [0, 1]$, in the evolution process, $\dot{x}_s = dx_s(t)/dt < 0$ for all t , and (4) converges to $x_s = 0$, which is the ESS in this scenario.
- When $\bar{\pi}_s(x_s) - \bar{\pi}_b(x_s) = 0$ has one and only one root x_s^* , and (4) converges to the ESS x_s^* .

Therefore, for each price p_o set by the content owner, we can find the stable number of subscribers $N_s = N_a \cdot x_s^*$, from which we can calculate the service provider’s utility. Hence, given the ESS of the mobile users, by backward induction, the service provider can easily choose the optimal content price to maximize his/her own payoff.

3.3. Analysis of Pricing Game with Heterogeneous Mobile Users

In the heterogeneous scenario where different mobile users value video quality differently, it is very difficult to represent the average payoff of the subscribers and that of the secondary buyers in a compact form. Hence, we start with the simple two-person game and find its ESS. We then extend the ESS into the scenario with multiple heterogeneous mobile users.

We first start with the two-player game. Assume that there are two mobile users with different $\{g_{Qi}, g_{Di}, c_i\}$. If both of them decide not to subscribe to the data plan, then they pay nothing and gain nothing from the service provider. Also, since there are no subscribers, the redistribution network does not exist, and both players’ utilities are 0. If both decide to subscribe to the data plan, then the redistribution network also does not exist since there is no secondary buyers. In this scenario, the utilities of player i is $Q_i = g_{Qi} * PSNR_{max} - g_{Di} D_q \left(\frac{K+1}{M}\right) - p_o$. If player 1 becomes a subscriber but player 2 decides not to subscribe, then player 1’s utility is $Q_1 + \pi_{1s}$, and player 2’s utility is π_{2b} . Here, π_{1s} and π_{2b} are the utilities that user 1 and 2 get from the redistribution network as a seller and a buyer, respectively. We can obtain the matrix form of the game shown in Table 1. In Table 1, each row represents user 1’s decision, and each column represents user 2’s decision. For each entry in the table, the first term is user 1’s payoff, and the second term is user 2’s payoff.

Let x_1 and x_2 be player 1 and 2’s probability of adopting the pure strategy ‘subscribe’, respectively. Then the expected payoff $\bar{\pi}_1(x)$ of user 1 when he plays the mixed strategy x_1 is

$$\bar{\pi}_1(\mathbf{x}) = Q_1 x_1 x_2 + [Q_1 + \pi_{1s}] x_1 (1-x_2) + \pi_{1b} (1-x_1) x_2. \quad (10)$$

Then, we can write the reciprocal dynamics of x_1 and similarly for x_2 as

$$\dot{x}_1 = x_1(1-x_1)[(Q_1 + \pi_{1s}) - (\pi_{1s} + \pi_{1b})x_2],$$

$$\dot{x}_2 = x_2(1 - x_2)[(Q_2 + \pi_{2s}) - (\pi_{2s} + \pi_{2b})x_1]. \quad (11)$$

An equilibrium point must satisfy $\dot{x}_1 = 0$ and $\dot{x}_2 = 0$, then from (11), we get five equilibria (0,0), (0,1), (1,0), (1,1), and $((Q_2 + \pi_{2s})/(\pi_{2s} + \pi_{2b}), (Q_1 + \pi_{1s})/(\pi_{1s} + \pi_{1b}))$.

If we view (11) as a nonlinear dynamic system, then the above five equilibria are ESSs if they are locally asymptotically stable. The asymptotical stability requires that the determination of the Jacobian matrix J be positive and the trace of J be negative. The Jacobian matrix J can be derived by taking the first-order partial derivatives of (11) with respect to x_1 and x_2 , and

$$J = \begin{bmatrix} (1 - 2x_1)D_1 & -x_1(1 - x_1)(\pi_{1s} + \pi_{1b}) \\ -x_2(1 - x_2)(\pi_{2s} + \pi_{2b}) & (1 - 2x_2)D_2 \end{bmatrix}, \quad (12)$$

where $D_1 = (Q_1 + \pi_{1s}) - (\pi_{1s} + \pi_{1b})x_2$ and $D_2 = (Q_2 + \pi_{2s}) - (\pi_{2s} + \pi_{2b})x_1$. By jointly solving $\det(J) > 0$ and $\text{trace}(J) < 0$, we can have the following optimal subscription strategies for mobile users under different scenarios:

- When $Q_1 + \pi_{1s} < 0$ and $Q_2 + \pi_{2s} < 0$, there is one ESS (0,0), and both users tend to not subscribe to the data plan.
- When $Q_1 - \pi_{1b} < -(Q_2 + \pi_{2s})$ and $(Q_2 + \pi_{2s})(Q_1 - \pi_{1b}) < 0$, there is one ESS (0,1), and the strategy profile user 1 and user 2 adopt converges to (not subscribe, subscribe).
- When $Q_1 - \pi_{1b} < -(Q_1 + \pi_{1s})$ and $(Q_1 + \pi_{1s})(Q_2 - \pi_{2b}) < 0$, there is one ESS (1,0), and user 1 tends to subscribe while user 2 tend to not subscribe to the data plan.
- When $Q_1 - \pi_{1b} > 0$ and $Q_2 - \pi_{2b} > 0$, there is one ESS (1,1), and both users tend to subscribe to the data plan.

We can see that when Q_1 is higher with larger g_{Q1} and g_{D1} , user 1 tends to subscribe to the data plan.

Based on the above discussion on the ESSs of the two-player game, we can infer that the users who value the video quality more (with higher g_{Q_i} and g_{D_i}) would intend to subscribe to the data plan. Users with smaller g_{Q_i} and g_{D_i} would tend to choose “do not subscribe” and become secondary buyers. However, if the content price p_o is too high so that the subscription gives all users negative payoff, no player would subscribe to the service.

3.4. Simulation Results

Here, we will verify the derived ESS and show by simulation results the optimal price for the content owner if he/she wants to maximize his/her utility. We first test on the homogeneous scenario that there are 6 mobile users who are initially uniformly located in a 100 meter by 100 meter square centered around the origin. The pricing game is played 100 times, and each secondary buyer changes its location after the game restarts. The distance between each secondary buyer’s locations in two consecutive games is normally distributed with zero mean and unit variance. The direction of each secondary buyer’s location change follows the uniform distribution. We use the video sequence “Akiyo” in QCIF format as in the single secondary buyer scenario. The mobile users changes their strategies and evolve according to (4).

In Figure 2, we show the utility of the service provider with heterogeneous mobile users with different evaluations of video quality and $M - K$ an evaluation of the quality of the mobile network reflecting how crowded the mobile network is. In Figure 2(a), all 6 mobile users’ gain weighting factor for video quality $g_Q=0.1$, but 2 of them have delay gain factor $g_D=0.1$, 2 of them with delay factor $g_D=0.15$, and the rest 2 of them are with delay factor $g_D=0.2$.

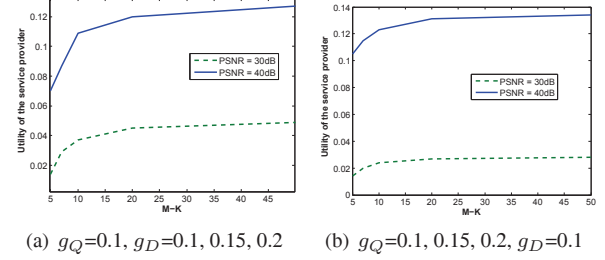


Fig. 2. Utilities of the service provider versus network quality with heterogeneous mobile users

From Figure 2(a), we can clearly see that providing higher-quality network service (larger $M - K$) gives the content owner lot more gain than when the network quality is poor. Also, the difference between low video quality (PSNR = 30dB) and high video quality (PSNR = 40dB) is less in Figure 2(a). In Figure 2(b), all 6 mobile users’ gain weighting factor for streaming delay $g_D=0.1$, but 2 of them have quality gain factor $g_Q=0.15$, and the rest 2 of them are with delay factor $g_Q=0.2$ per millisecond. Compare Figure 2(b) with Figure 2(a), it is obvious when some of the mobile users cares more about video quality, providing competitive video quality gives lot more gain to the service provider.

Also, it is clear from 2 that if the content owner provides better-quality network or video, its payoff can be increased. Also, for lower-quality videos, the content owner’s utility saturates earlier than high-quality videos with respect to network quality. Which means that if the content owner decides to offer low quality videos, to maximize its utility, it tends to offer low-quality network also.

4. CONCLUSION

In this paper, we investigate the service provider’s optimal pricing for mobile video data by analyzing the behavior between the content owner and the mobile service users. We model the dynamics between the content owner and users who are interested in the video content as a non-cooperative game, in which the mobile phone users decide whether to subscribe to the data plan after the service provider sets the price. We use the evolutionary game theory to analyze the evolution of the mobile users’ behavior and derive the evolutionarily stable equilibrium, which leads to the optimal price for the content owner to maximize his/her total income.

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