Stackelberg Game for Bandwidth Allocation in Cloud-based Wireless Live-streaming Social Networks

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***Abstract*—Multimedia social networks have been introduced as a new technology to enrich people's lives through enhanced multimedia distribution. On the other hand, a media cloud system can perform multimedia processing and storage, and provide heterogeneous multimedia services. However, the challenges still remain for end users (e.g., mobile devices and PCs) to receive multimedia streaming from the cloud system with satisfied quality-of-service (QoS). To address these challenges, an efficient multimedia distribution approach taking advantage of live-streaming social networks is innovated in this paper to deliver the media services from the cloud to both desktop and wireless end users. Our approach allows bandwidth limited mobile users to acquire live multimedia streaming from desktop users, directly based on their social relationships rather than from the cloud. When a number of mobile users compete for limited bandwidth access with the desktop users, a bandwidth allocation problem must be solved to meet all users' QoS requirements in the live-streaming social network. We formulate the problem as a two-stage Stackelberg game, in which both desktop users and mobile users target at maximizing their utilities. In our study, a noncooperative game is used to model the competition among the desktop users in terms of shared bandwidth and price in the first stage of the game. The second stage of the game models the behavior of a mobile user selecting the desktop users by an evolutionary game. In addition, a case study is conducted following the general Stackelberg game formulation, where the existence of a unique Nash equilibrium is proved. Based on our game modeling, we design protocols for both desktop and mobile users and evaluate them with numerical examples.**

***Index Terms*—Bandwidth allocation, evolutionary game theory, multimedia social networks, Stackelberg game, wireless live-streaming social networks.**

I. INTRODUCTION

A live-streaming social network consists of a content provider that provides live content and multiple users who watch the live content simultaneously. A peer-to-peer structure (i.e., SopCast [1] and PPlive [2]) of live-streaming social networks is becoming particularly popular, since this structure can, to some extent, improve the video quality and reduce delay by allowing users to share their media resources with each other. Recently, the handheld devices experienced an explosive growth, and increasingly more people prefer to watch multimedia streaming via their mobile devices such as smartphone, PDA, or iPad. Due to the limited computation and storage capabilities of these mobile devices, multimedia applications have not been adequately supported. On the other hand, the media cloud system has evolved as a powerful computing platform for scalable and connected mobile multimedia. However, how to provide high quality-of-service (Qos) multimedia services to the end users (i.e., mobile devices) from the cloud is still challenging. Further, the gradually mature 3G cellular network can provide access for wireless mobile users to enjoy live programs, but it requires the content provider to pay extra bandwidth for delivering its multimedia services. Wireless mobile users also need to pay for multimedia streaming downloading. Thus, this is not recommendable from both content providers' and wireless users' standpoints. We present wireless live-streaming social networks (WLSNs) to deal with the problem. Specifically, the networks allow the desktop users who are watching the same live program to share their live-streaming with the social related wireless users around them through *ad hoc* wireless communications. The network architecture provides the following advantages: 1) the charged cost for the wireless services can be saved for both content providers and their wireless mobile users; 2) high speed *ad hoc* communications such as WiFi (faster than 3G) between the desktop users and the mobile users can be utilized to improve the performance of multimedia distribution; and

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3) the charge-free and high quality of multimedia services motivate more people to prefer wireless devices to desktop PCs for watching live programs. Thus it can alleviate the bandwidth requirement from the desktop users. As the number of mobile users tend to be higher than that of desktop users, we need an efficient bandwidth allocation mechanism to coordinate the transmission between the mobile users and their desktop friends.

In this paper, a virtual trading market is built to model and address the bandwidth allocation problem, where the commodity is the wireless connections (i.e., bandwidth) which are sold to the mobile users by the desktop users. Each mobile user is assumed to symbolically pay to the chosen desktop user for sharing the live-streaming files. Here, the payment can be credit, token, or other equivalents. In this market, all desktop users and mobile users are considered selfish. First, the desktop users offer the size of bandwidth that they are willing to share and the price that they will charge from the mobile users. Then, the mobile users decide on which desktop user they can connect to under the predecided size of bandwidth and price. This naturally formulates a two-stage Stackelberg game, where the leaders refer to the desktop users and the followers refer to the mobile users. For the mobile users, an evolutionary game model [3] is applied to study their behavior. The mobile users are grouped into a number of populations. In each population, the mobile users can observe each others' strategy. The solution to the evolutionary game is analyzed by using the replicator dynamics [3] which is represented by a set of differential equations. When all equations achieve zero, the game equilibrium is obtained. For the desktop users, a noncooperative game model is employed to study their interactions. Their strategies comprise the size of shared bandwidth and the price to charge the connected mobile users. The strategy adjustment is based on the evolution among the mobile users who aim at maximizing their utilities. After developing a general formulation of the Stackelberg game, we also conduct a case study for two desktop users, in which the equilibrium is investigated by a proof.

The objective of this paper is to propose a new WLSN and address the bandwidth allocation problem in such network. We make three major contributions through this paper.

1) A new WLSN based on the cloud concept is developed to enable the desktop users to share live-streaming files with their surrounding friends with wireless devices.
2) We observe the bandwidth allocation problem in WLSN and then formulate this problem as a two-stage Stackelberg game, which contains: a) the leader game, i.e., a noncooperative game among desktop users; and b) the follower game, i.e., an evolutionary game among mobile users.
3) We perform theoretical analysis for both a general scenario and a specific case study with respect to the evolutionary equilibrium and the Nash equilibrium. Implementation protocols are also given for desktop users and mobile users to achieve equilibrium states.

In addition, we present extensive numerical examples to demonstrate the convergence behavior of the formulated Stackelberg game. Numerical results also indicate the performance in the evolutionary equilibrium and the Nash equilibrium.

The rest of this paper is organized as follows. Related work is briefly reviewed in Section II. In Section III, we describe the system model and the bandwidth allocation problem. Section IV formulates the bandwidth allocation problem as a two-stage Stackelberg game, and a case study for two desktop users is given in Section V. Section VI presents an implementation protocol and the evaluation on the proposed framework is shown in Section VII. Finally, we conclude the paper in Section VIII.

II. RELATED WORK

A. *Live-Streaming Social Networks*

Live-streaming social networks are a kind of multimedia social network in which people can exchange multimedia information such as digital video, audio, and images through handheld devices. Multimedia social networks are becoming an emerging research area and also have been the subject of many recent studies. In the study [4], Lin *et al.* found that full cooperation between users in peer-to-peer (P2P) multimedia social networks cannot be guaranteed, and some users may even behave dishonestly or maliciously. Then, the authors modeled users' behavior as a repeated game and proposed some cheat-proof and attack-resistant strategies based on incentive to motivate user cooperation. They also addressed security and copyright problems in [5], [6], and [7]. In [8], to balance the workload among network nodes, a multimedia social network is created over an overlay topology by following a cross-layer approach that jointly considers characteristics of the overlay at the application layer and schedulability of flows at the medium access control layer. It is found in [9] that YouTube [10] has a strong clustering property. Based on this property, a peer-to-peer video sharing social network, NetTube, was proposed aiming at replacing the traditional client/server architecture so as to reduce YouTube server load. The work in [11] focused on the combination of mobile multimedia and social-networking services, and presented a multimedia social-networking community, MoCaGoGo, for mobile devices. In MoCaGoGo, mobile users can share their multimedia resources on their cell phones. It uses a channel-based publish/subscribe model for information dissemination. Wu *et al.* in [12] addressed the video copy detection problem in video sharing social networks using a suffix array data structure. Lin *et al.* [13] proposed a framework for multimedia social network, SocioNet, based on the small-world theory. Besides, other studies also contribute to the multimedia social networks [14]–[19].

The aforementioned research work focuses on the studies of a variety of multimedia social networks from network design, user behavior analysis, and reducing network loads. However, these studies are mainly for addressing the issues in either a fully online social network or a fully mobile network. The social connections between desktop users and wireless mobile users are not exploited in the previous studies to share the media streaming among mobile and desktop users to improve multimedia QoS. In addition, the efficient resource (e.g., bandwidth) sharing model under a cloud-based infrastructure has not been well studied in the literature.

B. Game Theoretic Approaches in Multimedia Social Networks

The use of game theory has proliferated recently with a wide range of applications in wireless networks [20], [21], such as resource allocation [22]–[24], power control [25]–[27], routing [25]–[30], and spectrum trading [31]. In multimedia social networks, there are also studies based on game theoretic approaches. The authors in [32] proposed a delivery scheme for multimedia streaming content and formulated the spectrum allocation problem as an auction game. In [33], a strategy-proof Vickrey-Clarke-Groves (VCG) mechanism was introduced to design the resource management scheme for wireless multimedia applications, where wireless stations are rational and selfish players competing for limited multimedia resources. To obtain an efficient and fair resource allocation for multiple classes of traffic, the authors in [34] and [35] studied a two-person game for call admission control in code division multiple access (CDMA) mobile multimedia systems. Moreover, a cooperative game was formulated in [36] for the peer selection process in P2P media streaming networks with the purpose of improving the usage efficiency of P2P links. In [37], a digital rights management game was formulated for P2P streaming under different games such that some misbehavior of peers can be avoided. Apart from the applications of noncooperative and cooperative games shown above, evolutionary game theory has been applied in multimedia social networks as well. For example, an evolutionary game framework was employed in [38] to model the cooperation among peers in P2P video streaming systems and the evolutionary stable strategy was derived. In [39], a new approach for resource allocation and creation of distribution trees was developed for P2P video streaming under an evolutionary game framework. The approach is based on the conclusion drawn from the analysis of the famous Prisoners' Dilemma. Note that, the replicator dynamic was not analyzed in these literatures.

Despite the variety of applications where game theoretic approaches have been exploited, the game model in most of these works are based on a one-stage procedure. To the best of our knowledge, this paper presents the first contribution that proposes a new architecture of WLSNs and then applies a two-stage Stackelberg game model in the network with the purpose of efficiently sharing bandwidth among all users.

III. SYSTEM MODEL

In this section, we first describe a WLSN and then identify a bandwidth allocation problem in the network. Fig. 1 shows our proposed WLSN architecture, which comprises three main components:

1) *Live content provider* offers live programs to its network audiences including both desktop and mobile users, and it pays to the telecom operators for the communications services.

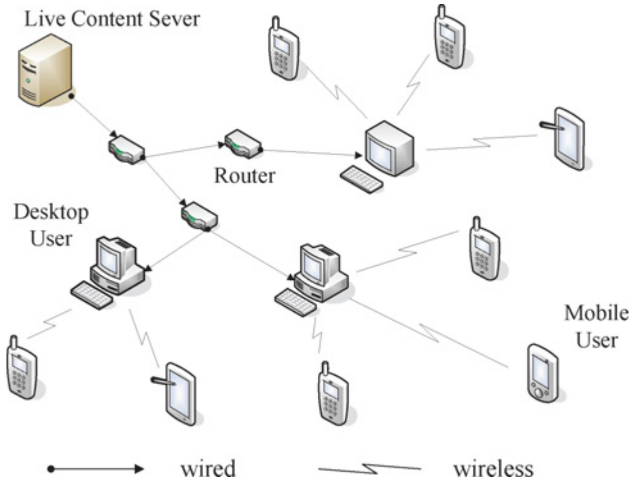

Fig. 1. Our proposed WLSN.

2) *Desktop users* watch the live programs offered by the content provider through Internet access. These users form a peer-to-peer live-streaming social network and can share their own resources with each other.
3) *Mobile users* watch the live programs by utilizing their desktop friends' resources without paying fees for wireless services to telecom operators. We assume that each mobile user can connect one of its desktop friends to watch the live programs.

Multimedia social networks are able to provide users with heterogeneous services. A variety of multimedia content like live-streaming and video on demand (VoD), video conferences, voice over IP (VoIP), photo sharing and editing, should be offered to meet different customers' demand. Furthermore, the network should be able to support adaptive quality of the multimedia content for users when the network condition (e.g., available bandwidth) varies. In a typical multimedia social network, multimedia files are usually stored in and provided to the users by a content provider's central server. Since the number of users in the network can be very high, the quality of these heterogeneous services may not be guaranteed. Furthermore, this kind of network is quite vulnerable to security problems. For example, it may suffer from denial of service (DoS) attack due to its centralized network infrastructure. These problems can be eliminated by adding a cloud framework to the content server. Following such reasoning, we have incorporated the cloud concept in our proposed WLSN.

A. Multimedia Cloud

Multimedia social networks are characterized by a large number of multimedia files with big size. The storage of this multimedia content is shown to be a significant challenge. This undesirable situation can be leveraged by making use of the method of infrastructure as a service (IaaS) in cloud computing [40]. Many organizations can provide commercial clouds that offer access to virtualized resources (storage, computation, and application) [41]. With the virtualized resources, the content provider can build a multimedia cloud (Fig. 2) that contains two main components:

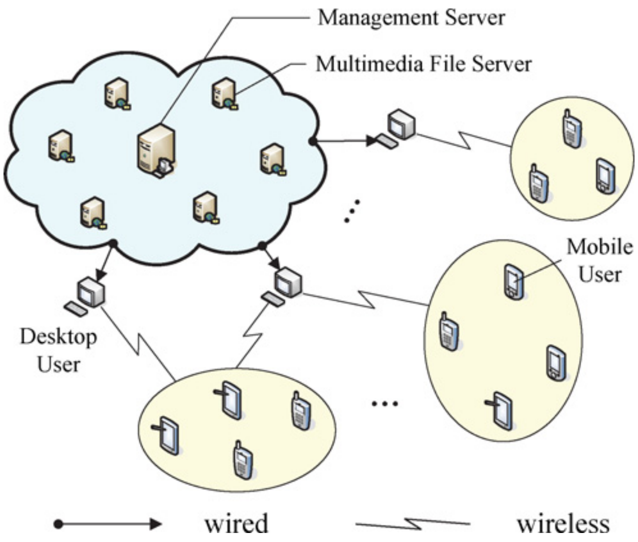

Fig. 2. Multimedia cloud for wireless live-streaming networks.

1) *Multimedia file server*: this server primarily provides the service of multimedia files storage for the content provider, and delivers the content to the end users in the network. Multimedia processing and file classification are also within its capability.
2) *Management server*: it functions as a central controller that schedules the distribution of enormous multimedia files among, and allocates tasks or requests from the end users.

More specifically, the content provider can distribute the multimedia files to a bunch of servers which may be placed at different locations. The users who require different programs can request the corresponding file servers. The multimedia file of a program can be divided into a number of clips and distributed to several servers. In this way, the working load of the servers can be balanced. Note that their requests are first reported to the head (i.e., management server) of the multimedia cloud. The head has the information of all saved files in a specific file server. Then, the requests are distributed to the corresponding server by the head. Upon receiving the requests, the server transmits relevant files to the end users with high speed.

B. Bandwidth Allocation Problem

With the high-quality live-streaming programs provided by the multimedia cloud, desktop users would like to share the live-streaming files to their mobile friends. Since a local wireless network such as WiFi is used instead of a wide-area access network to provide the live programs for mobile users, people with mobile devices can enjoy higher bandwidth without any charge. On one hand, people are encouraged to watch the live programs via their wireless devices. This is able to reduce the bandwidth insufficiency problem among the desktop users. On the other hand, the multimedia cloud needs to provide sufficient QoS for the mobile users to watch real-time live-streaming, although there is an inherent limitation of wireless bandwidth capacity and an increasing demand of the bandwidth. Therefore, efficiently sharing the wireless bandwidth between the mobile users and the desktop users becomes a very challenging issue.

We consider a WLSN consisting of a set $\mathcal{M}$ of desktop users and a set $\mathcal{N}$ of mobile users, $\mathcal{M} \equiv \{1, 2, \cdots, M\}$ and $\mathcal{N} \equiv \{1, 2, \cdots, N\}$. Some mobile users in this network may have common social properties, such as location, profession, interest, education, hobby and so on. In this sense, we can group these mobile users according to their social contexts. We suppose that these N mobile users are divided into a set $\mathcal{G}$ of groups, $\mathcal{G} \equiv \{1, 2, \cdots, G\}$. Users in the same group can communicate with each other freely, and private information can be exchanged among them. Furthermore, members in the same group can connect to distinct desktop friends if available, and each mobile user can connect to only one desktop user at a time.

In this WLSN, each desktop user is willing to share its live-streaming programs by allocating portion of wireless bandwidth to its mobile friends. Let b_i denote the size of bandwidth that desktop user i is willing to share. Generally, b_i is bounded, i.e., $0 \leq b_i \leq \bar{b}_i$ $(i \in \mathcal{M})$ where $\bar{b}_i$ is the maximum value of bandwidth that desktop user i can share. Let n_i denote the total number of mobile users connected to desktop user i. Without loss of generality, the mobile users connected to the same desktop user i are allocated the identical size of bandwidth, which is expressed as b_i/n_i. Let n_i^g be the number of mobile users in group g who choose desktop user i. Then, we have $n_i = \sum_g n_i^g$. Thus, the size of bandwidth for each mobile user in group g is given by $b_i / \sum_g n_i^g$.

For each mobile user, its strategy set is the set of desktop users to which this mobile user can connect to. Intuitively, in order to experience high-quality live video, each mobile user wishes to watch the live programs shared by the desktop friends with large size of allocated bandwidth. However, this may also lead to congestion in this specific desktop user if it is simultaneously connected by a large number of mobile users. To address the problem, a pricing scheme is presented here for the desktop users to dynamically adjust their load. The shared live-streaming programs are not free. Mobile users need to provide some kind of payment. We suppose that the mobile users connected to the same desktop user i are charged an identical price, which is denoted by p_i. It can be seen that there is an inherent tradeoff between bandwidth and price for each desktop user. Once all desktop users have made their individual decisions, their chosen strategies form a profile $(\mathbf{b}, \mathbf{p})$, where $\mathbf{b} = [b_1, b_2, \cdots, b_M]^T$ and $\mathbf{p} = [p_1, p_2, \cdots, p_M]^T$. The strategies profile for all desktop users except user i is denoted by $(\mathbf{b}_{-i}, \mathbf{p}_{-i})$. Then, $(\mathbf{b}, \mathbf{p}) = (b_i, \mathbf{b}_{-i}; p_i, \mathbf{p}_{-i})$.

IV. DESKTOP AND MOBILE USERS' INTERACTION: A STACKELBERG GAME APPROACH

In the WLSN, we establish a virtual market in which the desktop users are sellers and the mobile users are price takers. The desktop users sell bandwidth (wireless connections) to the mobile users at a certain price while the mobile users buy a connection from one desktop friend. The payment can be replaced by credit, token, or other equivalents. In this market, all desktop users and mobile users are selfish game players.

For the desktop users, they compete with each other, and make tradeoff between the size of bandwidth that they are willing to share and the price that they will charge. The main objective of the desktop users is to maximize their own utility. For the mobile users, they make the decision on which desktop user they will connect to.

Each desktop user has the right to decide the size of bandwidth and the price for utility maximization. Each mobile user, who competes with other mobile users, needs to decide the desktop user that it is willing to connect to under the announced bandwidth and price. Therefore, it is a typical two-stage leader-follower game which can be analyzed using a Stackelberg competition model [42]. In this Stackelberg game, the game followers are the mobile users buying wireless connections from the desktop users. Each mobile user makes the best responses to each proposed combination of bandwidth and price by the desktop users. The game leaders are the desktop users who offer wireless access to mobile users. Each desktop user has the knowledge of mobile users' best responses such that it can choose an optimal strategy to maximize payoff.

A. Evolution Among Mobile Users

We first study the evolutionary behavior among the mobile users who will select the desktop users for the bandwidth sharing. In this case, multiple mobile users may connect to the same desktop user, which may reduce the desktop user's utility and thereby it will increase the price in order to achieve higher utility. As a consequence, these mobile users may change their connections and switch to a different desktop user. This process can repeat many times until all users in the same group can achieve identical utility. As indicated, each mobile user behaves selfishly and chooses a desktop user according to its own utility maximization. However, there are many users in the network and it is very difficult to get all users' information as well as network status. Such information is necessary for an optimal decision. In this sense, the mobile users are not fully rational when making decisions. Therefore, to analyze the behaviors of the mobile users, we employ an evolutionary game framework which is a powerful tool for analyzing interactions among players with bounded rationality.

We define the basic components of the evolutionary game for the mobile users as follows.

1) *Players*, each mobile user in the network is a selfish and bounded-rational player in this evolutionary game.
2) *Population*, refers to the group of users in the network, and each group forms an independent population.
3) *Strategy*, the set of strategies refers to the desktop users available to each mobile user.
4) *Utility*, the utility of each player is defined as the satisfaction of allocated bandwidth minus its payment.

A mobile user is always willing to connect to a desktop user such that higher satisfaction is expected. The mobile users within a group can communicate with each other and exchange information about their strategies. If one user observes that another user choosing a different desktop user has higher utility, he may learn the strategy of the observed user and gradually change its connection with the hope of achieving higher utility. We assume that the mobile users choosing the same desktop user are allocated the identical size of bandwidth and charged an identical price. Then, the utility of a mobile user in group g connected to desktop user i is defined as

$$\pi_i^g = \mu\left(\kappa_w b_i(n_i)\right) - w_w p_i \tag{1}$$

where κ_w is a pre-defined parameter for various applications, w_w is the equivalent satisfaction per unit price contributing to the whole utility, and $\mu\left(\kappa_w b_i(n_i)\right)$ measures the satisfaction of allocated bandwidth. $\mu(\cdot)$ is supposed to be a concave function of $b_i(n_i)$. In this paper, the utility function $\mu(\cdot)$ is the frequently adopted logarithmic function, which is referred to as being proportionally fair. Then, the utility function (1) can be rewritten as

$$\pi_i^g = \log\left(\frac{\kappa_w b_i}{\sum_{g\in\mathcal{G}} n_i^g}\right) - w_w p_i. \tag{2}$$

As we have described that mobile users in the same group can learn from each other's strategy, the strategy of one player in a population can be replicated by other players in the same population. These replications form evolution in the population. Here, we introduce replicator dynamics to describe the evolution in the population. In the replicator dynamics, the share of a strategy in the population grows at a rate equal to the difference between the utility of that strategy and the average utility of the population [43]. In this case, we consider the set of strategies (i.e., the desktop users). For population (i.e., group) g, let $\mathbf{x}^g$ denote the vector of a population state whose ith element x_i^g is the population share of strategy i. Then, $\mathbf{x}^g$ can be expressed as

$$\mathbf{x}^g = [x_1^g, x_2^g, \cdots, x_M^g]^T. \tag{3}$$

Note that $\sum_i x_i^g = 1$ and $x_i^g > 0$.

In a WLSN, mobile users may not receive up-to-date data about the population state due to potential transmission latency. Therefore, they have to make decisions based on historical information about the other users. We consider this time delay in the replicator dynamics. The utility of a mobile user at time t is a function of the population state at time $(t-\tau)$ where τ denotes the time delay. The replicator dynamics is given by

$$\dot{x}_i^g(t) = x_i^g(t)\left(\pi_i^g(t-\tau) - \bar{\pi}_i^g(t-\tau)\right). \tag{4}$$

This equation demonstrates that the population share of a strategy providing higher utility will increase with time. When the shares of all strategies do not change, the evolution is over. This shows the convergence to a stable population state, i.e., the evolutionary equilibrium. By solving $\dot{x}_i^g(t) = 0$, the evolutionary equilibrium can be obtained. Since the rate of strategy selection is zero, no user has an incentive to change its chosen strategy in the evolutionary equilibrium.

B. Competition Among Desktop Users

Based on the result of the evolutionary game for the mobile users, the desktop users will compete with each other and update their strategies in order to maximize their own utilities.

We model the competition among the desktop users as a noncooperative game, and consider the Nash equilibrium (NE) as the solution to the game. In this noncooperative game, players refer to the desktop users. The strategies are the size of bandwidth that a player is willing to share and the price that a player charges. The utility is defined as the difference between the total payment from the mobile users who connect to this desktop user and the cost for transmitting live-streaming files.

In this noncooperative game, the utility function is defined as

$$U_i = w_d p_i \times \sum_{g \in \mathcal{G}} n_i^g(\mathbf{b}, \mathbf{p}) - c_i b_i \tag{5}$$

where w_d is the equivalent satisfaction per unit price contributing to the whole utility, $\mathbf{p} = [p_1, p_2, \cdots, p_M]^T$ is the strategy profile, and c_i is the cost per unit energy for data transmission. n_i^g is the total number of mobile users in group g choosing desktop user i, and is a function of $(\mathbf{b}, \mathbf{p})$. We also have $n_i = \sum_{g \in \mathcal{G}} n_i^g$.

An NE is a commonly used concept in solving game-theoretic problems. In the NE, no user can improve its own utility by unilaterally changing its strategy.

Definition 1: A strategy profile $(\mathbf{b}^*, \mathbf{p}^*)$ is the NE if, for each player i, $U_i(b_i^*, \mathbf{b}_{-i}^*; p_i^*, \mathbf{p}_{-i}^*) \geq U_i(b_i, \mathbf{b}_{-i}^*; p_i, \mathbf{p}_{-i}^*)$, for all $b_i \in [0, \bar{b}_i]$ and $p_i \in [0, +\infty)$.

The NE can be computed by finding the fixed point of the best response functions of all players [27]. For each player i, the best response function is defined as

$$\beta_i(\mathbf{b}_{-i}, \mathbf{p}_{-i}) = \quad arg \;\; \max_{b_i, p_i} U_i(b_i, \mathbf{b}_{-i}; p_i, \mathbf{p}_{-i}). \tag{6}$$

By finding $(b_i^*, p_i^*) \in \beta_i(\mathbf{b}_{-i}^*, \mathbf{p}_{-i}^*)$ for all players, we can obtain $(\mathbf{b}^*, \mathbf{p}^*)$. In other words, the NE equals to the solution of $(\mathbf{b}, \mathbf{p}) = \beta(\mathbf{b}, \mathbf{p})$ where $\beta(\mathbf{b}, \mathbf{p}) = [\beta_1(\mathbf{b}, \mathbf{p}), \beta_2(\mathbf{b}, \mathbf{p}), \cdots, \beta_M(\mathbf{b}, \mathbf{p})]^T$.

V. CASE STUDY: TWO DESKTOP USERS

In this section, we consider a specific scenario of WLSNs with two desktop users, i.e., $\mathcal{M} = \{1, 2\}$ in this case. We will exploit backward induction to develop the NE.

A. Replicator Dynamics of Mobile Users

We have demonstrated in Section IV-A that the evolutionary game converges to its evolutionary equilibrium when $\dot{x}_i^g(t) = 0$. The evolution will stop while the group members choosing different desktop users obtain identical utility since no user in this group can find another user with higher utility. Therefore, the evolutionary equilibrium can be obtained by solving the following equation:

$$\pi_i^g = \pi_{j \neq i}^g, \forall g \in \mathcal{G}. \tag{7}$$

In this particular case, the equation becomes

$$\log\left(\frac{\kappa_w b_1}{\sum_{g \in \mathcal{G}} n_1^g}\right) - w_w p_1 = \log\left(\frac{\kappa_w b_2}{\sum_{g \in \mathcal{G}} n_2^g}\right) - w_w p_2 \tag{8}$$

where the left-side term is the utility of the mobile users choosing desktop user 1, while the right-side term represents the utility of the mobile users choosing desktop user 2.

Let n^g denote the total number of mobile users in group g, thus $n^g = \sum_{i \in \mathcal{M}} n_i^g$. Substituting $n_i^g = x_i^g n^g$ into (8), we have

$$\log\left(\frac{\kappa_w b_1}{\sum_g x_1^g n^g}\right) - w_w p_1 = \log\left(\frac{\kappa_w b_2}{\sum_g (1 - x_1^g) n^g}\right) - w_w p_2. \tag{9}$$

After computation, the evolutionary equilibrium can be expressed as

$$\sum_g x_1^g n^g = \frac{\sum_g n^g}{\frac{b_2}{b_1} \cdot e^{w_w(p_1 - p_2)} + 1}. \tag{10}$$

The stability of the evolutionary equilibrium can be analyzed by evaluating the Jacobian matrix of the replicator dynamics [45]. The Jacobian matrix is given by

$$E = \begin{bmatrix} \frac{\partial \sigma x_1^a(\pi_1^a - \bar{\pi}^a)}{\partial x_1^a} & \frac{\partial \sigma x_1^a(\pi_1^a - \bar{\pi}^a)}{\partial x_1^b} \\ \frac{\partial \sigma x_1^b(\pi_1^b - \bar{\pi}^b)}{\partial x_1^a} & \frac{\partial \sigma x_1^b(\pi_1^b - \bar{\pi}^b)}{\partial x_1^b} \end{bmatrix} = \begin{bmatrix} E_{1,1} & E_{1,2} \\ E_{2,1} & E_{2,2} \end{bmatrix}.$$

The evolutionary equilibrium is considered stable if the following two eigenvalues of matrix E have negative real parts

$$\lambda(E) = \frac{(E_{1,1} + E_{2,2}) \pm \sqrt{4E_{1,2}E_{2,1} + (E_{1,1} - E_{2,2})^2}}{2}. \tag{11}$$

B. Competition Between Two Desktop Users

After the evolution of the mobile users, each desktop user will adjust its strategies to achieve higher utility or profit. We consider the situation when the shared bandwidth of both desktop user 1 and 2 are fixed; then the price is the single strategy. Hence, the non-cooperative game between these two desktop uses can be defined as a tuple $\Gamma =< \mathcal{M}, (P_i)_{i \in \mathcal{M}}, (U_i)_{i \in \mathcal{M}} >$, where $\mathcal{M} = \{1, 2\}$ is the set of players, i.e., the desktop users. $P_i = [0, +\infty)$ is the strategy set of player i, $p_i \in P_i$. Let $\mathbf{p} = (p_1, p_2)$ be the strategy profile when each player i chooses p_i. $U_i : \prod = P_1 \times P_2 \rightarrow R$ is the utility function of player i, (5) gives the general expression. Since the shared bandwidth is fixed, the utility function of player i can be rewritten as

$$U_i \quad = \quad w_d p_i \times (\sum_{g \in \mathcal{G}} x_i^g n^g) - c_i b_i \tag{12}$$

where $\sum_g x_i^g n^g$ can be obtained from the equilibrium of the evolutionary game among the mobile users shown by (10). After substituting (10) into (12), we have

$$U_i = w_d p_i \times \frac{\sum_g n^g}{\frac{b_j}{b_i} \cdot e^{w_w(p_i - p_j)} + 1} - c_i b_i. \tag{13}$$

This expression is very significant since it demonstrates the inherent interaction between the leaders game and the followers game.

The first-order derivative of U_i with respect to p_i is computed as

$$\frac{\partial U_i}{\partial p_i} = w_d (\sum_g n^g) b_i \times \frac{b_j \cdot e^{w_w(p_i - p_j)} + b_i - b_j \cdot e^{w_w(p_i - p_j)} w_w p_i}{[b_j \cdot e^{w_w(p_i - p_j)} + b_i]^2}. \tag{14}$$

Afterwards, the optimal price of each desktop user can be computed by setting $\frac{\partial U_i}{\partial p_i} = 0$; the resulting p_i is

$$p_i^* = \frac{1}{w_w} + \frac{1}{w_w}\frac{b_i}{b_j} \cdot e^{w_w(p_j - p_i)}. \tag{15}$$

By employing a Lambert-W function [31], p_i^* can be expressed as a best response function of p_j, which is given by

$$p_i^* = \beta(p_j) = \frac{1}{w_w}\left[1 + W\left(\frac{b_i}{b_j} \cdot e^{(w_w p_j - 1)}\right)\right]. \tag{16}$$

C. Nash Equilibrium for Non-Cooperative Game Between Desktop Users

In this noncooperative game, as shown in (16), each desktop user's marginal utility increases with its rival's higher price. Thus, if this game is proved to be a supermodular game [42], the existence of its NE is also proved.

Theorem 1: A pure NE exists in the noncooperative game for the competition among the desktop users.

Proof: Generally, a supermodular game has the following characteristics.

1) A strategy is a sublattice of some Euclidean space $\Re^K$.
2) A utility has increasing differences (strictly increasing differences) in all sets of strategies.
3) A utility is supermodular in its own strategy.

In the noncooperative game, since the strategy of player i is the price $p_i \in [0, \infty)$, characteristic 1) can be easily verified. For 2) and 3), they can be simultaneously verified if $\frac{\partial^2 U_i}{\partial p_i \partial p_j} \geq 0$ [42]. $\frac{\partial^2 U_i}{\partial p_i \partial p_j}$ can be computed as

$$\frac{\partial^2 U_i}{\partial p_i \partial p_j} = \frac{\partial \beta_i}{\partial p_j} = \frac{W(z)}{1 + W(z)} \tag{17}$$

where $z = \frac{b_i}{b_j} \cdot e^{(w_w p_j - 1)}$ and it can be proved that $z > 0$. Since

$$z = W(z)e^{W(z)} \tag{18}$$

we can obtain $W(z) > 0$ if $z > 0$, and further we can have $\frac{\partial^2 U_i}{\partial p_i \partial p_j} \geq 0$.

Now, these three characteristics are successively verified, and thus the noncooperative game is a supermodular game that has an NE. ■

Theorem 2: The noncooperative game has a unique NE.

Proof: Theorem 1 states that there exists an NE in the non-cooperative game, we prove that the NE is unique. By employing the Lambert-W function again, we can express p_i as its self-mapping function as follows:

$$p_i = M_i(p_i) = \beta_i(\beta_j(p_i)) = \frac{1}{w_w}\left(1 + W\left(\frac{e^{(w_w p_i - 1)}}{W(\frac{b_j}{b_i} \cdot e^{(w_w p_i - 1)})}\right)\right). \tag{19}$$

Since $P_i = [0, +\infty)$ is a compact subset of real numbers, the key aspect of the uniqueness proof is to realize that the self-mapping function is a contraction. We define the Jacobian matrix as

$$E' = \begin{bmatrix} \frac{\partial^2 M_i}{\partial p_i^2} & \frac{\partial^2 M_i}{\partial p_i \partial p_j} \\ \frac{\partial^2 M_j}{\partial p_i \partial p_j} & \frac{\partial^2 M_j}{\partial p_j^2} \end{bmatrix} = \begin{bmatrix} 0 & \frac{\partial \beta_i}{\partial p_j} \\ \frac{\partial \beta_j}{\partial p_i} & 0 \end{bmatrix}. \tag{20}$$

Let λ denote the largest absolute eigenvalue of the Jacobian matrix E'. Then, we have

$$\lambda = \sqrt{\frac{\partial \beta_i}{\partial p_j} \times \frac{\partial \beta_j}{\partial p_i}}. \tag{21}$$

The condition for being a contraction is that $\lambda < 1$. It can be seen that $\frac{\partial \beta_i}{\partial p_j} < 1$ from (17), and thus we have $\lambda < 1$. This means that the self-mapping function of each desktop user is a contraction. Therefore, the uniqueness of the NE is proved. ■

VI. IMPLEMENTATION PROTOCOL

In this section, we will present protocols for the mobile users to evolve their choices and also the desktop users to adjust their strategies based on the results of the Stackelberg game.

A. Evolution Protocol for Mobile Users

We present an iterative algorithm for the mobile users to converge to the evolutionary equilibrium. Based on the replicator dynamics, each mobile user changes its strategy to maximize its own utility. In order to achieve the evolutionary equilibrium, an evolution protocol is presented for each mobile user. Since the users in the same group can exchange information, the current choice and utility of one mobile user is available to others, but not available to the users in different groups. We assume that a mobile user can also receive the average utility of its own group. A user changes its choice with some possibility if finding another user having higher utility in the same group. When all users in the same group obtain equal utility, the evolution is completed. The specific procedure of this protocol is described as follows.

1) Initially, each mobile user connects to an available desktop user randomly;
2) Each user computes its utility using the allocated bandwidth and the charged price by the connected desktop user according to (2). The allocated bandwidth is measured by this mobile user himself since the total number of mobile users connected to the same desktop user in (2) is unavailable.
3) After communicating with the other users in the same group, each user gets its data about choice and utility, and then computes the average utility of the group as
$$\bar{\pi}^g(t) = \frac{\sum_i n_i^g(t - \tau) \cdot \pi_i^g(t - \tau)}{n^g(t - \tau)}. \tag{22}$$
4) If the average utility is greater than its own utility, the mobile user changes its connection to another desktop user who offers higher utility with a possibility of
$$\theta(t) = \frac{\bar{\pi}^g(t) - \pi_i^g(t)}{\bar{\pi}^g(t)}. \tag{23}$$
Otherwise, the user keeps the current connection
5) Repeat procedure 2) to 4).

As indicated by the evolution protocol, all users in the same group can obtain equal utility at the equilibrium. Since

Algorithm 1 Executed by each mobile user

```
Build initial connection
repeat
    Compute utility using the received price and measured bandwidth
    Get information about the choices and the utility of all other users in the same group
    Compute the average utility $\bar{\pi}^g(t)$
    if $\bar{\pi}^g(t) > \pi_i^g(t)$ then
        Change the connection with probability $\theta(t)$
    else
        Maintain the current connection
    end if
until all mobile users in the same group have equal utility.
```

the mobile users choosing the same desktop user can also receive equal utility regardless of the group they belong to, the evolution can provide desirable fairness for the whole system if a desktop user is connected by multiple group members. Algorithm I shows the algorithm that is executed by each mobile user.

B. Competition Protocol for Desktop Users

For each desktop user, the information about other desktop users may not be available. However, such information is very critical for computing the optimal parameters with respect to bandwidth and price in the NE. With the purpose of adjusting strategies toward a direction of increasing their utility, the desktop users can update the size of bandwidth and the price by using the following learning-based algorithm, i.e.

$$b_{i0}(t+1) = b_i(t) + \frac{\nu_b}{I}\left[U_i\left(\mathbf{b}(t), \mathbf{p}(t)\right) - U_i\left(\mathbf{b}(t-I), \mathbf{p}(t-I)\right)\right] \tag{24}$$

and

$$p_{i0}(t+1) = p_i(t) + \frac{\nu_p}{I}\left[U_i\left(\mathbf{b}(t), \mathbf{p}(t)\right) - U_i\left(\mathbf{b}(t-I), \mathbf{p}(t-I)\right)\right] \tag{25}$$

where I is the buffer size recording information about the game, and ν_b and ν_p are used for desktop users to control the speed while adjusting their strategies.

Once the bandwidth and the price are updated, each desktop user broadcasts these refreshed values to the connected mobile users. Then, it is the mobile users' own responsibility to adjust their strategies, i.e., the connections. Since the desktop users are not aware the duration of each evolution, they set a waiting time T_w for the next strategy update. When the results in (24) and (25) keep unchanged, it is regarded that the NE is approximately achieved. Algorithm 2 shows the implementation protocol executed by each desktop user.

Algorithm 2 Executed by each desktop user

```
For each desktop user:
Set the initial bandwidth willing to share, $b_{i,0}$ and price charged for the bandwidth, $p_{i,0}$
repeat
    Wait a period time $T_w$ for the evolution among mobile users
    Update the size of bandwidth and the price, set $b_i(t+1) = \max\{\min\{b_{i0}(t+1), \bar{b}_i\}, 0\}$, and set $p_i(t+1) = \max\{p_{i0}(t+1), 0\}$
    $t = t + 1$
until $b_i$ and $p_i$ are both unchanged.
```

TABLE I

PARAMETERS

Parameter	Value
$\mathcal{M}$, the set of desktop users	$\{1, 2\}$
$\mathcal{G}$, the set of groups of mobile users	{A, B}
$\bar{b}_i$, maximal size of bandwidth	50 units
n^g, the number of mobile users in each group	25
τ, the time delay	1
T_w, the waiting time	100
ν_b, the rate of bandwidth adjustment	1
ν_p, the rate of price adjustment	0.05

VII. NUMERICAL RESULTS

In this section, we evaluate the performance of the proposed game-theoretic approach in the WLSN. In addition, we will investigate the impacts of critical parameters on the system evolution and performance. We consider a WLSN with two desktop users and two groups of mobile users, then $\mathcal{G} = \{A, B\}$. For example, a football match between team a and team b is going to be broadcasted online by the content provider. Desktop users can watch this match on their PC with wired broadband service while wireless device users can watch this match through the connection to a desktop user to get its living-streaming file. According to the team they support, these mobile users can be classified into two groups. There are n^a wireless supporters for team A and n^b wireless supporters for team B in this wireless live-streaming network, respectively.

Table I lists the value of the system parameters in the numerical examples. Each desktop user can allocate the wireless bandwidth with a maximal size of 50 units to mobile users. If not specified, the number of mobile users in each group is equally set to 25. The desktop users will wait $T_w = 100$ for the next strategy update. The rates of bandwidth and price adjustment are $\nu_b = 1$ and $\nu_p = 0.05$, respectively. For the utility function, we set $w_d = 1$ for the desktop users and $\kappa_w = 100$, $w_w = 0.5$ for the mobile users.

A. Evolutionary Behavior of Mobile Users

We adopt the phase plane of the replicator dynamics to show the evolutionary behavior of mobile users. We focus on a particular round of evolution, starting from the desktop users giving their strategies (i.e., bandwidth and price) and ending with the mobile users reaching an equilibrium. The size of allocated bandwidth and the price are $b_1 = b_2 = 30$ units and $p_1 = 2$, $p_2 = 4$, respectively. Fig. 3 shows the phase plane of the replicator dynamics. The figure shows the direction of the strategy adaption of mobile user population to the evolutionary equilibrium. It can also be observed that different initial population states converge to different evolutionary equilibria. However, they provide the same utility for all

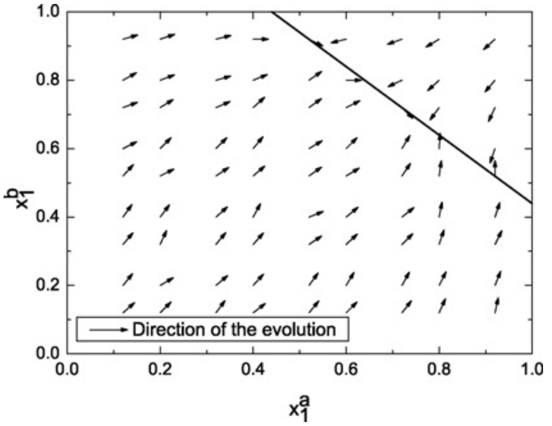

Fig. 3. Phase plane of the replicator dynamics when $b_1 = b_2 = 30$ units and $p_1 = 2$, $p_2 = 4$. The solid line represents evolutionary equilibria.

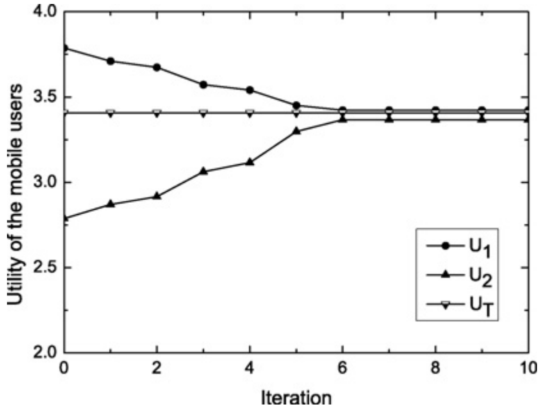

Fig. 4. Convergence of the evolution among mobile users to the equilibrium when the initial population state is $(x_1^a, x_1^b) = (0.6, 0.4)$. U_1 and U_2 represent the utility of mobile users in group A and B, respectively, while U_T is the theoretical utility.

mobile users. Furthermore, the phase plane indicates that the basin of attraction for the replicator dynamics is the entire feasible region $0 < x_1^a, x_2^a < 1$. Fig. 4 shows the convergence of the evolutionary behavior when the initial population state is $(x_1^a, x_1^b) = (0.6, 0.4)$. The system takes six iterations of strategy selection for the mobile users to reach the evolutionary equilibrium $(0.76, 0.68)$. In the equilibrium, the utility of all mobile users in both group A and B are nearly identical.

B. Evolutionary Equilibrium

Fig. 5 shows the evolutionary equilibrium in terms of the number of mobile users in group B. In this example, the number of mobile users in group A is fixed as 25. The size of shared bandwidth is 30 units for each desktop user. The curves show that the number of mobile users connected to desktop user 1 increases with the increasing number of users in group A. When the price of desktop user 1 becomes higher, the number of mobile users connected to desktop user 1 decreases. Fig. 6 shows the evolutionary equilibrium in terms of the number of mobile users in group B when the price is set as 2 for each desktop user. The results indicate that the number of mobile users choosing desktop user 1 increases with more mobile users in group A. While desktop user 1 allocates more bandwidth to mobile users, more mobile users make a decision to connect to desktop user 1.

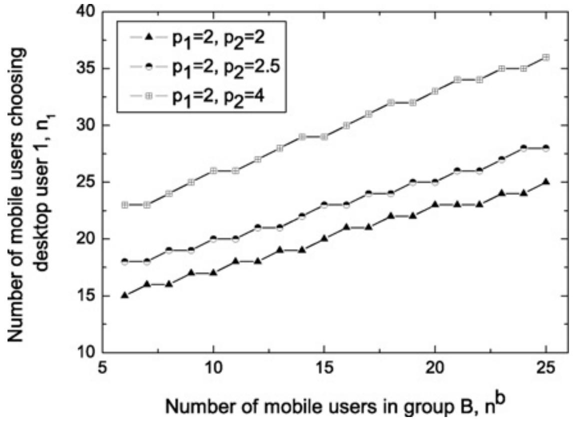

Fig. 5. Evolutionary equilibrium in terms of the number of mobile users when the bandwidth is 30 *units*.

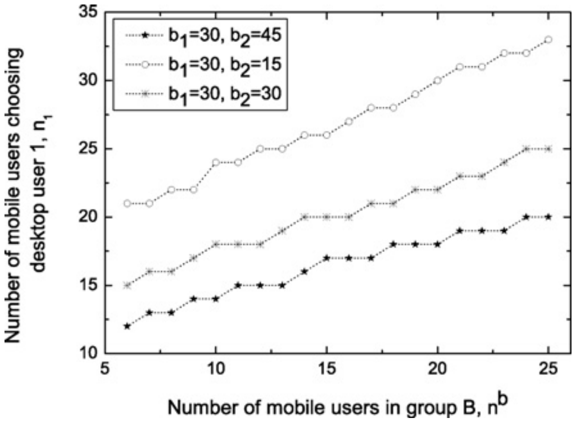

Fig. 6. Evolutionary equilibrium in terms of the number of mobile users when the price is 2.

C. Best Responses of Desktop Users

Fig. 7 shows the best response of each desktop user. In this example, desktop user 1 and desktop user 2 have 30 units and 15 units of shared bandwidth, respectively. As we can see, the best response of both desktop users are increasing in the non-cooperative game. This observation demonstrates that their strategies are strategic complements. The gradient of the best response of desktop user 1 is constantly smaller than 1, which is different from that of desktop user 2. This is because desktop user 1 allocates more bandwidth than desktop user 2 to the mobile users. It is observed that there is only one intersection point of these two best responses. Hence, the NE is unique and given by $(4.516, 3.590)$. To achieve higher utility, desktop user 2 may have to increase its shared bandwidth to the mobile users.

We further consider the best responses of the desktop users when both the size of bandwidth and the price are variable. Fig. 8 shows the best responses of two desktop users in terms of the size of bandwidth. If one of the desktop users increases its shared bandwidth, more mobile users will switch from its rival to the desktop user. The other desktop user will perform a different operation since it needs to raise the satisfaction and compensate the loss from switched mobile users. However, when the prices of both desktop users increase, the shared

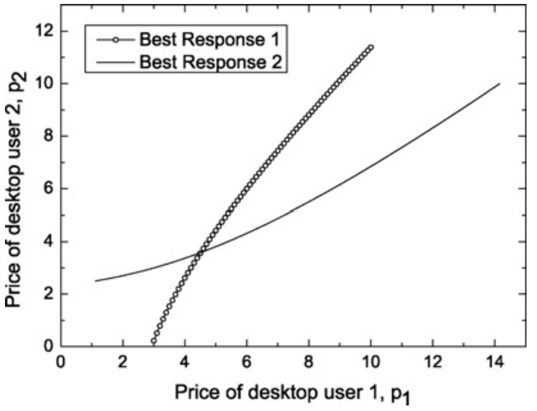

Fig. 7. Best responses of the desktop users when price is the strategy.

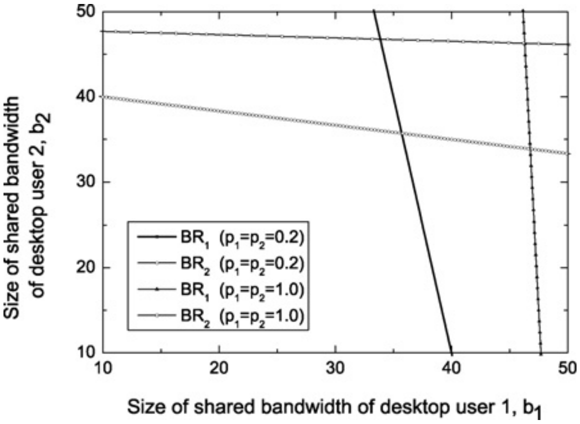

Fig. 8. Best responses of the desktop users when the bandwidth and the price are strategies.

bandwidth at the best response of each desktop user increases as well since higher price will lead to greater utility. The NE of the competition between two desktop users is represented by the intersection point in the figure, which is $(b_1^*, b_2^*) = (35.714, 35.714)$ when the price (p_1, p_2) is $(0.2, 0.2)$, and $(b_1^*, b_2^*) = (46.296, 46.296)$ when the price (p_1, p_2) is $(1, 1)$.

D. Nash Equilibrium

Fig. 9 shows the NE in terms of the number of mobile users. In this instance, the number of mobile users in group A ranges from six to 25 while the number of mobile users in group B is fixed as 25. The curves show that the size of shared bandwidth increases almost linearly with the increasing number of mobile users in group A. When the prices of both desktop users increase, the size of shared bandwidth becomes larger. This matches with the best responses of the desktop users as illustrated in Fig. 8. Such increasing pattern becomes slow with even higher price.

VIII. CONCLUSION

We proposed a cloud-based WLSN in which desktop users received multimedia services from a multimedia cloud and they shared their live contents with mobile friends through wireless connections. This network architecture offered advantages of saving the cost for network services and

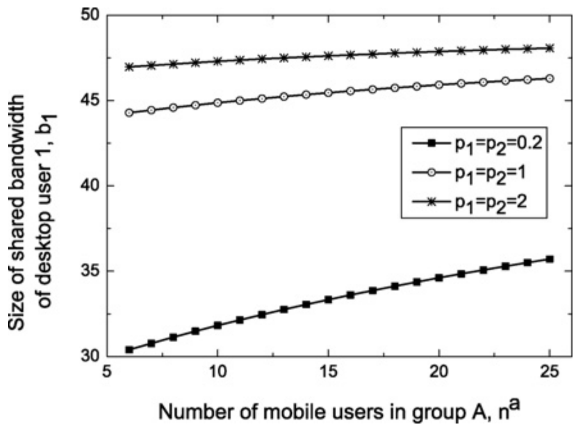

Fig. 9. Nash equilibrium in terms of the number of mobile users.

satisfied the increasing demand on bandwidth requirements. In this multimedia social network, we formulated a bandwidth allocation problem with the objective to share bandwidth efficiently for both desktop users and mobile users. This problem has been designated as a Stackelberg game which contains: 1) the leader game, i.e., a non-cooperative game among desktop users; and 2) the follower game, i.e., an evolutionary game among mobile users. We performed theoretical analysis for both a general scenario and a specific case. In particular, the existence of a unique Nash Equilibrium was proved. In addition, we implemented the proposed game-based scheme with detailed protocol specifications. Both theatrical analysis and simulation results showed the convergence and efficiency of the proposed scheme.

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