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Reward mechanisms for P2P VoIP networks

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Abstract As we have seen, P2P VoIP software, such as Skype, has emerged from the current generation of telecommunication systems. However, establishing communication applications based on P2P networks without considering the operational models of the Internet presents potential dangers. In this study, we treat a VoIP telephone conversation as a dynamic game and compare the ex post reward mechanism with the ex ante reward mechanism in forward versus discard and QoS routing. Our simulation results point out that the ex post reward mechanism is better than the ex ante reward mechanism in forward versus discard; however, the opposite holds true in QoS routing when the expected number of periods is sufficiently large. In addition, this study considers the reward mechanisms and the platform provider's benefit to find the optimal number of supernodes in a transmission path.

Keywords Reward mechanisms · Moral hazard · Communication · P2P VoIP networks

1 Introduction

Nowadays, Peer-to-Peer (P2P) technology is widely used all over the Internet because of its potentiality and flexibility. In contrast to client-server architecture, P2P uses diverse connectivity between participants in a network and the cumulative bandwidth of network participants rather than conventional centralized resources where a relatively low number of servers provide the core value to a service or application [1]. P2P VoIP software, such as Skype, is one successful application that is based on this novel technology. Currently, by integrating P2P VoIP software with Public Switched Telephone Network (PSTN) and offering inexpensive telephone calls, Skype, an application of Kazza architecture, has emerged from the current generation of telecommunication systems. According to market surveys conducted by [2, 3], the impact of the solution provided by Skype has significantly decreased the revenues of traditional telephone companies, especially for long-distance calls.

Skype maintains a central registration server, but all other components for searching the user directory and setting up connections are implemented by a decentralized P2P architecture [4]. The nature of P2P not only reduces Skype's spending on establishing expensive infrastructure, but also improves the reliability of voice connection. In the current architecture of Skype, the P2P VoIP network consists of super nodes and clients. When a user joins the Skype network, the user's computer always starts as a client node. If the client has sufficient resources, such as a high-speed CPU, memory and network bandwidth, and if it is directly connected to the Internet (not behind any NAT or firewalls), Skype automatically promotes the client to the super node [5]. The responsibility of these super nodes is to perform user directory services and to relay traffic for computers behind firewalls and NAT that are not able to establish connections directly [6]. If the direct end-to-end connection between two users is crowded, Skype initiates re-routing on application layers by relaying the traffic over a third-party machine to avoid congested or faulty paths [7–9].

Several subjective methods and mechanical techniques can be used to measure voice quality, such as mean opinion

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score (MOS), perceptual evaluation of speech quality (PESQ), and E-model [10, 11]. These help ensure users will be satisfied with end-to-end transmission performance. The quality of communication applications is affected by the underlying network behavior and the technology built-mechanisms [12]. The most critical indicators associated with network behavior are jitter, delay, and packet loss. Assuring qualified quality of service (QoS) for users on IP networks remains the most challenging issue to be solved. When the number of voice packets lost exceeds a certain threshold, it results in obstacles in the conversation. In general, the conversation becomes disjointed if the end-to-end delay exceeds 150 ms [13]. Therefore, for high-quality communication, the network must be able to guarantee certain minimum levels of QoS for communication applications.

1.1 Problems and motivation

Although P2P VoIP services, such as Skype, are considered to be generally reliable, over the years, a number of users have complained about various types of connectivity and quality problems [14–16]. The problems are mainly due to the large number of users and insufficient supernodes involved in delivering packets [17–19]. An empirical study shows that Skype's score dropped from 7.8 to 7.4 in 2007; in addition, the overall score for PC-to-phone calls made using Skype is also down. Sound quality, ease of setup, and reliability all took a hit [20]. Experiments in [21] also show that the voice quality of Skype is no better than traditional VoIP platforms.

There are dangers in establishing VoIP applications based on P2P networks without considering the operational models of the Internet [18]. First, once a machine becomes a supernode, its bandwidth will be used to carry irrelevant traffic. Second, because P2P VoIP applications may bypass network security, supernodes incur unknown security risks and become a target of hackers. Thus, P2P VoIP users may attempt to change their roles from supernodes to ordinary clients or narrow the bandwidths used in P2P VoIP applications. Moreover, some universities and government agencies have prohibited Skype in their jurisdiction or have required users within their networks to disable supernode functionality to avoid relaying traffic [22, 23]. As a result, the overall communication quality is degraded significantly and a large percentage of communication sessions have unacceptable quality when the situation is deteriorating.

There are several VoIP service providers in the Internet communication market, such as Packet8, ViaTalk, VoicePulse, Verizon VoiceWing, and Vonage. Each of the five companies delivers reliable and high-quality connections, and only charges a relatively low service fee [24]. Therefore, if communication quality affects market share, when competition among VoIP companies intensifies, P2P VoIP platform providers should propose a reward mechanism to solve the problem of non-cooperative supernodes in communication networks. Regarding the implementation of a reward mechanism, although most existing popular commercial P2P VoIP networks have not adopted reward schemes for improving the QoS, several studies have investigated incentive mechanisms in P2P routing [25–27]. In addition, a few micro-payment mechanisms for P2P networks [28] have been proposed in recent years. Conceptually, these micro-payment mechanisms can also be applied in P2P VoIP networks. Furthermore, these rewards might be implemented as "rule based" policies, as in the case of Bit-torrent [29]. For example, a specific amount of routing services could be required before making a VoIP call. The VoIP users would need to perform a series of contributive routings in order to receive better communication service at a later time. In this study, we mainly focus on the economic design of reward mechanisms, not on implementing reward systems for specific P2P VoIP networks. Our approaches can provide useful insight for the development of incentive mechanisms.

1.2 Findings and contribution

In this study, to facilitate cooperation among the supernodes, we develop two different reward mechanisms, ex post and ex ante reward mechanisms. The ex post reward refers to the reward paid after the supernodes' actions, whereas the ex ante reward refers to the reward paid before the supernodes' actions. We analyze scenarios in which the costs and number of supernodes are common knowledge and compare the reward mechanisms under two different settings: forward versus discard and QoS routing. Both reward mechanisms can solve the hidden-action problem in P2P VoIP networks in which a group of supernodes help relay voice traffic. Investigating the impact of system parameters on the supernodes and the payoffs of P2P VoIP platform providers, we identify the characteristics of the reward mechanisms and point out when to use each one. Our simulation results point out that the ex post reward mechanism is better than the ex ante reward mechanism in forward versus discard; however, the opposite holds true in QoS routing when the expected number of periods is sufficiently large. The results show that the ex ante reward mechanism can take advantage of long-term cooperation to get rid of the effect of network uncertainty. The remainder of this paper is organized as follows. In the next section, we review prior research and highlight contributions. In Sect. 3, we introduce our model and examine the reward mechanisms in forward versus discard and QoS routing. Section 4 investigates the impacts of system parameters and presents numerical examples. In Sect. 5, we discuss other advanced issues. Finally, we conclude our research and address future studies in Sect. 6.

2 Related literature

Designing and planning communication network is a complicated job that includes physical links, capacity selection, logical network configuration, channel assignment, and traffic routing on the logical network. Park et al. [30] address the physical SONET network design problem of selecting stackable, unidirectional rings connecting central office nodes and remote nodes. As a solution, they develop a Lagrangian relaxation procedure augmented with a simulated annealing algorithm. From the viewpoint of VoIP service providers, one major challenge is controlling delay when substantial demand fluctuates. Du et al. [31] suggest that sharing and trade agreements with larger content can be particularly effective. In addition, they also point to the ability of intermediation services to enhance the overall gains from resource sharing arrangements. Cheng's results [32] argue that it is possible for nonprofit ISPs to provide high quality Internet dial-up capacity at a low price and to recover all the costs.

However, end-users in the Internet have the motivation and ability to optimize their performance by altering their existing TCP flow and congestion control protocols, giving rise to a noncooperative game [33]. Feldman et al. [34] study the problem of selfish behavior in network routing. They develop a principal-agent model, where the principal is a pair of communication endpoints that attempt to communicate over a multi-hop network. The agents are the links that lie on the path between the endpoints. They are capable of forwarding messages among themselves. The routing policy discussed in the setting explored by Feldman et al. is the same as the one studied in this work. Recently, several new architectures have been proposed in the context of the Internet to provide more visibility and transparency into networks, such as those in [35–37]. The various proposals for acquiring network topology and performance information may imply that we can treat network information as common knowledge [34]. In this study, we model a conversation as a dynamic game and develop ex post and ex ante reward mechanisms to facilitate cooperation among the supernodes. Other studies of dynamic games involved in the domain of communication are presented in [38, 39].

Indeed, many incentive mechanisms have been considered in previous research; however, most of them either focus on P2P file sharing or traditional network routing services. One of the most significant differences between the present study and other studies is that we consider routing service to be randomly terminated by VoIP users. In addition, most existing incentive mechanisms only offer rewards after the communication work is finished. In addition to the popular setting, we also consider another approach in which a reward is offered before the communication work starts. Therefore, the present study is innovative in that it compares two different reward mechanisms in the general routing policies adopted by supernodes in P2P VoIP network. Based on the comparisons, we can examine the impact of communication time on reward mechanisms implemented in P2P VoIP networks.

3 The model

We consider a P2P VoIP network in which supernodes help relay voice traffic during VoIP telephone conversations, as shown in Fig. 1, where the network is coordinated by a P2P VoIP platform provider.

To gain market share, the platform provider attempts to improve communication quality by enticing the supernodes in the P2P network to exert high effort in packet forwarding. For the sake of simplicity, we assume that each supernode in the P2P network has only two possible

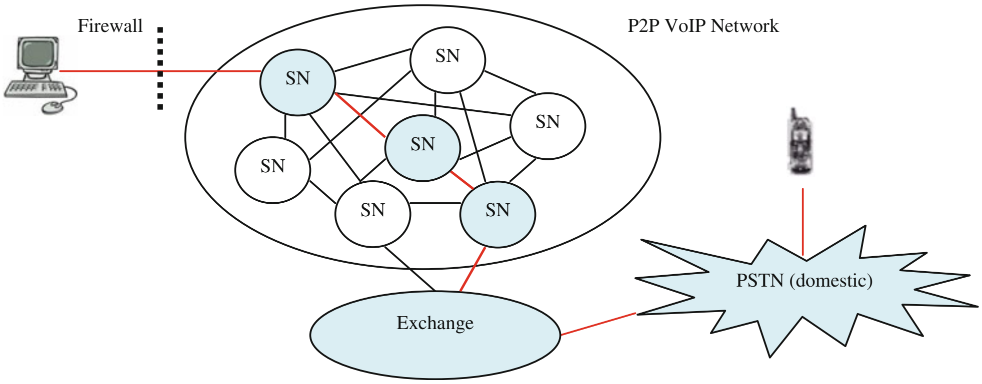

Fig. 1 An example of P2P VoIP network

Table 1 Notation

Notation	Description
$a_i \in \{0, 1\}$	The effort action
c_i^F, c_i^Q	The effort cost of the supernode i
$q(n)$	The probability of good communication quality when all exert high-effort action
s_i^G, s_i^B	The payment of the "Good" ("Bad") outcome in the ex post reward mechanism
ρ_i	The payment in the ex ante reward mechanism
w_i	The opportunity cost of the supernode i
$x \in \{x^G, x^B\}$	The outcome of communication quality
F_i	The liability in the ex ante reward mechanism
Π_i^c	The expected payoff of the cooperation strategy in the ex ante reward mechanism
Π_i^s	The expected payoff of the fraud strategy in the ex ante reward mechanism
π_i	The platform provider's expected payoff
δ	The probability that the game is played at the next period
λ_0	The platform provider's benefit in a time slice when the outcome is "Good"

actions, high-effort action and low-effort action, denoted as $a_i = 1$ and $a_i = 0$, respectively (see Table 1 for a complete list of notations). Therefore, we define the effort cost of each supernode i as $C(a_i) = c_i a_i$. That is, we normalize $C(a_i)$ to be zero when $a_i = 0$ holds.

Because supernodes can drop or delay voice packets for a variety of reasons without the notification of P2P VoIP users, in this study, we consider two routing policies—forward versus discard and QoS routing. These different routing polices are both composed of high-effort action and low-effort action. More specifically, in QoS routing, the supernodes can choose between offering high-quality service (allocating high bandwidth) and low-quality service (allocating low bandwidth). QoS routing may correspond to service differentiation P2P networks in which a source node can forward packets to request nodes with different bandwidths according to the bandwidth bidding messages sent by the request nodes [40]. In forward versus discard, the supernodes can choose between forwarding (i.e., high-effort action) and dropping voice packets (i.e., low-effort action). In the present model, forwarding voice packets and offering high-quality service are the same, whereas discarding voice packets and offering low-quality service have different functions and meaning. If one of the supernodes discards voice packets, the communication quality at a time slice cannot satisfy the quality threshold demanded by the VoIP platform provider. However, in QoS routing policy, it is possible for the communication quality at a time slice to satisfy the quality threshold even if all supernodes offer low-quality service.

If the supernode i refuses to help the platform provider relay voice traffic, it receives the reserved payoff w_i (that is, opportunity cost) by offering other services. These supernodes' effort decisions are not observable, but the communication quality can be measured by the platform provider.

A VoIP telephone conversation is composed of several time slices. Here, we view each time slice as a single stage game; therefore, we can treat a VoIP telephone conversation as a dynamic game in this study. The communication quality at each time slice is denoted by $x \in \{x^G, x^B\}$, where x^G and x^B stands for the "Good" and "Bad" outcomes, respectively. Consider a specific transmission path chosen in a VoIP telephone conversation in which there are n supernodes, identified as $i = 1, 2, \ldots, n$, involved in forwarding packets. When any of the supernodes in the transmission path drops voice packets in a time slice, the communication quality in the time slice cannot be maintained at a high level. Therefore, we assume the "Bad" outcome always occurs as long as any of the supernodes chooses low-effort action in forward versus discard. That is,

$$\Pr\left(x^B \middle| \exists i, a_i = 0\right) = 1 - \Pr\left(x^G \middle| \exists i, a_i = 0\right) = 1. \tag{3.1}$$

On the other hand, when all of the supernodes exert high-effort, the probability of good communication quality is a function of the number of supernodes in the transmission path, as follows:

$$\Pr\left(x^G \middle| \forall i, a_i = 1\right) = q(n). \tag{3.2}$$

In other words, even though all supernodes in the P2P network exert high effort in packet forwarding, the communication quality may be bad with probability $1 - q(n)$ due to network uncertainty. As a result, the platform provider cannot directly infer whether one of the supernodes exerts low effort in packet forwarding from the outcome of communication quality. Since transfer speed itself is a function of the aggregate effort of the machines participating in the transfer [41], we assume $q'(n) > 0$ and $q''(n) < 0$ That is, the probability of good communication quality increases with the number of supernodes in the transmission path, but the improvement rate of communication quality is decreasing.

In QoS routing, the "Good" outcome may still happen with a lower probability even if all supernodes in a transmission path exert low-effort action. Formally, the probability of good communication quality is given by

$$\Pr\left(x^G \middle| \forall j \neq i, a_j = 1, a_i\right) = \begin{cases} q(n), & \text{if } a_i = 1 \\ \hat{q}_i(n), & \text{if } a_i = 0 \end{cases} \tag{3.3}$$

where $0 \le \hat{q}_i(n) < q(n)$.

Note that forward versus discard is a special case of QoS routing when $\hat{q}_i(n) = 0$ holds. For analytical convenience, we denote $\hat{q}_i(n)$ as $\hat{q}(n)$ and assume that $q(n)$ and $\hat{q}(n)$ in each time slice are identical. As for the platform provider's profit, the provider can charge access fees from users according to the outcome of communication quality. The benefit of the platform provider from the outcome is denoted by $\lambda(x)$, where $\lambda(x^G) = \lambda_0$ and $\lambda(x^B) = 0$.

3.1 Ex post reward mechanism

An illustration of the time schedule of the ex post reward mechanism is shown in Fig. 2.

The flow of the ex post reward mechanism in a time slice is as follows. First, the platform provider reveals the contract. Since each supernode's action is unobservable, the platform provider can strengthen communication quality by offering a reward contingent on the communication quality, x, as follows:

$$s_i(x) = \left(s_i^B, s_i^G\right),\quad \text{where } s_i^B = s_i(x = x^B) \text{ and } s_i^G = s_i(x = x^G). \tag{3.4}$$

Then, each supernode decides whether to accept the contract. If supernode i accepts the contract, it can choose to exert high effort or low effort. If supernode i rejects the contract or exerts low effort, it can receive the payoff w_i by offering other services at the time slice. Finally, communication quality at the time slice is realized. Each supernode accepting the contract would receive the payment $s_i(x)$ according to the outcome of communication quality. Therefore, we give the following proposition to demonstrate how a platform provider designs an optimal contract to entice all supernodes in the P2P network to choose high-effort action.

Proposition 1 *For the ex post reward mechanism, the following payment schedule can induce a Nash equilibrium in each time slice in which all supernodes exert high-effort.*

$$s_i^G - s_i^B \geq \frac{c_i + w_i}{q(n) - \hat{q}(n)} \text{ and } q(n)s_i^G + (1 - q(n))s_i^B \geq c_i + w_i.$$

Moreover, the optimal contract is given by $s_i^G = \frac{c_i+w_i}{q(n)-\hat{q}(n)}$ *and* $s_i^B = -\frac{\hat{q}(n)}{1-q(n)}s_i^G$.

All proofs can be found in the "Appendix".

The expected payment the supernode i receives is:

$$E[s_i] = c_i + w_i \tag{3.5}$$

In fact, there are multiple combinations of s_i^G and s_i^B which can form cooperating Nash equilibrium and yield the same expected payment given in Eq. 3.5. Here, we illustrate the optimal contract with one of these combinations. If the platform provider can enforce that the supernodes compensate for the "Bad" outcome (i.e., $s_i^B < 0$), the expected payment $E[s_i]$ can be kept at the

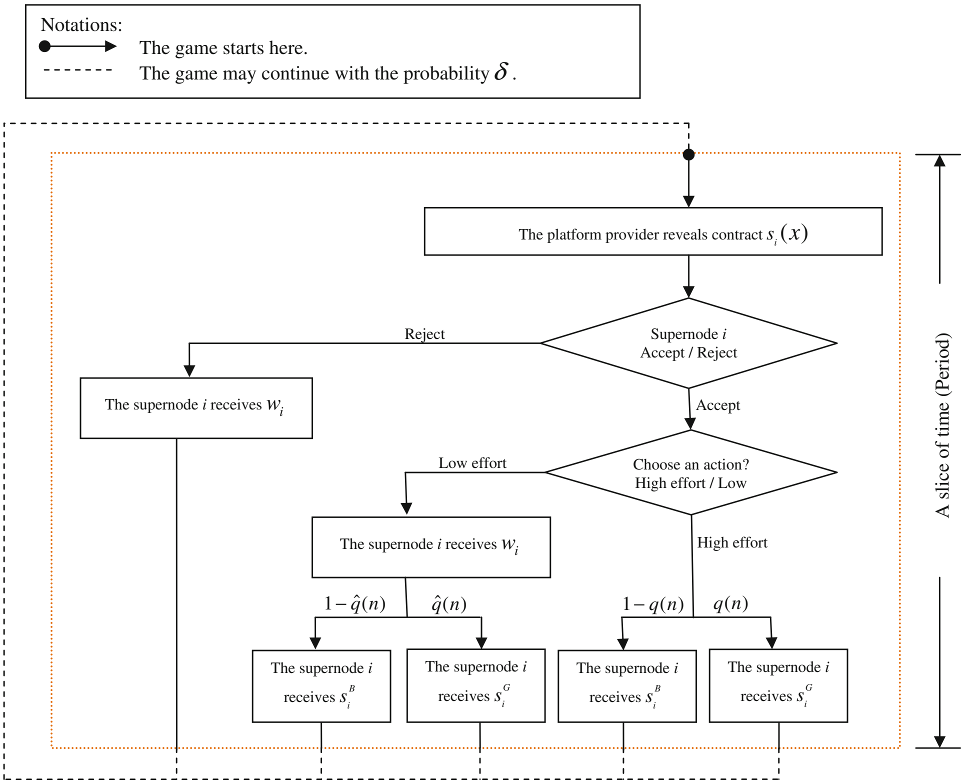

Fig. 2 The supernode i's time schedule in ex post reward mechanism provided that all other supernodes exert high effort in packet forwarding

lowest level. Thus, the ex post reward mechanism can be considered as a benchmark for other reward mechanisms. The proposition shows that cooperation in the P2P VoIP network can arise as long as the expected payment by the platform provider is higher than each supernode's effort cost plus opportunity cost (i.e., $c_i + w_i$). However, in business practice, it may be infeasible for a principal to ask agents to pay compensation for certain reasons at the end of a contract. Therefore, we only consider $s_i^B = 0$ throughout the present study. From the viewpoint of the VoIP platform provider, whether the reward can completely cover the cost of supernodes is one of the key factors in offering high quality VoIP services.

3.2 Ex ante reward mechanism

Actually, the supernodes in the ex post reward mechanism can sign a reward contract contingent on outcome to induce high-effort action. However, it may be difficult for a third party (such as court) to enforce the contract, perhaps because the appropriate measures of output include the quality of output, unexpected difficulties in the conditions of production, and so on [42]. Therefore, in some scenarios, the ex ante reward mechanism could be more suitable than the ex post reward mechanism. The settings of the ex ante reward mechanism are as follows.

Consider the following repeated game in QoS routing. In the ex ante reward mechanism, the term "period" refers to a time slice. The platform provider reveals the contract before the repeated game. If these supernodes accept the contract, the platform provider pays each supernode ρ_i in the first stage. Otherwise, they can never gain any reward in the repeated game. In the second stage, each supernode accepting the contract chooses either high-effort action or low-effort action. If supernode i chooses low-effort action, that is, moral hazard, it can gain payoff w_i by offering other services during the current period. Finally, the communication quality at a slice of time is realized. Since VoIP telephone service is terminated when users finish their conversation, we may assume that the repeated game ends after a random number of repetitions. If the game is still played in the next period (that is, the conversation between two users is continued), the game returns to the first stage. Therefore, in order to prevent charlatanism from exerting low effort, the platform provider requires all supernodes which agree to help relay voice traffic pay a liability F_i in the current period if the communication quality in the previous period is "Bad". Figure 3 shows supernode i 's time schedule of the game provided that all other supernodes exert high-effort in packet forwarding.

As follows, we define $\delta \in (0,1)$ as the probability that the game will be played in the next period (that is, the conversation continues). This defines two strategies for the supernodes to consider: the cooperation strategy and the fraud strategy. The cooperation strategy means each supernode exerts high-effort action in each period, whereas the fraud strategy means one of the supernodes exerts low-effort action in each period, provided all others adopt for the cooperation strategy.

If all supernodes exerted high-effort, then the outcome of communication quality would be "Bad" with the probability $1 - q(n)$, in which case, the platform provider

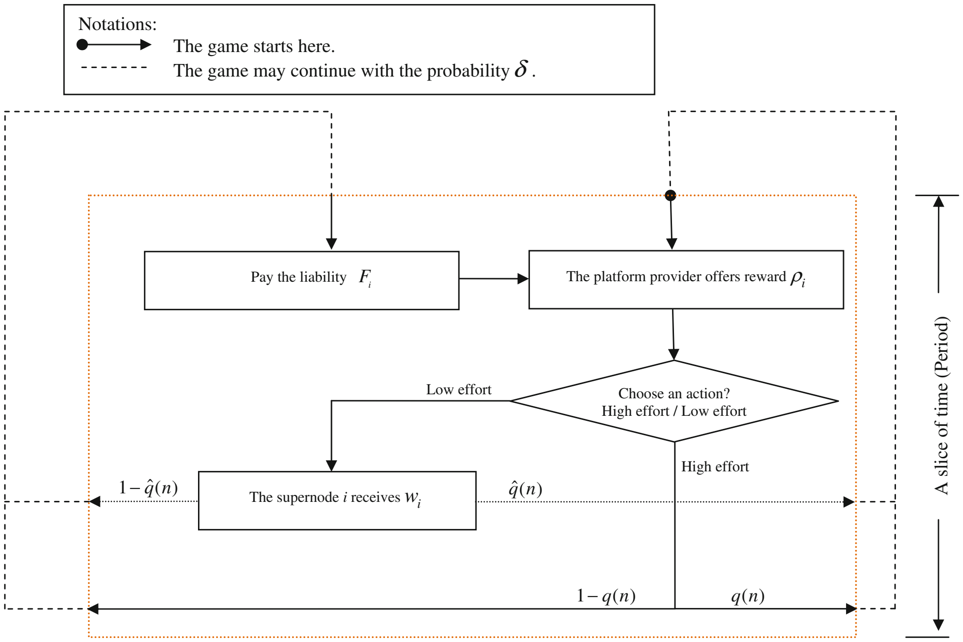

Fig. 3 The supernode i's time schedule in ex ante reward mechanism provided that all other supernodes exert high effort in packet forwarding

could charge liability F_i in the next period. By considering the expected total payment in a conversation, the platform provider's expected payoff during a conversation is given by its expected benefit minus the expected total payment. The platform provider's expected benefit during a conversation is given by

$$\theta \equiv \sum_{t=0}^{\infty} \delta^t \left(\Pr\left(x^G \middle| \forall j, a_j = 1\right) \lambda\left(x^G\right) + \Pr\left(x^B \middle| \forall j, a_j = 1\right) \lambda\left(x^B\right) \right) = \frac{\lambda_0 q(n)}{1-\delta} \tag{3.6}$$

Then, we can set up an optimization model for maximizing the platform provider's expected payoff subject to a supernode's IR (individual rationality constraints) and IC (incentive compatibility constraints) constraints as follows.

$$\begin{array}{ll} \underset{\rho_i, F_i}{\text{Max}} & \theta - \left(\rho_i + \sum\limits_{i=1}^{n} \sum\limits_{t=1}^{\infty} \delta^t \left(\rho_i - \Pr\left(x^B \middle| \forall j, a_j = 1\right) F_i \right) \right) \\ \text{s.t.} & \text{for every period } t \\ (IR) & \Pi_{i,t}^c \geq w_i/(1-\delta) \\ (IC) & \Pi_{i,t}^c \geq \Pi_{i,t}^s \end{array} \tag{3.7}$$

The function of the individual rationality constraints (IR) is to ensure each has incentive to sign the contract, whereas the function of the incentive compatibility constraints (IC) is to prevent opportunistic supernodes from adopting the fraud strategy. In order to keep the number of supernodes fixed in the repeated game, the value of ρ_i is critical because nobody would accept the contract when ρ_i is insufficient. For the individual rationality constraints in Eq. 3.7, because the supernode i's expected payoff $\Pi_{i,t}^c$, where $t \geq 1$, is given by $\Pi_{i,t=0}^c$ or $\Pi_{i,t=0}^c - F_i$, depending on whether the previous outcome is "Good" or "Bad", we can only consider $\Pi_{i,t=0}^c - F_i \geq w_i/(1-\delta)$ in the optimization model.

Theorem 1 *The cooperation strategy is a subgame-perfect Nash equilibrium strategy for the ex ante reward mechanism if the following inequalities hold:*

$$\rho_i \geq (c_i + w_i) + (1 - \delta q(n)) F_i \text{ and } F_i \geq \frac{c_i + w_i}{\delta(q(n) - \hat{q}(n))}.$$

The Theorem shows that to prevent the opportunistic supernodes from exerting low-effort action, the liability must be larger than a specific threshold. Thus, based on sufficient reward and appropriate liability, the VoIP platform provider can offer high quality VoIP service. However, the higher the liability the platform provider charges, the higher the reward it spends in the reward mechanism. In order to decrease the motivation of the supernodes to lower service quality, the liability mechanism is necessary. However, the platform provider can lower the liability to reduce the implementing cost of the reward mechanism.

Next, utilizing Theorem 1, we address the range of liability and analyze the impact of network uncertainty on the ex ante reward mechanism.

Corollary 1 *In the ex ante reward mechanism, the range of liability is given by $\underline{F}_i \leq F_i \leq \bar{F}_i$, where $\underline{F}_i = \frac{c_i + w_i}{\delta(q(n) - \hat{q}(n))}$ and $\bar{F}_i = \frac{\rho_i - c_i - w_i}{1 - \delta q(n)}$.*

When the liability is smaller than $\underline{F}_i$, the supernodes have no incentive to adopt the cooperation strategy in packet forwarding. Instead of cooperating, they would receive the reward and exert low-effort in each period when the liability is less than the threshold. Thus, to entice all supernodes to exert high-effort in the ex ante reward mechanism, the liability should be allocated within the appropriate range. The corollary displays the importance of network quality because the ex ante reward mechanism cannot operate (that is, the liability doesn't exist) when network uncertainty is sufficiently high. On the other hand, because of $\partial \underline{F}_i / \partial \delta < 0$ and $\partial \bar{F}_i / \partial \delta > 0$, longer conversation is beneficial to the mechanism design.

Corollary 2 (1) *The minimal reward and liability in the ex ante reward mechanism are given by $\rho_i^{\min} = (1 - \delta \hat{q}(n)) F_i^{\min}$ and $F_i^{\min} = \frac{c_i + w_i}{\delta(q(n) - \hat{q}(n))}$. Moreover, the minimal reward and liability are optimal for the platform provider.*

(2) *The minimal reward in the ex ante reward mechanism may be less than that in the ex post reward mechanism under certain conditions. Formally, $\rho_i^{\min} \leq s_i^G$ when $(1-\delta)/\delta \leq \hat{q}(n)$.*

The optimal decision of the platform provider in the ex ante reward mechanism is to adopt $\rho_i^{\min}$ and $F_i^{\min}$. In order to deter opportunistic supernodes from exerting low effort, $F_i^{\min}$ is always larger than $\rho_i^{\min}$. The minimal reward $\rho_i^{\min}$ increases with the liability and the effort and opportunity cost of each supernode, but decreases with the expected number of periods and network quality. Because the function of incentive compatibility constraints is to ensure that the payoff of the cooperation strategy is better than the fraud strategy, when the probability the game plays in the next period is sufficiently low or the probability of a "Good" outcome when one exerts low-effort action in packet forwarding is sufficiently high, the platform provider has to offer a relatively high reward to entice all supernodes to adopt the cooperation strategy rather than the fraud strategy. In QoS routing, when $\hat{q}(n)$ is higher than zero so as to affect the amount of rewards, we find that the ex ante reward may be less than the ex post reward as long as the expected number of periods is sufficiently large. On the other hand, in forward versus discard, the ex ante reward is always higher than the ex post reward.

4 Mechanism comparisons and practical implications

In this section, we use the minimal rewards derived from previous sections to examine the expected total payment of the platform provider in the ex post reward mechanism and the ex ante reward mechanism. Here, we assume $\hat{q}(n) = \alpha q(n)$, where $0 \le \alpha < 1$. Since the low-effort and high-effort actions have entirely different meanings in forward versus discard and QoS routing, we define each supernode i's effort cost as $c_i \in \{c_i^F, c_i^Q\}$, where F and Q represent forward versus discard and QoS routing, respectively. In forward versus discard, the platform provider's expected total payment in the ex post reward mechanism is given by

$$P_1 = \sum_{i=1}^{n} \sum_{t=0}^{\infty} \delta^t \left(c_i^F + w_i\right) = \frac{1}{1-\delta} \sum_{i=1}^{n} c_i^F + w_i \tag{4.1}$$

Based on the result of Lemma 2, which can be found in the Appendix, if the platform provider adopts the ex ante reward mechanism in forward versus discard, its expected total payment is given by

$$\begin{aligned} P_2 &= \sum_{i=1}^{n} \frac{\rho_i - (1-q(n))\delta F_i}{1-\delta} \\ &= \left\{ \frac{1}{1-\delta} + \frac{1}{\delta q(n)} \right\} \sum_{i=1}^{n} c_i^F + w_i \end{aligned} \tag{4.2}$$

In QoS routing, the platform provider's expected total payment in the ex post reward mechanism is given by

$$\begin{aligned} P_3 &= \sum_{i=1}^{n} \sum_{t=0}^{\infty} \delta^t \frac{q(n)}{q(n) - \hat{q}(n)} \left(c_i^Q + w_i\right) \\ &= \frac{q(n)}{(q(n) - \hat{q}(n))(1-\delta)} \sum_{i=1}^{n} c_i^Q + w_i \end{aligned} \tag{4.3}$$

If the platform provider adopts the ex ante reward mechanism in QoS routing, its expected total payment is given by

$$\begin{aligned} P_4 &= \sum_{i=1}^{n} \frac{\rho_i - (1-q(n))\delta F_i}{1-\delta} \\ &= \left\{ \frac{1}{1-\delta} + \frac{1}{\delta(q(n) - \hat{q}(n))} \right\} \sum_{i=1}^{n} c_i^Q + w_i \end{aligned} \tag{4.4}$$

4.1 The impact of system parameters

To derive analytical results, we first use a special case where $c_i^F = c_i^Q = c$ and $w_i = w$ to analyze the impact of the number of supernodes and the expected number of periods on the total expected payment, as shown in Table 2. Because the findings in forward versus discard can be derived by incorporating $\alpha = 0$ in QoS routing, we only deal with QoS routing in the following propositions. Then, we utilize normal distribution for the effort cost and opportunity cost of each supernode to graph the impact of the system parameters on the platform provider's expected payoff.

Proposition 2 *When the expected number of periods is small (large), the P2P VoIP platform provider's expected total payment in the ex ante reward mechanism deceases (increases) with the expected number of periods. Formally, the sign of $\partial P_4/\partial \delta$ is the same as that of $J(\delta)$, where*

$J(\delta) \equiv \delta^2(1-\alpha)q(n) - (1-\delta)^2$.

The reason for the above result is given as follows. The parameter δ has two totally different effects on the platform provider's expected total payment. First, because the platform provider has to pay the ex ante reward to each supernode for each period, a negative effect is formed on the expected total payment when the number of periods increases. Second, when the expected number of periods decreases, the platform provider has to raise the amount of rewards to prevent the supernodes from exerting low-effort action. In other words, when the expected number of period increases, the platform provider can offer a lower ex ante reward to each supernode; consequently, a positive effect is formed on the P2P platform provider's expected total payment. Therefore, we have the interesting results associated with δ. If the VoIP platform provider adopts the ex ante reward mechanism, it can then think about how to encourage VoIP users to make longer calls. For example,

Table 2 Impacts of system parameters on platform provider's expected total payment

Routing type	Forward versus discard		QoS routing	
Reward mechanism with respect to	Ex post reward (∂P_1)	Ex ante reward (∂P_2)	Ex post reward (∂P_3)	Ex ante reward (∂P_4)
$\partial \delta$	+	+/−	+	+/−
∂n	+	+/−	+	+/−

+: stands for positive effect

−: stands for negative effect

the VoIP platform provider can give users discounts when the duration of any call exceeds a basic threshold or charge normal rates and a connection fee for any call.

Proposition 3 *Under certain conditions, the P2P VoIP platform provider's expected total payment in the ex ante reward mechanism may decrease with the number of supernodes when n is sufficiently small. Formally,* $\partial^2 P_4 / \partial n^2 > 0$ *if the equation* $\partial P_4 / \partial n = 0$ *holds for n in some cases.*

Intuitively, the platform provider's expected total payment in the ex ante reward mechanism should increase with the number of supernodes. However, when the number of supernodes is sufficiently small and the improvement rate of communication quality is sufficiently high, the platform provider's expected total payment may decrease with the number of supernodes because individual reward decreases with probability $q(n)$. VoIP platform providers adopting the ex ante reward mechanism can consider increasing the number of supernodes in a connection. Although intuition may dictate that allocating a greater number of supernodes in a connection would increase cost, it is possible that this action can reduce the platform provider's cost when the number of supernodes in a connection is rare.

4.1.1 *Numerical results*

In the following numerical experiment, the effort cost and opportunity cost of each supernode are drawn from normal distribution where the mean and standard deviation are given by $N_c(\mu, \sigma) = N_c(200, 50)$ and $N_w(\mu, \sigma) = N_w(300, 50)$, respectively. The numerical results of $\pi_i \equiv \theta - P_i$ are shown in Fig. 4a–d. The other parameters are given by $q(n) = 0.9 - 1 / (100n)^{0.3}$, $\alpha = 0.35$, and $\lambda = 10^5$.

Figure 4a exhibits that the platform provider can develop an optimal recruitment strategy for reward mechanisms. The optimal recruitment strategy would depend on the length of VoIP sessions, network quality, supernode costs, and the difference between high-effort action and low-effort action in VoIP quality. If network quality is excellent or the expected number of periods is large, the ex ante reward mechanism may perform better than the ex post reward mechanism, as shown in Fig. 4b and c. Accordingly, when network quality is poor or most VoIP sessions are very short, the platform provider should consider the ex post reward mechanism rather than the ex ante reward mechanism. Figure 4d shows the impact of low-effort action on the platform provider's expected payoff. The figure points out that the ex ante reward mechanism may be worse than the ex post reward mechanism for the platform provider when α is sufficiently small (e.g., forward versus discard); however, when α is sufficiently large, the opposite holds true. This result can be attributed to the influence of $\hat{q}(n)$ and δ. When the value of $\hat{q}(n)$ increases, the platform provider adopting an ex post reward mechanism has to pay more to entice all supernodes to exert high effort. However, when the value of δ is sufficiently large, the ex ante reward mechanism takes advantage of long-term cooperation because each supernode wishes to receive the reward in all periods, rather than a single period; as a result, compared with the ex post reward mechanism, the platform provider can reduce its payment in the ex ante reward mechanism.

4.2 Optimal number of supernodes

Given a specific reward mechanism and routing type, if the platform provider wants all supernodes to exert high-effort, the optimal number of supernodes in a transmission path is derived from the following equations. Theses equations are given by solving $\partial \pi_i / \partial n = 0$, where $\pi_i = \theta - P_i$ and $i \in \{3, 4\}$.

$$\begin{cases} \frac{\lambda_0 q'\left(n_1^*\right)}{c+w} - \frac{1}{1-\alpha} = 0, & \text{ex post reward mechanism} \\ \frac{\lambda_0 q'\left(n_2^*\right)}{c+w} - \frac{(1-\delta)}{\delta(1-\alpha)} \cdot \frac{q\left(n_2^*\right) - nq'\left(n_2^*\right)}{q\left(n_2^*\right)^2} - 1 = 0, & \text{ex ante reward mechanism} \end{cases} \tag{4.5}$$

Proposition 4 *For the two reward mechanisms, the optimal number of supernodes increases with* λ_0 *but decreases with c, w, and* α*. Moreover, the optimal number of supernodes in the ex ante reward mechanism increases with* δ*.*

The results exhibit that platform providers adopting either reward mechanism have incentive to increase the number of supernodes in a transmission path when their revenue increases or supernodes' costs decrease. If the difference in VoIP quality between high-effort action and low-effort action decreases, the platform provider would reduce the number of supernodes to maximize its payoff. On the other hand, the influence of the expected number of

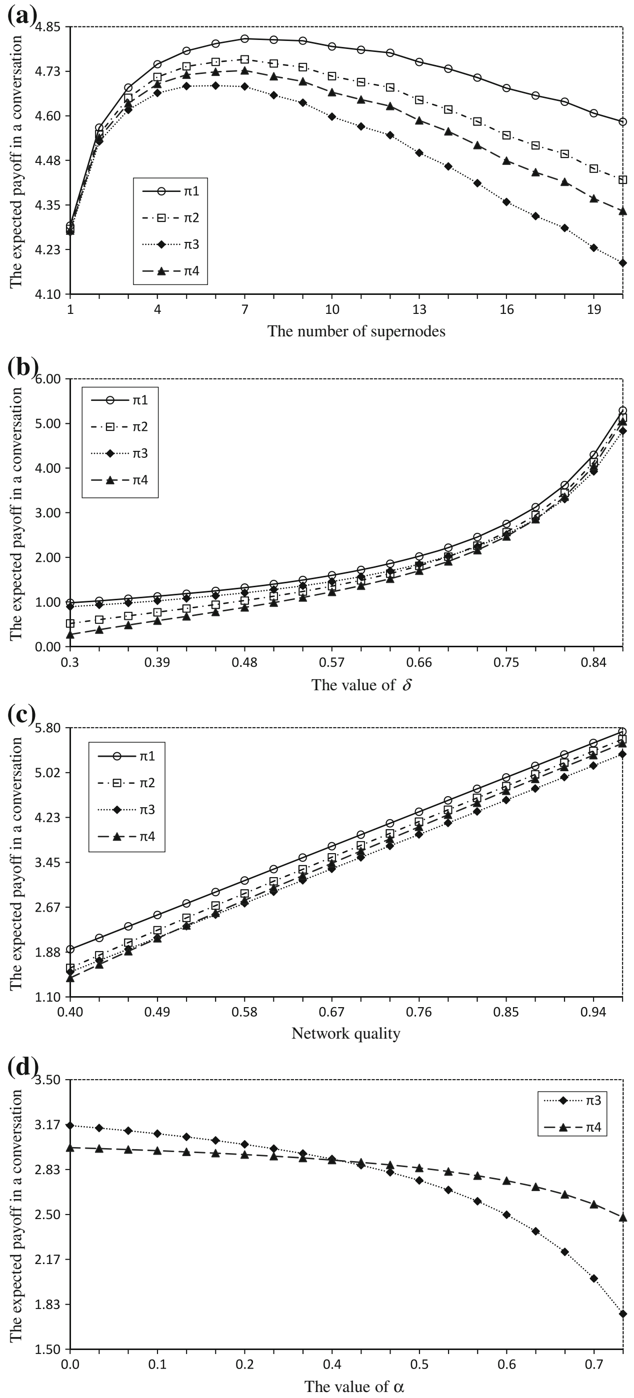

Fig. 4 **a** The platform provider's expected payoff in a conversation ($\delta = 0.85$), **b** The platform provider's expected payoff in a conversation ($n = 20$), **c** The platform provider's expected payoff in a conversation ($n = 20$, $\delta = 0.85$), **d** The platform provider's expected payoff in a conversation ($n = 20$, $\delta = 0.75$, $q(n) = 0.9$)

periods is the only difference between the two reward mechanisms. Although the expected number of periods affects the optimal number of supernodes in the ex ante reward mechanism, it is irrelevant to the optimal number of supernodes in the ex post reward mechanism. For VoIP platform providers adopting the ex ante reward mechanism, increasing the number of supernodes in a connection can enhance the stability of the connection. Thus, VoIP platform providers should differentiate between VoIP users according to their durations of communication. For example, the platform providers can offer users different fares for different durations of communication and allocate corresponding numbers of supernodes in connections according to the chosen fare.

Proposition 5 *When the expected number of periods is sufficiently large (small), the optimal number of supernodes in the ex ante reward mechanism is larger (smaller) than that in the ex post reward mechanism. Formally,* $n_1^* < n_2^*$ *if* $L(n_2^*) < 0$ *and* $n_1^* > n_2^*$ *if* $L(n_2^*) > 0$, *where* $L(n_2^*)$ *is defined by*

$$L(n_2^*) \equiv \frac{q(n_2^*) - nq'(n_2^*)}{q(n_2^*)^2} - \frac{\alpha\delta}{(1-\delta)}.$$

Because the quality of received audio is affected by the number of supernodes in a transmission path, P2P VoIP quality is closely associated with the adoption of a reward mechanism. Given the same number of supernodes, we find that the ex ante reward mechanism can result in better VoIP quality than the ex post reward mechanism as long as these supernodes can provide services for a long period of time. On the contrary, when the expected number of periods is sufficiently small, the opposite holds true. If most of the VoIP sessions are terminated in a short period of time, the platform provider adopting the ex ante reward mechanism has to decrease the number of supernodes in order to compensate for losses in the incentive program due to an increase in reward. Under these circumstances, the platform provider should adopt the ex post reward mechanism instead of the ex ante reward mechanism. VoIP platform providers can decide the number of candidate supernodes based on the type of reward mechanism. For example, when VoIP users prefer to make longer calls, the number of candidate supernodes in the ex ante reward mechanism should be higher than in the ex post reward mechanism.

4.3 Practical implications

In practice, the roles of traditional telephone service providers and P2P VoIP platform providers are incumbent and entrant, respectively. In the work of mechanism design, we offer some useful implications as follows. First, when QoS is of high quality, the most serious challenges faced by telephone service providers stems from Internet telephone. However, although traditional telephone service providers may lose the market for long-distance access, they still makes profits from short-distance access because all Internet calls on P2P VoIP platforms to a PSTN telephone number still require short-distance access. That is, because of the advantage of the first mover as the incumbent, traditional telephone service providers lock in most subscribers throughout the world. Second, the fraction of people who use the platform also affects the platform provider's profit. Therefore, free platform policy has become a useful strategy for platform providers to increase market share.

Third, platform providers can strengthen their voice compression algorithm so as to reduce the impact of network uncertainty on communication quality. Moreover, in the current IPv4 architecture (Internet Protocol version 4), all nodes in the Internet adopt best effort delivery and compete for bandwidth with one another. Therefore, IPv6 architecture, the next generation IP protocol, should be intensively promoted. It has been designed with the QoS mechanism which adds two columns, traffic class and a flow label. Traffic class refers the source that provides congestion control and non-congestion control traffic, whereas the flow label is created to provide real-time applications and special services. Finally, communication quality is strongly affected by the quality of the user's network environment, rather than the quality of the backbone network, especially in P2P VoIP networks. Thus, platform providers may charge different access fees contingent on subscribers' network environments (for example, available bandwidth).

5 Discussion

In this section, we discuss a couple of advanced issues relevant to this study. To begin with, we reconsider the ex ante reward mechanism in which each supernode knows the probability that the conversation will continue into the next period decreases with time. Then, we examine the causes of free-riding for the two reward mechanisms.

5.1 Continuous conversation rate

In this study, we assume that the probability of the conversation continuing into the next period is given by δ, no matter how long the conversation has already lasted. In fact, the longer a conversation continues the lesser the likelihood of it continuing into future periods. Accordingly, in this section, we substitute $\delta(t)$ for δ and examine whether novel outcomes result in the ex ante reward mechanism as time increases. Formally, $\delta(t)$ is defined by

$$\delta(t) \equiv \Pr(\text{the } t \text{ period would arrive} \mid \textit{the } t-1 \text{ period has arrived}) \tag{5.1}$$

Based on the above consideration, the features of $\delta(t)$ are given by $\partial\delta(t)/\partial t < 0$.

Proposition 6 *If the probability that the conversation continues into the next period decreases with time, the incentive for supernodes to cheat will increase with time.*

With Proposition 6, we find that moral hazard arises when the probability that the game will be played in the next period decreases with time. In other words, these supernodes make less effort to avoid disconnection when the time t is sufficiently large. From the point of view of the platform provider, one solution is to design a dynamic reward mechanism in which the ex ante reward increases with time to encourage the supernodes to exert high effort. However, a better solution to avoid moral hazard is to keep a stable and sufficiently high δ. This can be achieved by appointing these supernodes to serve respective local area networks, rather than a specific connection. That is, once a VoIP connection request arrives, the supernodes can help relay VoIP packets as long as the VoIP packets pass the local area networks they reside in. In addition, the results also highlight that the ex post reward mechanism can overcome the weakness of δ since the ex post reward mechanism is irrelevant to δ. So far, we have focused on how to encourage each supernode to exert high-effort in a given session. Subsequently, we will further discuss whether there are other equilibria in which some supernodes choose to cooperate and others do not.

5.2 Free-riding problem

In the two reward mechanisms, it is possible that some supernodes choose to free ride on others exerting high effort. Thus, we define the probability of good communication quality by $q(n,k)$ where there are k supernodes exerting high effort. For example, $q(n)$ and $\hat{q}(n)$, the notations used in previous sections, can be described as $q(n,n)$ and $q(n,n-1)$, respectively. The following proposition addresses the conditions in which the free-riding problem may occur in the reward mechanisms.

Proposition 7 *Multiple equilibria exist in the two reward mechanisms as follows:*

(1) *The pure equilibria in the ex post reward mechanism are given by*

$$\begin{cases} \text{all supernodes cooperate,} & \text{if } \frac{c_i+w_i}{q(n,n)-q(n,n-1)} \leq s_i^G \\ k \text{ supernodes cooperate,} & \text{if } \frac{c_i+w_i}{q(n,k)-q(n,k-1)} \leq s_i^G \leq \frac{c_i+w_i}{q(n,k+1)-q(n,k)} \\ \text{no supernodes cooperate,} & \text{if } s_i^G \leq \frac{c_i+w_i}{q(n,1)-q(n,0)} \end{cases}$$

where $s_i^B = 0$.

(2) *The pure equilibria in the ex ante reward mechanism are given by*

$$\begin{cases} \textit{all supernodes cooperate}, & \textit{if } \frac{c_i+w_i}{\delta(q(n,n)-q(n,n-1))} \le F_i \\ \textit{k supernodes cooperate}, & \textit{if } \frac{c_i+w_i}{\delta(q(n,k)-q(n,k-1))} \le F_i \le \frac{c_i+w_i}{\delta(q(n,k+1)-q(n,k))} \\ \textit{no supernodes cooperate}, & \textit{if } F_i \le \frac{c_i+w_i}{\delta(q(n,1)-q(n,0))} \end{cases}$$

where if $k \geq 1$ *and* $\rho_i \geq (1 - \delta q(n,0))F_i$ *if* $k = 0$.

We find that the free-riding problem in the ex post reward mechanism may occur when the platform provider offers insufficient rewards. On the other hand, the problem may also occur in the ex ante reward mechanism when the platform provider sets up inappropriate liabilities. Notice that the function of the ex ante reward is to ensure that each supernode has incentive to sign the contract, rather than exert high effort. Consequently, when the platform provider sets up inappropriate liabilities, the free-riding problem still occurs even if the amount of rewards for “Good” outcome is raised. From the viewpoint of the supernodes exerting high effort, it is unfair that some supernodes can gain the reward without any effort. From the viewpoint of the platform provider or VoIP users, P2P VoIP quality would be degraded if some supernodes in transmission paths only exerted low effort. Therefore, in order to conquer the negative effects resulting from the free-riding problem, the platform provider has to raise the amount of rewards if it adopts the ex post reward mechanism and set a higher level of liability if it adopts the ex ante reward mechanism.

6 Conclusion

This study develops ex post and ex ante reward mechanisms to overcome the hidden-action problem existing in P2P VoIP networks, in which the supernodes can choose to forward packets or discard packets. Both reward mechanisms can solve the hidden-action problem in P2P VoIP networks in which a group of supernodes help relay voice traffic. Subsequently, we extend the model into a QoS setting in which the supernodes can choose between offering low-quality service (allocating low bandwidth) and high-quality service (allocating high bandwidth). We find the ex post reward mechanism is better than the ex ante reward mechanism in forward versus discard; however, when the expected number of periods is sufficiently large, the opposite holds true in QoS routing. The results show that the ex ante reward mechanism can take advantage of long-term cooperation to get rid of the effect of network uncertainty. To run the reward mechanisms smoothly, the platform provider should select qualified supernodes with sufficient and spare bandwidths because the success of the reward mechanism depends on network quality and the effort cost and opportunity cost of the supernodes. In addition, our study considers the reward mechanisms and the benefit to the platform provider to find the optimal number of supernodes in a transmission path.

Research on P2P VoIP networks has been mainly experimental or empirical. Our study adds to this stream by analyzing a pivotal, but rarely addressed issue. That is, how to develop suitable reward mechanisms for P2P VoIP networks. The analysis in this study is based on a simplified model of P2P VoIP networks. However, the model captures important characteristics of P2P VoIP networks including network uncertainty, the length of communication, supernodes’ effort costs, packet forwarding, and bandwidth allocation. The context of this study could serve as a foundation on which further analysis of reward mechanisms in P2P VoIP networks can be undertaken. For example, the simulation with topology and data set description can actually be implemented to better understand the applicability of reward mechanisms. On the other hand, several problems remain to be solved by future research. First, in this study, we assume the effort costs and opportunity costs of the supernodes are common knowledge; therefore, the results derived from the reward mechanisms can be further refined as a perfect Bayesian equilibrium. Second, more research is required on how reward mechanisms could be integrated in real networks. In addition, a type revelation problem exists in which each supernode honestly reports individual type (for example, effort cost) to induce a Nash equilibrium. Finally, given the benefit of platform providers and network topology, the model can be extended to study optimal sets of supernodes to be contracted.

Appendix

Proposition 1

Proof We first assume all exert high-effort except the supernode i. For simplicity, we define R_H and R_L as follows.

$$\begin{aligned} R_H &\equiv \Pr\left(x^G \middle| \forall j, a_j = 1\right) s_i^G + \left(1 - \Pr\left(x^G \middle| \forall j, a_j = 1\right)\right) s_i^B - c_i \\ R_L &\equiv \Pr\left(x^G \middle| \forall j \neq i, a_j = 1, a_i = 0\right) s_i^G \\ &\quad + \left(1 - \Pr\left(x^G \middle| \forall j \neq i, a_j = 1, a_i = 0\right)\right) s_i^B + w_i \end{aligned}$$

Obviously, when $R_H \geq R_L$ and $R_H \geq w_i$ hold, we have the cooperating Nash equilibrium. Moreover, because $q(n)s_i^G + (1 - q(n))s_i^B$ is the expected payment by the platform provider, solving $R_H = w_i$ yields the optimal contract.

Lemma 1 *When all supernodes exert high-effort in each period (that is, the cooperation strategy), the expected value of each supernode i's payoff is given by* $\Pi_{i,t=0}^c = \frac{\rho_i - c_i - \delta(1-q(n))F_i}{1-\delta}$. *Moreover, if the supernode i adopts the fraud strategy, its expected payoff is given by* $\Pi_{i,t=0}^s = \frac{\rho_i + w_i - \delta(1-\hat{q}(n))F_i}{1-\delta}$.

Proof Because the liability resulting from bad communication quality at the current period is paid in the next period, the expected value of each supernode's payoff is: $\Pi_{i,t=0}^c = (\rho_i - c_i) + \delta\left(\Pi_{i,t=0}^c - (1 - q(n))F_i\right) = \frac{\rho_i - c_i - \delta(1-q(n))F_i}{1-\delta}$.

If the supernode i adopting the fraud strategy is willing to pay the liability, its payoff is given by$\Pi_{i,t=0}^s = (\rho_i + w_i) + \delta\left(\Pi_{i,t=0}^s - (1 - \hat{q}(n))F_i\right) = \frac{\rho_i + w_i - \delta(1-\hat{q}(n))F_i}{1-\delta}$.

Lemma 2 *When all supernodes adopt the cooperation strategy, the platform provider's expected payment to the supernode i in the ex ante reward mechanism is given by* $\frac{\rho_i - \delta(1-q(n))F_i}{1-\delta}$.

Proof In the ex ante reward mechanism, the platform provider has to pay the reward ρ_i to the supernode i in each period. In addition, it may receive the liability from the supernode i with the probability $\Pr\left(x^B \middle| \forall j, a_j = 1\right)$. Therefore, its expected payment to the supernode i is given by$\rho_i + \sum_{t=1}^{\infty} \delta^t \left(\rho_i - \Pr\left(x^B \middle| \forall j, a_j = 1\right)F_i\right) = \frac{\rho_i - \Pr\left(x^B \middle| \forall j, a_j = 1\right)\delta F_i}{1-\delta}$.

Lemma 3 *When* $\rho_i \geq (c_i + w_i) + (1 - \delta q(n))F_i$ *holds, the supernode i adopting the cooperation strategy is willing to pay the liability.*

Proof If the supernode i rejects the contract, its reserved payoff is given by $w_i/(1-\delta)$. Therefore, if $\Pi_{i,t=0}^c - F_i \geq w_i/(1-\delta)$ holds, the supernode adopting the cooperation strategy is willing to pay the liability in all periods. That is,

$$\begin{aligned} &\Pi_{i,t=0}^c - F_i \geq w_i/(1-\delta) \Rightarrow \Pi_{i,t}^c \geq w_i/(1-\delta), \\ &\quad \forall t \Rightarrow \rho_i \geq (c_i + w_i) + (1 - \delta q(n))F_i. \end{aligned}$$

Theorem 1

Proof Theorem 1 is based on lemma 1 and lemma 3. Because of the constraint $\rho_i \geq (c_i + w_i) + (1 - \delta q(n))F_i$, the supernode adopting the cooperation strategy would pay the liability in the game and any of the subgames. The following inequalities ensure the payoff of the cooperating strategy is better than the fraud strategy.

$$\begin{aligned} \Pi_{i,t=0}^c \geq \Pi_{i,t=0}^s &\Rightarrow \Pi_{i,t}^c \geq \Pi_{i,t}^s, \forall t \\ &\Rightarrow \frac{\rho_i - c_i - \delta(1 - q(n))F_i}{1-\delta} \\ &\geq \frac{\rho_i + w_i - \delta(1 - \hat{q}(n))F_i}{1-\delta} \\ &\Rightarrow F_i \geq \frac{c_i + w_i}{\delta(q(n) - \hat{q}(n))} \end{aligned} \tag{A.1}$$

Corollary 1

Proof The relation between $\underline{F}_i$ and F_i is derived from Eq. A.1 in the proof of Theorem 1, whereas the relation between $\bar{F}_i$ and F_i is derived from Lemma 3.

Corollary 2

Proof To begin with, we can easily derive $\rho_i^{\min}$ and $F_i^{\min}$ from Theorem 1. Obviously, $\rho_i^{\min} < F_i^{\min}$. Moreover, the platform provider's expected payment in Lemma 2 implies that $\rho_i^{\min}$ and $F_i^{\min}$ are the optimal solution for the platform provider. The reason is as follows. First, from Eq. A.1 we know that the value of F_i cannot be affected by ρ_i; thus, we only consider $\rho_i^{\min}$. Second, plugging $\rho_i^{\min}$ into the platform provider's expected payment, we find that the platform provider's expected payment is given by

$$\frac{\rho_i^{\min} - (1 - q(n))\delta F_i}{1-\delta} = \frac{(c_i + w_i) + (1-\delta)F_i}{1-\delta}.$$

Obviously, $\rho_i^{\min}$ and $F_i^{\min}$ are the optimal solution for the platform provider. Finally, comparing $\rho_i^{\min}$ with s_i^G, we have the following result.

$$\begin{aligned} \rho_i^{\min} \leq s_i^G &\Rightarrow \frac{(1 - \delta\hat{q}(n))(c_i + w_i)}{\delta(q(n) - \hat{q}(n))} \leq \frac{c_i + w_i}{q(n) - \hat{q}(n)} \\ &\Rightarrow (1-\delta)/\delta \leq \hat{q}(n) \end{aligned}$$

Proposition 2

Proof Because $\partial^2 P_4/\partial\delta^2 > 0$, we can figure out the minimal value of P_4 by solving $\partial P_4/\partial\delta = 0$. Because $\partial P_4/\partial\delta = 0$ implies $\frac{1}{(1-\delta)^2} - \frac{1}{\delta^2(1-\alpha)q(n)} = 0$, we can define $J(\delta)$ by $\delta^2(1-\alpha)q(n) - (1-\delta)^2$

Proposition 3

Proof The equation $\partial P_4/\partial n = 0$ implies $q(n) - nq'(n) \leq 0$. If $\partial P_4/\partial n = 0$ holds for some n, we have $\partial^2 P_4/\partial n^2 > 0$ due to $q(n) - nq'(n) \leq 0$.

Proposition 4

Proof We can confirm $\lambda_0 q(n_2^*)/n > c + w$. Otherwise, the platform provider's expected payoff wouldn't be positive (i.e., $\pi_4 < 0$). Subsequently, we claim $q(n_2^*) - nq'(n_2^*) > 0$. Suppose not, we can induce a contrary conclusion by the following inequalities.

$$\because \lambda_0 q'(n_2^*) - \frac{(c+w)(1-\delta)}{\delta(1-\alpha)} \cdot \frac{q(n_2^*) - nq'(n_2^*)}{q(n_2^*)^2} - (c+w) = 0$$

$$\therefore \lambda_0 q'(n_2^*) - (c+w) < 0 \Rightarrow \lambda_0 q(n_2^*)/n < c+w$$

Based on the above result, we can straightforwardly observe the impact of the system parameters on the platform provider's expected payoff.

Proposition 5

Proof First, $\frac{\partial \pi_4}{\partial n}\Big|_{n=n_2^*} = 0$ implies $\frac{\lambda_0 q'(n_2^*)}{c+w} = \frac{(1-\delta)}{\delta(1-\alpha)} \cdot \frac{q(n_2^*) - nq'(n_2^*)}{q(n_2^*)^2} + 1$. Considering $\frac{\partial \pi_3}{\partial n}\Big|_{n=n_2^*}$, we find that the sign of $\frac{\partial \pi_3}{\partial n}\Big|_{n=n_2^*}$ is the same as that of $\frac{q(n_2^*) - nq'(n_2^*)}{q(n_2^*)^2} - \frac{\alpha\delta}{(1-\delta)}$. Because $q(n_2^*) - nq'(n_2^*) > 0$ has been shown in Proposition 4, we can easily confirm $\frac{\partial \pi_3}{\partial n}\Big|_{n=n_2^*} > 0$ when δ approaches zero and $\frac{\partial \pi_3}{\partial n}\Big|_{n=n_2^*} < 0$ when δ approaches one. Because π_3 is a concave function of n, we have $n_1^* > n_2^*$ if $\frac{\partial \pi_3}{\partial n}\Big|_{n=n_2^*} > 0$ and $n_1^* < n_2^*$ if $\frac{\partial \pi_3}{\partial n}\Big|_{n=n_2^*} < 0$.

Proposition 6

Proof We define $\phi(t)$ by $\phi(t) \equiv \sum_{i=t}^{\infty} \prod_{j=t}^{i} \delta(j)$ where $t \geq 1$. In period $t - 1$, the difference between the expected payoffs results from the cooperation strategy and the fraud strategy is given by $\Pi_i^c - \Pi_i^s = \phi(t)((q(n) - \hat{q}(n))F_i - (c_i + w_i)) - (c_i + w_i)$. Obviously, the difference decreases with t. That is, the incentive for supernodes to cheat increases with time.

Proposition 7

Proof Because we have shown the case in which each supernode exerts high effort in the two reward mechanisms, in the following, we only consider partial cooperation and the case in which each supernode exerts low effort. In the ex post reward mechanism, we define the expected payoffs of exerting high effort and low effort by $R^c(n,k)$ and $R^s(n,k)$, given k supernodes exerting high effort. The condition in which there are k supernodes exerting high effort is:

$$R^c(n,k) \geq R^s(n,k-1) \Rightarrow s_i^G \geq \frac{c_i + w_i}{q(n,k) - q(n,k-1)}$$

$$R^s(n,k) \geq R^c(n,k+1) \Rightarrow \frac{c_i + w_i}{q(n,k+1) - q(n,k)} \geq s_i^G$$

The condition in which each supernode exerts low effort is given by

$$R^s(n,0) \geq R^c(n,1) \Rightarrow \frac{c_i + w_i}{q(n,1) - q(n,0)} \geq s_i^G$$

In the ex ante reward mechanism, we define the expected payoffs of exerting high effort and low effort by $\Pi_i^c(n,k)$ and $\Pi_i^s(n,k)$, given k supernodes exerting high effort. The condition in which there are k supernodes exerting high effort is:

$$\Pi_i^c(n,k) \geq \Pi_i^s(n,k-1) \Rightarrow F_i \geq \frac{c_i + w_i}{\delta(q(n,k) - q(n,k-1))}$$

$$\Pi_i^s(n,k) \geq \Pi_i^c(n,k+1) \Rightarrow \frac{c_i + w_i}{\delta(q(n,k+1) - q(n,k))} \geq F_i$$

$$\Pi_i^c(n,k) - F_i \geq \frac{w_i}{1-\delta} \Rightarrow \rho_i \geq (c_i + w_i) + (1 - \delta q(n,k))F_i$$

$$\Pi_i^s(n,k) - F_i \geq \frac{w_i}{1-\delta} \Rightarrow \rho_i \geq (1 - \delta q(n,k))F_i$$

Obviously, regarding the bound of ρ_i, we only need $\rho_i \geq (c_i + w_i) + (1 - \delta q(n,k))F_i$. Moreover, the condition in which each supernode exerts low effort is given by

$$\Pi_i^s(n,0) \geq \Pi_i^c(n,1) \Rightarrow \frac{c_i + w_i}{\delta(q(n,1) - q(n,0))} \geq F_i$$

$$\Pi_i^s - F_i \geq \frac{w_i}{1-\delta} \Rightarrow \rho_i \geq (1 - \delta q(n,0))F_i$$

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