Abstract—In this paper, we provide a comprehensive treatment of QoS guarantee for mobile streaming applications through a contract-ruled approach. We envision a peer-to-peer streaming system as a QoS trading market, where the involved parties, Services Provider (SP), End User (EU) and assisting peers, are all real economic entities that are organized with contractual constraints for achieving a stable and guaranteed QoS output. The QoS trading in the market is classified into two parts, a basic contract that establishes the business agreement between an interested EU and a SP and a subcontract that achieves a desired joint QoS output. The proposed scheme can benefit all parties.

I. INTRODUCTION

The increasing demand for mobile streaming services calls for efficient QoS technologies. A promising solution is to introduce peer-to-peer (P2P) technologies into current infrastructure to improve the service quality, where the peers close to an End User (EU) can assist a Service Provider (SP) to provide services in a fashion of P2P mode, namely peer-assisted mode. A typical application scenario is that, in an airport lounge, a passenger can watch some popular programs provided by SP, which are actually hosted by some potential passengers nearby through Wi-Fi communications. The popularity of mobile devices capable of accessing to multiple wireless networks, e.g., 3G and Wi-Fi, opens up the possibility of providing such services. However, typical mechanisms taken for the QoS performance in P2P networks are not adequate for wireless networks. EUs in such networks tend to keep stationary within an hour while the nearby peers that can provide peer-assisted services are limited. Moreover, due to the limits of computation and battery capabilities of handhelds, mobile users likely decline to participate such peer-assisted services. Thus, it is important to develop a pertinent mechanism for to enable an effective QoS while allowing all participants to benefit from mobile P2P streaming (P2PS) services significantly.

In this paper, we propose a comprehensive framework for QoS guarantee in mobile P2P scenarios through a contract-ruled approach. The contract theory, also known as principal-agent theory, regulates the activities between a principal and an agent, where the agent has to fulfill the obligations specified in the contract, and in return it will receive some remuneration from the principal. We envision a mobile P2PS system as a QoS trading system as a QoS trading market, where the commodity traded is the available bandwidth as it has the dominant impact on the EU’s valuation of the QoS. We organize the involved parties, SP, EUs and assisting peers, with contractual constraints and classify the QoS trading in the market into two parts (as shown in Fig. 1(a)): One is a basic contract that establishes the business agreement between an interested EU and a SP, where the EU acts as a principal and the SP is an agent. The basic contract specifies the corresponding QoS requirements of the EU for a given service price. The other is a subcontract that models the transactions between the SP and assisting peers, where the SP acts as a principal and the assisting peers are agents, respectively. The contract theory is appropriate for providing mobile streaming services since it can efficiently regulate the roaming peers in the context of contracts to fulfill contractual obligations, as well as motivate peers’ self-interests in participating in the provision of peer-assisted services.

A realization for mobile P2PS services is exhibited in Fig. 1(b): Consider a service region where 3G and Wi-Fi accesses are both available for EUs. Generally, streaming services provided through Wi-Fi are more stable and economical than 3G. SP prefers to employ assisting peers to provide mobile streaming services through Wi-Fi, for the reason of enhancing programs’ QoS and reducing operating cost. An interested EU sends a program request to SP along with its bandwidth requirement. On receiving the request, SP calculates the needed bandwidth resource and selects proper assisting peers from the candidate peers within EU’s Wi-Fi coverage using a sealed bid auction. The assisting peers start to provide the agreed joint QoS to the EU after signing a subcontract with SP. In exchange, they will get compensation to subsidize their dissipative power and bandwidth costs. Here,
the candidate peers refer to the peers that have reserved the cache (e.g., peers have ever watched the requested program) and are willing to get payoff from providing their resources.

II. Basic QoS Contract

A. Economic Model for Basic Contract

Consider a mobile P2P network with \( n \) mobile peers and a SP, which make their decisions merely on the basis of expected utility and price. Each mobile peer can either be an EU, which entertains programs provided by the SP, or an assisting peer, who can get payoff from contributing its idle resource in the peer-assisted mode. The SP provides the EU some mobile streaming services with QoS guarantee, which is promised by a basic contract. According to the contract, the EU pays for the streaming services and in return it will be served with a contractual QoS. The contract mainly consists of three components: 1) a performance component that specifies the agreed QoS metric, i.e., the bandwidth that the SP promises to provide; 2) a payment component that specifies the payment of EU; 3) a time component which defines the effective time of the contract.

In this basic contract, the SP earns revenue by providing QoS-promised mobile P2PS services. However, there is inherent uncertainty in the mobile P2PS services due to many factors, such as unexpected disturbance in the transmission process, the lack of efficient assisting-peers management. Such uncertainty has negative business effects on EUs since EUs may get different failure rate estimations. We denote that EU independently estimate about the performance of the QoS, they will be compensated certain money rebate when the delivered QoS. The service with unsatisfied quality will lead to a reduced trade probability between the SP and EUs. To mitigate the EU’s concerns about QoS uncertainty, we apply a QoS contingent price tariff with money rebate [1]. For example, the SP promises a QoS level. EUs monitor their long-term QoS and will be compensated certain money rebate when the actual performance is below the promised level.

Assume the SP adopts the QoS contingent price tariff with a constant rebate, thus the basic contract can also be considered as a QoS contingent contract. The SP announces a price \( P \) associated with the promised QoS level. The final price paid by the EU is contingent, which depends on the realized QoS level. For instance, if the SP and EU have reached an agreement on a standard bandwidth level \( B \), the EU will receive a rebate \( r \in [0, P] \) when the actual bandwidth \( B \) the EU receives falls below the promised bandwidth level \( B \). The committed QoS level is judged by statistical QoS guarantees. This can be achieved by dividing the entire effective time of the contract into many timeslots; in each timeslot, the EU monitors whether its QoS level is below the contractual QoS level; at the end of the contract’s life, a failure rate can be calculated. A contingent contract becomes uncommitted if the actual failure rate the EU incurs is greater than a given threshold, and the EU will receive a rebate. Since EU and SP independently estimate about the performance of the QoS, they may get different failure rate estimations. We denote that EU (and SP) has a failure rate estimation \( \mu \) (and \( \theta \)) respectively.

Therefore, the contingent price structure for EU and SP can be mathematically formulated as \( P_{EU} = P - \mu r \) and \( P_{SP} = P - \theta r \).

The SP has to undertake a constant cost \( C \) for providing the mobile P2PS services, and if the SP fails to deliver the promised bandwidth level, an additional cost \( c \) incurs due to the failure handling process, i.e., some extra processes are required in managing the failure of the QoS task. Thus, the cost of the SP can be described as \( C_{SP} = C + \theta c \).

Thus, SP’s expected revenue function can be expressed as:

\[
R_{SP} = (P - \theta r) - (C + \theta c).
\]

EUs are heterogeneous in their valuations of the services. We assume that the EU’s valuation is a random variable \( v \) that distributes uniformly in \([0, 1]\). We assume the EU with valuation \( v \) will receive a positive utility \( U(v) \) when the delivered service meets the promised quality level; Otherwise, it will suffer additional negative utility \( L(v) \). Thus, the expected utility of the EU is \( U_{EU} = U(v) - \mu L(v) \).

It is reasonable to assume that both \( U(v) \) and \( L(v) \) increase when \( v \) increases, which implies that the EU with a higher valuation incurs proportionately a higher positive utility (or negative utility) when the promised QoS level is met (or missed). For simplicity of exposition, we use linear functions for both positive and negative utilities, i.e., \( U(v) = v \) and \( L(v) = q v \) throughout this paper, where \( q \in (0, 1) \) is a coefficient. The EU can estimate its expected revenue as:

\[
R_{EU} = (1 - q \mu)v - (P - \mu r).
\]

The benefits of applying the contingent contract for SP is summarized as the following proposition:

**Proposition 1:** The QoS contingent contract is able to attract more EUs to subscribe mobile P2PS services comparing with the single price contract, when EUs underestimate the SP’s QoS.

B. Optimal Basic Contract Payment Scheme

Given the revenue functions of EU and SP, we can study the strategic interaction between two parties: EUs and SP. In the context of the QoS contingent contract, we consider the EUs of the entire network as a single party. In what follows, the singular term “EUS” refers to all EUs of the entire network.

The QoS contingent contract is naturally a two-stage of Stackelberg game [2], where in the first stage, SP acts as a leader by setting the price \( P \) and the rebate \( r \), and the EUS acts as a follower to determine the service demand. Let \( D(P, r) \) denote the demand function of EUS, which characterizes the changing of the EUS’ service demand in face of the SP’s price changing. Following the market discipline, the increasing price will force certain EUs with low valuation to quit services and result in the decreasing service demand, and vice versa. SP can choose its optimal price to maximize its revenue by estimating EUS’ demand function. We can derive the Sub-game Perfect Equilibrium (SPE) of the Stackelberg game by applying the concept of the backward induction: Firstly, in the second stage, for the given price \( P \) and the rebate \( r \), EUS determines its service demand. Then back in the first stage, SP, acting as the leader of the Stackelberg game, is aware of the demand function \( D(P, r) \) of EUS and seeks to choose its optimal price.
\(P^*\) and \(r^*\) to maximize its revenue. The EUS’ demand function is depicted in Lemma 1.

**Lemma 1:** The EUS’ demand function, i.e., the fraction of EUS which has the willingness to subscribe the services is
\[
D(P, r) = 1 - v_m = 1 - \frac{P - \mu r}{1 - \phi \mu}.
\]

Given the demand function of EU, the problem for SP is how to carefully set the price so as to maximize its revenue. The SP’s expected revenue under the contingent contract is
\[
R_{SP} = (P - \theta r - C - \theta c) \cdot D(P, r).
\]

The optimal contingent contract provided by SP that achieves its maximal revenue should satisfy
\[
(P^*, r^*) \in \arg \max_{P^*} (P - \theta r - C - \theta c) \cdot D(P, r).
\]

By solving the above problem, we can obtain the SPE of the QoS contingent contract, which contains two possible optimal price schemes when the information about the QoS is asymmetric, i.e., \(\mu \neq \theta\). The result is depicted in Lemma 2.

**Lemma 2:** The SPE of the QoS contingent contract contains two possible optimal price schemes: contingent price with full rebate \((r = P^*)\)
\[
P^* = \frac{1}{2} \left( \frac{1 - \phi \mu}{1 - \mu} + \frac{C + \theta c}{1 - \theta} \right)
\]
or single price without rebate \((r = 0)\)
\[
P^* = \frac{1}{2} \left[ 1 - \phi \mu + (C + \theta c) \right].
\]

From Lemma 2, we show that SP has two possible optimal contracts at the equilibrium state. The following proposition states the conditions when SP chooses the corresponding optimal contract:

**Proposition 2:** SP will prefer to offer a contingent contract when EUS underestimate the performance of services, i.e., \(\mu > \theta\), otherwise SP will prefer to offer a single price contract.

We can see that the SP’s private information about its QoS plays a crucial role in making contingent payment attractive, and the value of contingent payment increases when SP is more confident of the QoS, relative to EUS. Since the mobile P2PS service is a new technology, EUS may be unfamiliar with it. There may exist significant gap in belief of QoS between SP and EUS, the contingent payment can serve as an effective signaling mechanism for new entrants.

**C. Pareto Improvement in Basic Contract**

Though we have obtained the equilibrium price \(P^*\) of the basic contract, we can verify that it is not the price of Pareto efficient, i.e., SP non-cooperatively maximizing its own revenue will result in corresponding loss of EUS’ welfare. In fact, if SP makes some compromise, i.e., SP decreases price and EUS expands its service demand, they may both derive better revenues. We aim to optimize the basic contract such that the system consisting of the EU and SP can achieve Pareto efficiency. Considering the revenue function of a single EU with valuation \(v\) in Eq. 2, the total revenue of EUS is represented as
\[
R_{EUS} = \int_{v_m}^v [(1 - \phi \mu)v - (P - \mu r)]dv,
\]

where \(v_m\) is the marginal valuation that any EU with the valuation below \(v_m\) will choose to quit the system.

Let \(Z = 1 - v_m\) denote the service demand of EUS, Eq. 8 can be further reduced to
\[
R_{EUS} = (1 - \phi \mu)(2 - Z)Z - (P - \mu r)Z.
\]

Accordingly, the revenue of SP can also be rewritten as
\[
R_{SP} = (P - \theta r)Z - (C + \theta c)Z.
\]

In Eq. 9, the first item \((1 - \phi \mu)(2 - Z)Z\) is the utility that the EUS gets from the service demand \(Z\), the second item \((P - \mu r)Z\) is the total payment from the fraction \(Z\). Essentially, the payment \((P - \theta r)Z\) and \((P - \mu r)Z\) only serve to allocate the total revenue between the EUS and SP. We may find an optimal basic contract that maximizes the total revenue through a bargain process, i.e., SP sets the services’ price to maximize its revenue, EUS bargains with SP by varying its service demand. We can use the Nash Bargain Solution (NBS) [3] to get a Pareto efficient contract. Mathematically, we seek the optimal strategy profile \(\{P^*, Z^*\}\) by solving the following problem
\[
\max_{P^* \in SP} R_{EUS} \cdot R_{SP}.
\]

**Proposition 3:** There exists an optimal Nash equilibrium with pareto efficiency for the basic contract and at the equilibrium, \(\{P^*, Z^*\}\) satisfies:
\[
P^* - \theta r = C + \theta c, Z^* = 1 - \frac{(C + \theta c)(\mu - \theta r)}{2(1 - \phi \mu)}.
\]

Proposition 3 shows that the basic contract can improve both parties’ welfare and achieve Pareto efficiency by applying the NBS. This bargain process possibly happens, especially under a competitive market with multiple SPs, where EUS will obtain a certain bargaining power and SP cannot get high revenue by setting an arbitrary price. Notice that the optimal price \(P^* - \theta r = C + \theta c\), i.e., the expected marginal profit of SP equals to its marginal cost, which indicates that SP cannot further improve its revenue by reducing the price. From the NBS we can see that the optimal EUS’ service demand \(Z^*\) is related to the SP’s marginal cost \(C + \theta c\), and the less SP’s marginal cost, the larger EUS’ service demand. We can further verify that \(Z^*\) varies directly with \(\mu - \theta r\), which implies that when EUS underestimates the QoS of SP, i.e., \(\mu - \theta > 0\), SP is able to extract a higher service demand by offering a larger rebate \(r\), which verifies the result in Proposition 1.

**III. Multi-agents QoS Subcontract**

**A. Economic Model for Subcontract**

When SP signs a basic QoS guarantee contract with an EU, SP first needs to arrange its contracted task (i.e., providing streaming services to the EU with specified QoS) to the assisting peers. SP then initiates an auction process in order to select a proper number of assisting peers to carry out the QoS task. The selected peers form a QoS work team and SP will sign a bandwidth exporting subcontract with them, namely multi-agents QoS subcontract, where SP and all the members of the work team are principal and agents, respectively.

According to the multi-agents QoS subcontract, the work team should export a specified joint bandwidth output to the given EU which has a contractual deal with SP. In return, the team members will receive some monetary compensation from SP in respect of the QoS output they have provided. The team
profits will be distributed among team members based on the proportion of their contributed bandwidth in the QoS work. The joint bandwidth of the work team directly determines the monetary profits of the whole QoS work.

Consider a subcontract with a SP and a work team including \( m \) agents. We assume the useful bandwidth supplying of the agents is \( \{b_1, \ldots, b_m\} \), the bandwidths provided by the team agents determine a joint bandwidth \( B = \sum_{i=1}^{m} b_i \) that exports to the EU. We assume that the joint bandwidth can be quantitatively evaluated by a monetary function \( M(B) \), where \( M(B) \) is strictly increasing, concave, and differentiable with \( b_i \). Since SP derives \( M(B) \) from the QoS task, it should pay some remuneration to the agents. Let the remuneration of agent \( i \) be \( r_i(b_i) \), the revenue of SP in this subcontract is

\[
R_{SP} = M(B) - \sum_{i=1}^{m} r_i(b_i).
\]

For agent \( i \) in the work team, its revenue comes from the remuneration \( r_i(b_i) \) on a basis to its bandwidth providing. Generally, providing such bandwidth will generate a cost denoted by \( c_i(b_i) \). Here we assume that the cost function \( c_i(b_i) \) is differentiable and strictly convex as \( b_i \) increases. Hence, the revenue of agent \( i \) can be described as \( R_i = r_i(b_i) - c_i(b_i) \).

For the subcontract that consists of SP and multiple agents, there exists a noncooperative game where the agents always seek to maximize their own revenues by deciding how much bandwidth they will provide and the SP aims to obtain a desired joint bandwidth output. What merits our concern is whether there exists a profit allocation scheme that leads to a Pareto optimal Nash equilibrium. That is, agents can satisfy their self-interests and none of them would violate this equilibrium; meanwhile, both SP and agents can obtain a certain degree of revenue, and the aggregated revenue of SP and agents are maximal. The optimal bandwidth \( b_i^* \) provided by agent \( i \) that achieves Pareto optimality should satisfy:

\[
b_i^* \in \arg \max_{b_i} \{M(B) - \sum_{i=1}^{m} c_i(b_i)\}, \quad s.t.: B = \sum_{i=1}^{m} b_i. \tag{12}
\]

Due to the inadequate profit allocation scheme, the free-riding problem always yields and leads to an inefficient Nash equilibrium, which will be discussed in the next subsection.

### B. Free-riding Problem in Subcontract

Assume the work team has accomplished the contractual QoS work, SP needs to allocate the team profits among the agents. A typical profit allocation scheme is full-sharing allocation, where SP distributes the profits collected from the joint bandwidth output among the agents according to the contributions of the team members, which is expressed as:

\[
r_i(b_i) = s_i \cdot M(B), \quad s.t.: \sum_{i=1}^{m} s_i = 1, \tag{13}
\]

where \( s_i \cdot M(B) \) stands for agent \( i \)'s share ratio of the whole monetary profits. Thus, the revenue of agent \( i \) is rewritten as:

\[
R_i = s_i \cdot M(B) - c_i(b_i). \tag{14}
\]

The full-sharing allocation scheme might be the most general allocation scheme that the SP can adopt. However, we have the following proposition.

### Proposition 4: The full-sharing profit allocation scheme cannot result in an efficient Nash equilibrium with a desired bandwidth output.

Following Proposition 4, we can see that the free-riding problem always occurs in the full-sharing allocation scheme, since the individual agent cannot satisfy its self-interest by performing the work of bandwidth providing. This problem will become worse when the individual's QoS contribution cannot be measured accurately, e.g., SP fails to distinguish the exact QoS contribution of an individual peer from a joint QoS output. This may happen, as the subcontract is signed between the SP and work team, but the joint QoS output is received by the third entity EU. Due to the lack of effective supervision, agents cannot be penalized sufficiently for the deviation of performing QoS task, some agents always have incentive to capitalize on this control deficiency, which finally leads to an inefficient bandwidth output.

### C. Profit Allocation Scheme with Team Penalty

The free-riding problem is essentially due to the deficient profit allocation scheme. In this regard, we propose the following profit allocation scheme with team penalty so as to assure a sufficient bandwidth output: SP sets a target of bandwidth output that the QoS work team should achieve, if the target is achieved, a monetary profit for the joint bandwidth output will be assigned to and shared by all of the team agents. Otherwise, each team agent will suffer a penalty.

Assume the penalty of agent \( i \) is \( k_i \), the profit allocation scheme with team penalty can be mathematically written as

\[
s_i \cdot M(B), \quad B \geq \tilde{B}; \quad s_i \cdot M(B) - k_i, \quad B < \tilde{B}. \tag{15}
\]

We summarize the following proposition about the profit allocation scheme with team penalty:

### Proposition 5: In the multi-agents QoS contract, the profit allocation scheme with team penalty is able to lead to an efficient Nash equilibrium.

By applying such profit allocation scheme, each team agent has incentive to provide bandwidth as SP expects, and induces a positive bandwidth output. It can also be verified that the efficient equilibrium achieves when the joint bandwidth output \( B \) meets the target bandwidth \( \tilde{B} \).

### IV. Conclusions

In this paper, we have developed a framework of QoS guarantee in mobile P2PS systems through a contract-ruled approach. The proposed approach can be viewed as a more rigorous case of incentive mechanism with several additional specifications. To the best of our knowledge, we are the first to tackle the QoS guarantee problem in mobile streaming applications by using the contract. We believe that it can shed light on the deployment and evolution of practical mobile streaming markets.

### References

