

Auction-based Resource Allocation for Wireless Local Area Networks in Metropolitan Areas

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Abstract— In this work, we focus on using pricing as an incentive mechanism to encourage self-interested access points to participate in a public wireless network. Specifically, we employ a centralized model to aggregate all of the access points deployed by different businesses into a federated market, enabling wireless clients to select the cost-effective access service with the consistent quality. The proposed pricing scheme is based on a second-price auction protocol. In addition to the cost-performance concern on the wireless access service, a travel-expense is introduced as another concern to the wireless clients for the service selection among different access points. Finally, we show that the proposed scheme outperforms a fixed-rate pricing scheme in terms of network utilization and resource allocation efficiency via simulation.

Keywords— Pricing, Wireless Local Access Network, Auction, Travel-expense, Quality of Service

I. INTRODUCTION

In the recent years, we are witnessing a tremendous gain in the popularity of IEEE 802.11 Wireless Local Area Network (WLAN). In the U.S., several companies have declared their intentions to build and support nationwide WLAN networks, with tens of thousands of hot spots for providing broadband IP connectivity. On the other hand, a majority of city dwellers have a broadband connection and a personal access point at home. In dense metropolitan areas such as San Francisco, there is sufficient density of access points to achieve near-ubiquitous WLAN by sharing access amongst residents.

Owners of WLANs would share their networks with the public if they could be adequately compensated. In this sense, pricing could be used as an incentive mechanism to encourage self-interested access points to share their networks [1].

In this work, we propose a novel pricing scheme under which the overall payment charged grows proportionally with the time the client gains access initially, and ceases when he no longer intends to connect. The proposed pricing scheme is based on a second-price auction mechanism, which is best known for its high efficiency in terms of resource allocation. In the proposed scheme, in addition to the cost-performance concern on the wireless access service, a travel-expense is introduced as another concern to the wireless clients for the service selection among different access points.

The motivation of the work presented in this paper is to put forward a simple pricing scheme that (i) provides the right incentives for both access points and clients to follow the scheme and not to cheat so that the order in this federated market can be maintained spontaneously; (ii) improves network utilization and social welfare by introducing a second-price auction mechanism and enabling a mechanism for wireless clients to select nearby access points based on price concerns.

II. SYSTEM MODEL

We consider that multiple basic service sets (BSS) exist simultaneously in a certain area, such as a park or a community. Each BSS consists of an access point, and wireless clients who reach the access point directly.

All access points in our model are registered with a trusted central authority - aggregator. The aggregator attaches its brand name to access points, so as to ensure that a consistent Quality of Service (QoS) is offered among the access points deployed by different businesses. Wireless clients are registered with the aggregator as well. By using a single account, a client can get an access service from any one of the federated access points, which have the same brand name of the aggregator. The aggregator can be distributed, as certification companies are, to avoid being a bottleneck.

A. Quality of Service

There are many factors that can influence the QoS, such as the number of clients coexisting, the power output, the type of antenna, the density of the building environment and the distance between a client and an access point [2]. To simplify the model in the study on pricing scheme, here we assume that the QoS provided by a branded access point is merely determined by the bandwidth allocated [3].

In this work we assume that, with an agreement between the aggregator and each access point, the same amount of dedicated bandwidth is offered among all the federated access points such that a consistent QoS is provided by different businesses.

B. Web Browsing Utility

When the allocated bandwidth stays unchanged, the client is considered to have a web browsing utility function [4]: his

overall utility grows proportionally with the time the client gains access initially, and ceases when he no longer intends to connect.

C. Service Pool

The network and the access point's uplink here are considered to have a limited capacity [5]. Any client's connection request at the access point, that has not enough bandwidth for allocation, will not be accepted. This kind of limitation imposes the access point a bandwidth capacity constraint on her profit maximization problem.

Time is divided into discrete time slots [6]. An access service is an amount of dedicated bandwidth in time slots. The collection of available access services from all access points is considered as a service pool. We represent the available access services authorized to access point i using a set $A_i = \{a_i^j\}_{j \in \{1, 2, \dots, n_i\}}$, where

- a_i^j is the j -th element in the set
- n_i is the overall number of available access services which belong to access point i .

$A = \bigcup_{i=1}^S A_i$ is defined as the set of all the access services in the pool, where S is the total amount of access points in the federated market. The total number of access services in A is defined as $n = \sum_{i=1}^S n_i$.

As for client k , his valuation of the l -th service item in set A is defined as u_k^l .

We assume that $u_k^l = u_k^h$ for $l, h \in \{1, 2, \dots, n\}$ and $l \neq h$, since a certain amount of dedicated bandwidth is offered among all the federated access points. For simplicity, we write u_k^l and u_k^h as u_k standing for client k 's valuation. In this model, the clients have their individual valuations of the access service, which are appropriately decided based on their demands and experience.

D. Non-interruptible Service

Each new client requests for an access service over the slot and the aggregator replies with an allocated access point as well as the slot price. Based on the client's valuation of service, the client chooses to accept the price and connect to the access point, or to reject and leave. The price negotiation processes are executed one client after another within the aggregator according to their arrival time.

During the service, as discussed in [7], although the access point will wish to cease service to clients or increase the price over time to obtain higher profit, it is reasonable to believe that clients will be discouraged from buying such a kind of service since it is unrealistic to require clients to monitor the varying price continuously. Therefore, we assume that the price cannot be changed during the session of service for a particular client, and that the service is non-interruptible (an

access point cannot suspend the service as long as the client can keep paying, while the client can disconnect voluntarily).

Let $p_{k,i}$ denote the slot price offered by access point i for a slot-unit service. Finally, after the session of service, the overall payment $P_{k,i}$ is:

$$P_{k,i} = p_{k,i} \times T_k \quad (1)$$

where T_k is the number of time slots that client k connected.

III. TRAVEL-EXPENSE-BASED SECOND-PRICE AUCTION (TESA) PROTOCOL

In the centralized model, within the unified market access points have the incentive and the capability to attract the wireless clients in their own coverage, as well as the clients out of their coverage to use their service in order to maximize their profits. On the other hand, the clients can move from one place to another for selecting a service based on the price concerns. To enable this service selection capability and form a more efficient market, the access service information (e.g., price, QoS, etc.) of each access point should be provided in a unified market. We model the problem as a second-price auction game for an identical item in an aggregator network. Some fundamental concepts in this auction are briefly summarized as below:

- the identical item for auction is an access service per time slot
- the access point is the seller (the terms "access point" and "seller" are used interchangeably in the following)
- the wireless client is the buyer (the terms "wireless client" and "buyer" are used interchangeably in the following)
- the aggregator acts as an auctioneer and a pricing authority

Vickrey (1961) suggests asking the buyers to bid on the good and awarding the good to the highest bidder at the second highest price [8]. This mechanism has the following desirable property. It is a dominant strategy for each agent to truthfully reveal his/her valuation and if each agent plays a dominant strategy, the outcome will be Pareto efficient [9]. Informally, Pareto efficient situations are those in which it is impossible to make one person better off without necessarily making someone else worse off.

A. Definition

In this work, the price negotiation processes are assumed to be executed one client after another within the aggregator. Namely, a single buyer and multiple sellers, rather than a single seller and multiple buyers cooperate in this market simultaneously. In addition, a wireless client who is out of access points' coverage would move to the access points for an access service, which incurs another kind of cost to the buyer. For the two reasons, the auction protocol is different from the classical second-price auction and we name it as the Travel-Expense-based Second-Price auction (TESA) protocol.

We consider that only the nearby sellers can compete for the client, since it is not realistic for a client to move a long

distance for an access service. To be precise, only the bids of sellers residing within a certain distance (r_k) from the client are valid bids in the auction. The seller whose transmission range covers the client is hereafter termed as “direct seller” of that client. On the other hand, the seller whose transmission range does not cover the client (but the seller is within r_k distance from the client) is hereafter termed as “indirect seller” of that client.

Furthermore, we denote Travel Expense per time slot (TE) as the cost of moving per time slot. Within the relatively not long distance designated by the client himself, TE is assumed to be identical for the client acquiring an access service from all of the “indirect sellers”.

Definition 1 (TESA protocol). *Sellers residing within a certain distance from the client compete for providing service. The sellers bid on the item without knowing the bids of the other sellers. A seller with the lowest bid wins but the price charged is the second-lowest bid. Note that the bid(s) of “indirect seller(s)” should be incremented by TE to compete with the bid(s) of “direct seller(s)” for the client.*

B. Example

For ease of understanding, an example is illustrated in Fig.1. Let buyer k 's valuation for TE be w_k . Access point a, b and c are of capacity to provide service and they reside within r_k from the client k , while the client resides only within the transmission range of access point c. In this case, the bids of access point a and b should be incremented by w_k to compete with the bid of access point c for the client.

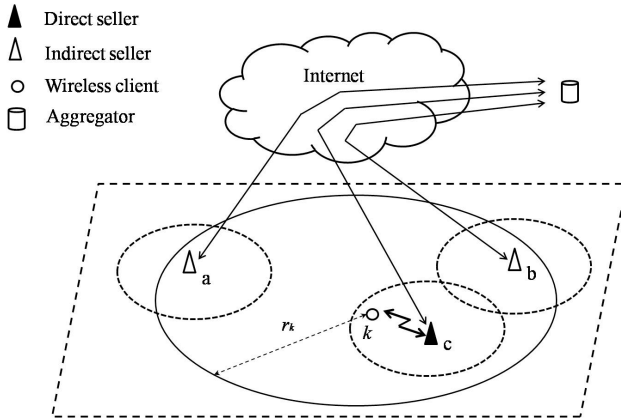


Figure 1. Illustration of valid bids in an auction

In particular, we assume that the bids of access point a, b, c and w_k are 10, 15, 20 and 15, respectively. The expectable outcome is: access point c wins the auction and the price charged is the second lowest price, i.e., 25.

IV. COMMUNICATION PROTOCOL

To illustrate the whole process in the proposed TESA protocol-based pricing scheme, a framework of a possible communication protocol designed in this work is presented in this section. The communication protocol indicating the interaction among the buyer, the sellers and the aggregator is illustrated in Fig.2. For simplicity, it is assumed that three access points (a, b and c) exist. Similar to that depicted in Fig.1, the client k resides in the coverage of AP c, while he is out of the coverage of AP a and AP b.

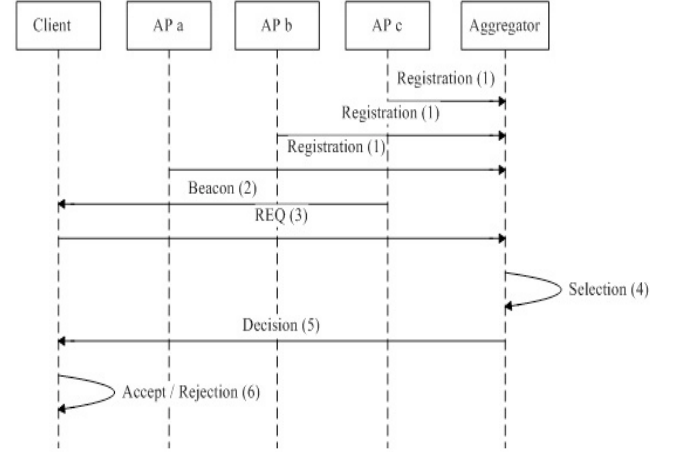


Figure 2. Communication protocol for the TESA protocol-based scheme

A. Steps Involved in Negotiation

Step 1: Federated access points register their bids on the item, and location information by sending a registration package. The aggregator maintains the information contained in the package, until the access points update them.

Step 2: Client k arrives at federated access point c, which is referred as “direct seller”, and receives beacon packets.

Step 3: Client k requests for an access service by sending a REQ package through all of the “direct sellers”. In this way, the aggregator is notified whether the client exists in the coverage of each access point or not afterwards. w_k is contained in the REQ package. Furthermore, to notify the aggregator how far he is willing to move for getting a cheaper access service, the client's location information as well as r_k are also contained in the REQ package.

Step 4: Based on the information contained in the registration and REQ packages, the aggregator replies with an allocated access point as well as the slot price according to the TESA protocol.

Step 5: The aggregator sends the decision back to the client through the “direct sellers”. When the client is out of the coverage of the allocated access point, the location information of the allocated access point should be sent back as well.

Step 6: When an access point is successfully allocated, the client has to choose to accept the price and connect to the access point, or to reject and leave.

Repeat Step 3 to 6 when a new client requests for an access service.

B. Security and Trust Relevant Issues

In Step 5, the “direct sellers” have the motivation to intentionally increase the TE cost declared by clients to prevent the clients from moving to other “indirect sellers”. The sensitive data conveyed in the messages for negotiation between the aggregator and the access point / client should be protected, e.g., through using the secured tunnel technologies. For instance, sensitive fields in the messages can be encrypted using the keys shared between each end. These keys may be registered in the aggregator or other sites for authentication, authorization purposes. When malicious intermediate nodes like the access point modified the data, the receiver can check the consistence of data. For instance, a checksum mechanism can be employed. The malicious access point detected could be punished later. To focus on the pricing scheme, the detailed security and trust relevant issues are out of the current scope of this study and considered as the future work.

V. EVALUATION SCENARIO

In this section, we evaluate the performance of the TESA protocol-based pricing scheme in a federated wireless access network through simulation studies.

A. A Pricing Scheme Used for Comparison

A FIFO fixed pricing scheme [3] is used for comparison. As in TESA protocol-based pricing scheme, the price charged in FIFO fixed pricing scheme cannot be changed during the session of service for a particular client; the service is non-interruptible; and any client's connection request at the access point that has not enough bandwidth for allocation will not be accepted. The distinctions between the two schemes are that:

- rather than a price dynamically decided by multiple access points in TESA protocol-based pricing scheme, the price charged by a certain access point is decided by the access point unilaterally in FIFO fixed pricing scheme.
- FIFO fixed pricing scheme does not provide a mechanism enabling clients to move from one place to another.

A comparative analysis in terms of network utilization and allocation efficiency is conducted between the two pricing schemes.

B. Simulation Settings

The detailed simulation settings are summarized as follows:

- access points are randomly placed in a 1000 m × 1000 m area
- each access point can serve at most 25 clients within a distance of 50 m
- the number of access points varies from 0 to 280
- as a simple mathematical model, clients are assumed to arrive according to a Poisson process at rate $\lambda = 20$ per min

- clients stay for a time which is exponentially distributed with average time $h = 120$ min. The load of clients' requests $L = \lambda \times h$ is set to 2400
- sellers' bids on the item, clients' valuations on the item, and the TEs are uniformly distributed in a range of [0,100]

In the real-world large-scale WLAN environment, only nearby sellers who are within the r_k distance from the client can compete for the client, since it is not realistic to request a client to move a long distance for obtaining an access service. In the simulations, for simplicity, we relax this distance restriction and assume that all the sellers in the 1000 m × 1000 m area can compete for the client.

The prices in FIFO fixed pricing scheme is set to the bid of each seller plus 0, 10 and 20 (i.e., ‘pft’ in Fig. 3, 5).

VI. NUMERICAL RESULTS

A. Rates of Successful Leasing

Firstly, we focus our simulation study on the rates at which clients can successfully lease channels from access points under the two pricing schemes. The results can be used to illustrate the network utilization affected by the pricing schemes.

From Fig.3, we can see that with the number of access points increasing, the market gradually becomes saturated under both of the two pricing schemes. Moreover, the results of comparisons between the two pricing schemes show that the proposed TESA protocol-based pricing scheme performs better in improving the network utilization than the FIFO fixed pricing scheme.

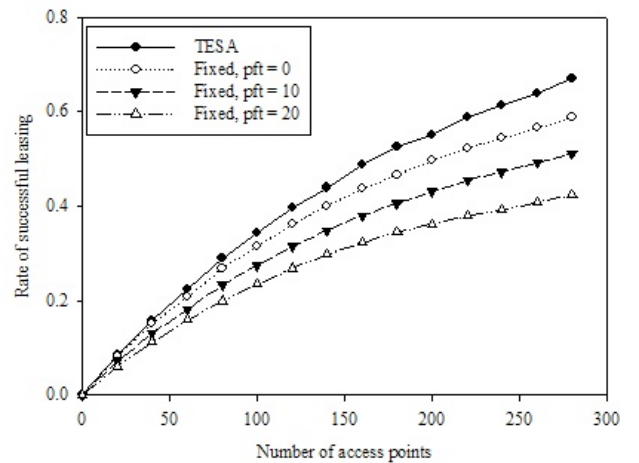


Figure 3. Rates of successful leasing versus number of access points

Generally, there are three reasons why the clients fail to acquire channels from access points for both the proposed TESA protocol-based and the FIFO fixed pricing schemes:

- there is no “direct seller” that could forward the client's REQ package to the aggregator

- the client is within the coverage of at least one “direct seller”, while all the “direct seller(s)” and “indirect seller(s)” already have the maximum number of wireless clients
- the client is within the coverage of at least one “direct seller”, and at least one “direct seller” or “indirect seller” is of the capacity for providing service, while price negotiation fails, i.e., the price charged cannot be accepted by the clients

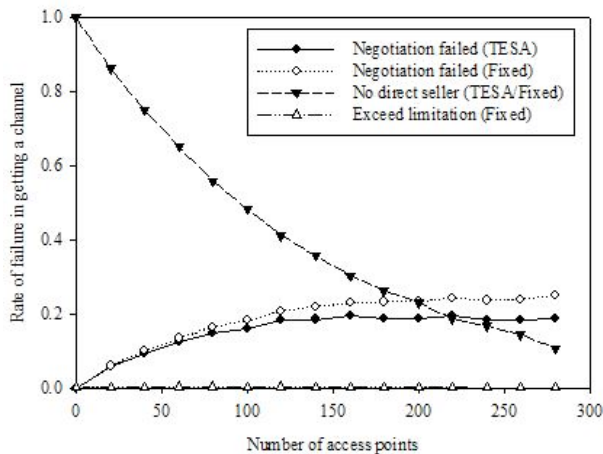


Figure 4. Rates of failure in getting a channel

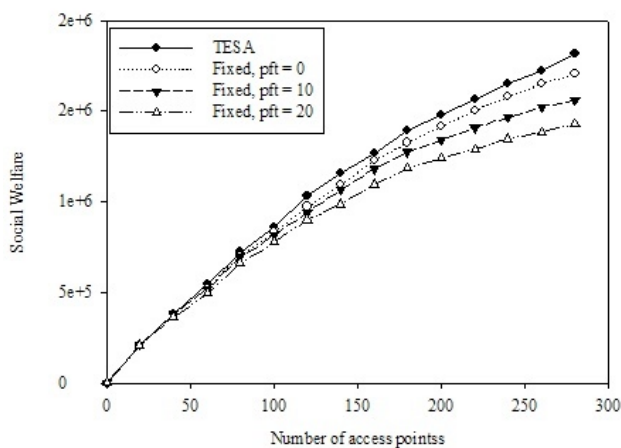


Figure 5. Social welfare versus number of access points

For the FIFO fixed pricing scheme, it should be noted that there is no “indirect seller”, since it does not provide a mechanism enabling clients to move from one place to another. In the proposed TESA protocol-based pricing scheme, the possibility of failure for the second reason is 0, because of the assumption that all the sellers in the 1000 m × 1000 m area

can compete for the client. In the FIFO fixed pricing scheme, the possibility of failure for the second reason is higher than that of the TESA protocol-based pricing scheme, but it is negligibly low as shown in Fig.4. The rates of failure for the other reasons are also shown in Fig.4. It can be seen that the TESA protocol-based pricing scheme outperforms the rival mainly due to the advantage in improving the rate of successful price negotiation.

B. Social Welfare

Secondly, we focus our simulation studies on the social welfare under the two pricing schemes. Social welfare consisting of consumer surplus and producer surplus is the basic tool that economists use to study the efficiency of resource allocation in the market.

In Fig.5, the result of comparison between the two pricing schemes indicates that the proposed scheme achieves performance gains over the FIFO fixed pricing scheme in terms of resource-allocation-efficiency.

VII. CONCLUSIONS

In this paper, in order to foster a ubiquitous wireless network access environment easily by involving more people to provide wireless access services for clients, we present an incentive pricing scheme based on a novel second-price auction, namely, the TESA protocol-based pricing scheme. Then we illustrate how the proposed pricing scheme guides mobile nodes to move from one place to another based on price concerns. Simulation results show that the proposed scheme can achieve a better social welfare and network utilization than the FIFO fixed pricing scheme. Regarding the interference among overlapped access points, as it degrades the utilization of spectrum resources, the number of client-free-placed access points in one area should be restricted so as to avoid the interference. For the interference concern, it is out of the scope of this paper, and we treat it as our future work.

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