The wireless communication systems of the future are envisioned to integrate multiple wireless access technologies to provide high-speed communication services to mobile users in a seamless manner. Pricing will be one of the important issues in such a heterogeneous wireless access system. Through a proper pricing mechanism, a service provider offering wireless access services in a heterogeneous environment would like to achieve the highest revenue, while mobile users would like to achieve the highest satisfaction from service usage. In the following, we briefly review the related work on pricing for homogeneous wireless networks. Subsequently, we consider heterogeneous wireless networks, where different technologies (e.g., WiMAX and WiFi) are available to the users in the same coverage area, and different wireless access networks are operated by different service providers.

From an economic point of view, pricing plays an important role in trading any resource or service. The most important objective of trading is to provide benefits to both the sellers and the buyers. Therefore, the price must be chosen so that the revenue of the sellers is maximized while the highest satisfaction is achieved by the buyers. There are two main factors influencing the price setting, namely, user demand and competition among service providers. Price and demand are functions of each other. If demand is high, a high price can be charged by a service provider (i.e., a seller) to earn more revenue. On the other hand, if demand is low, the price must be reduced to attract more mobile users (i.e., the buyers). Competition among the service providers also impacts the price setting. In particular, the service providers can compete with each other to offer wireless access services through price adjustment. Typically, if the services are substitutable (even though different), users buy a service that provides the highest satisfaction at the lowest price. If one service provider reduces its offered price to attract more users and gain higher revenue, this will impact the revenues of other sellers who will try to compete by reducing their offering prices as well. The pricing problem in wired networks was considered in [1], where price and transmission rate were optimized for elastic traffic. However, network heterogeneity and service competition were not considered. In this article we focus on the pricing problem in heterogeneous wireless networks.

A classification of pricing schemes in wireless networks is shown in Fig. 1. The pricing models can be either of two types — non-competitive or competitive pricing models (Fig. 2). In a non-competitive model, a service provider negotiates with the users to determine the price. In a user competition model, the users offer prices (which maximize their utility) to the service provider (e.g., auction mechanism). In a service provider competition model, service providers adjust their price to achieve the highest revenue. In a service provider and user competition model, which is the most common model, both the service providers and the users compete to achieve their objectives.

Pricing in Homogeneous Wireless Networks

Non-Competitive Pricing: Optimization-Based Approach — In a non-competitive pricing model, there is only one service provider who adjusts its offered price to maximize its rev-
The willingness of a user to pay was determined by the price mission rate to the users such that its revenue is maximized. For a given pricing function (e.g., flat price or linear price), a service provider allocates trans-area networks (WLANs). For a given pricing function, the optimal price can be chosen to maximize the revenue for commercial services. An optimization formulation can be used to obtain the optimal admission control policy (i.e., whether a new connection can be accepted into a system or not). Then, the optimal price was obtained that maximizes network revenue.

In a multihop network, traffic of a user can be routed among the nodes in a multihop network. A non-cooperative game was formulated, and Nash equilibrium was used to obtain the transmission power and the price (per unit transmission power).

In cognitive wireless networks, where primary (or licensed) users can offer (or sell) spectrum opportunities to secondary (i.e., unlicensed) users, competitive pricing for spectrum trading becomes an important issue. The pricing method in this competitive environment can be either secondary user driven [7] or primary user driven [9]. In a secondary user-driven scheme, the secondary users request (i.e., bid) for the spectrum, and a primary user makes a decision on price and allocates spectrum opportunities to the secondary users accordingly. On the other hand, in a primary user-driven scheme, primary users determine the prices of available spectrum. A secondary user makes its decision based on offered spectrum price and quality of wireless transmission on the corresponding spectrum. In both the cases, the competition can be modeled as a non-cooperative game, and the solution on spectrum pricing can be obtained from the Nash equilibrium.

In a multihop network, traffic of a user can be routed through multiple nodes to the destination. As a result, a user must pay the intermediate nodes for functioning as relays. This pricing problem in a multihop network was considered in the literature, for example, in [13]. In this case, the relay nodes can optimize the price charged to the upstream nodes of a traffic flow to maximize the profit. A non-cooperative game model was developed to obtain the competitive solution among the nodes in a multihop network.
Pricing in Heterogeneous Wireless Access Networks

To design a pricing model for a heterogeneous wireless access network, the following issues must be considered:

• **Heterogeneity of wireless access** — The capacity, coverage area, frequency band of operation (e.g., licensed or unlicensed band), and the quality of service (QoS) provisioning mechanisms are different for different wireless access systems.

• **Competition among multiple service providers** — The different access networks are operated by different service providers, and each of the service providers wants to maximize its revenue.

• **Inequality in service offering** — Inequality in service offering by the different wireless access networks may arise due to several reasons (e.g., different coverage area, data rate, and mobility support).

• **Service substitutability** — Wireless services from the different access networks may not be perfectly substitutable. This may be due to some of the mobile terminals not being equipped with all of the radio interfaces supported in the system. Also, for better energy conservation, some users may prefer short-range wireless access to long-range wireless access.

• **Vertical hand off** — The connection of a mobile user can be handed over vertically between different types of networks, for example, from a WiFi network to a WiMAX network when a user moves out of a WiFi cell. In this case, the pricing scheme must be developed by considering the possibility of vertical hand off.

The following three different approaches, namely, auction [10], optimization [11], and demand/supply [12]-based schemes have been used for developing pricing models for heterogeneous wireless networks:

• **Auction-based scheme** — In [10], a user periodically bids for the radio resource by informing the service provider of the price and the QoS requirement. Then, the service provider makes a decision on resource allocation that maximizes its revenue. In this multi-unit sealed-bid auction, a manager agent facilitates negotiation between a mobile user and a service provider.

• **Optimization-based scheme** — In [11], a service allocation and pricing method based on optimization was proposed for a heterogeneous wireless network consisting of WLAN, universal mobile telecommunications system (UMTS), and global system for mobile communications (GSM) networks. The capacity of the system was optimally allocated to different service types (e.g., voice and data). The objective was to maximize the revenue of a service provider (and hence network utilization) under the capacity constraint of each of the access networks.

• **Demand/supply-based scheme** — In [12], a resource allocation framework was proposed for heterogeneous wireless networks based on the concept of demand/supply in microeconomics. The supply function was obtained by solving an optimization formulation to maximize the revenue of a service provider, whereas the demand function was obtained by solving a utility maximization problem for a user. The equilibrium was defined as the price at which demand equals supply. Based on this equilibrium price, network selection and admission control methods were developed.

However, the above works did not consider competition among multiple service providers owning different radio access networks. Because the service providers have their own
interests in a heterogeneous environment, a competition exists among the service providers, and the price offered by one service provider will impact the price offered by other providers. This situation can be modeled as an oligopoly market, and subsequently, non-cooperative game models can be used to analyze this market and to obtain the optimal pricing that satisfies each of the service providers.

A summary of the related work on pricing in wireless networks is provided in Table 1.

### Oligopoly Market Model

In economics, oligopoly is defined as a situation where a small number of firms (i.e., oligopolists) dominate a particular market [14]. In this market structure, the firms compete with each other independently to maximize their profits by controlling the quantity or the price of the supplied commodity. The decision of each firm is influenced by the actions of other firms. The behavior of each of the firms, given the actions of other firms, can be analyzed by using non-cooperative game theory. In this case, the best action (i.e., to maximize profit) of one firm, given the actions of other firms, is defined as the best response. This best response can be obtained by formulating a profit maximization problem. Then, based on the best responses of all firms, the solution of this oligopoly market (e.g., the Nash equilibrium) can be obtained.

In the context of wireless networks, the service providers can be considered as the firms in an oligopoly market. These service providers compete with each other to offer wireless service to the mobile users. Because the service providers are independent and rational, to maximize their revenue/profit, the best responses can be defined and used to obtain the solution of the competition. Different oligopoly market structures, and hence, different game models, can be formulated for the different competition scenarios.

### Bertrand Game — Competition in Price

In a Bertrand game, there are a finite number of service providers who decide on the service prices simultaneously. Given the price offered by a service provider, based on a demand function, the amount of requested bandwidth from the mobile users can be determined. For example, if the price is high, the amount of requested bandwidth from the users will be small and vice versa. Then, the profit is computed and

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**Table 1. Resource allocation and pricing in wireless networks and different demand functions.**

<table>
<thead>
<tr>
<th>Paper</th>
<th>Description</th>
<th>Demand function</th>
<th>Interpretation</th>
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<tr>
<td>J. Hou et al.</td>
<td>Congestion control based on pricing in hard-capacity cellular networks</td>
<td>$D = q^2(p - p_0)$</td>
<td>Demand in terms of percentage of user $(D)$ who will accept price $p$ given normal price $p_0$</td>
</tr>
<tr>
<td>Q. Wang et al.</td>
<td>Network pricing and admission control for public safety and commercial services</td>
<td>$D = k_1 - k_2p$</td>
<td>User demand in terms of arrival rate $(D)$ is a linear function of price with parameters $k_1$ and $k_2$</td>
</tr>
<tr>
<td>J.-W. Lee et al.</td>
<td>Utility maximization-based power allocation in CDMA wireless networks</td>
<td>$D = \max_q (U(\gamma(q)) - pq) \quad \text{(Di)}$</td>
<td>Power demand $(D)$ is a solution of transmit power $q$ based on net utility maximization, where $U(\cdot)$ is a utility function of SIR $\gamma$</td>
</tr>
<tr>
<td>L. Badia et al.</td>
<td>Revenue maximization in multimedia WLANs</td>
<td>$D = 1 - e^{-kmnp^m}$</td>
<td>Power demand $(D)$ is a solution of net utility maximization, where $U(\cdot)$ is the utility function of transmit power vector $q$</td>
</tr>
<tr>
<td>C. U. Saraydar et al.</td>
<td>Non-cooperative game formulation for distributed power control and pricing in CDMA networks</td>
<td>$D = \max_q U(q) - pq \quad \text{(Di)}$</td>
<td>Transit power demand $(D)$ is a solution of net utility maximization, where $U(\cdot)$ is the utility function of transmit power vector $q$</td>
</tr>
</tbody>
</table>
| J. Sun et al.  | Wireless channel allocation based on second-price auction algorithm          | $D_i = \mathbb{E}(\mathbb{X}_{1i} \geq p)$, where $1_{p_i \geq p_j} = \begin{cases} 1 & \text{if } p_i \geq p_j \\ 0 & \text{otherwise} \end{cases}$ | Payoff or throughput demand $(D)$ depends on expected channel quality $X_i$ and is a function of price 
| S. Gandhi et al. | General framework for wireless spectrum auction                           | Piecewise linear price-demand (e.g., $D = (B - p_i)/A$)                      | Spectrum demand $(D)$ is a linear function of price $p_i$ |
| Y. Xing et al. | Pricing in competitive spectrum market with multiple sellers               | $U = \alpha(q - q') + (1 - \alpha)(p' - p)$                                    | A user demands spectrum if utility $U$ is maximized where $q$ and $p$ denote the quality and price whose lower bound and upper bound are $q'$ and $p'$, respectively; $\alpha$ is a model parameter which lies between 0 and 1 |
| W. Zhang [11] | Bearer service allocation and pricing in heterogeneous wireless networks   | $D = Ap^n$                                                                     | Bandwidth demand $D$ is controlled by price elasticity $\epsilon$ and demand potential $A$ |
| H. Chan et al. | Utility-based network selection for heterogeneous wireless networks        | $D = \max N(U(r) - pr)$                                                        | Bandwidth demand $D$ is a solution $r$ of user revenue maximization gained from utility function $U(r)$ under $N$ active users |

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used in a profit maximization problem for a service provider to obtain the best response in terms of service price. The Nash equilibrium is located at the point where all the best responses intersect with each other.

Stackelberg Game — Leader-Follower Competition

In a leader-follower market, there is at least one service provider defined as the leader who can make the decision and commit the strategy on the price before other service providers who are defined as followers. In this case, the strategy chosen by the leader can be observed by the followers, and the followers can adapt their decisions accordingly. The best responses of the firms in this leader-follower competition can be obtained as in the Bertrand game model. However, in a Stackelberg game, due to the timing in decision making, the interaction between the leader and the followers is dynamic rather than static.

The leader can choose a strategy such that the profit is maximized, given that the followers will choose their best responses. This is defined as the Stackelberg equilibrium and can be obtained by backward induction technique. With backward induction, the best response of the follower is obtained first (i.e., in the same way as that for a Bertrand model). Then, this best response is used to compute the profit of the leader, and the leader chooses a strategy for which the profit is maximized.

Service Competition and Pricing in a WiMAX and WiFi-Based Heterogeneous Wireless Access Network

We present a model for service competition and pricing in an integrated WiMAX and WiFi network where the WiMAX and the WiFi service providers compete with each other in terms of price charged to the mobile users in a particular service area. Two cases of price competition among the service providers are considered. First, we consider the case where both the WiMAX and the WiFi service providers offer their prices at the same time (i.e., simultaneous-play game). The solution of this competition is given by a Nash equilibrium for which both of the service providers are satisfied with the solution in terms of prices. Second, we consider the case where the WiMAX service provider offers its price before the WiFi service provider (i.e., leader-follower game) — that is, the WiMAX service provider has priority in offering its price. This could be, for example, due to the larger service area covered by a WiMAX network. The WiFi service provider can observe the price offered by the WiMAX service provider and then decide on its price. The solution of this competition is the Stackelberg equilibrium for which the WiMAX service provider can maximize its profit.

System Model

We consider the heterogeneous wireless access environment in Fig. 3 with two service areas. Although broadband wireless-access service based on WiMAX is available in the first area (i.e., the outside circle), both WiMAX and WiFi services are available in the second area (i.e., the inside circle). The WiMAX service provider offers a premium class of service to \( n_p \) users for whom the transmission delay is the major QoS performance (e.g., real-time polling service in the WiMAX QoS framework). The WiMAX service provider charges these users at a flat rate of \( P_p \) (per unit of allocated bandwidth). In the second service area, WiMAX and WiFi service providers compete with each other to offer wireless access services to the users in the best-effort service class. A best-effort user can switch between the WiMAX and WiFi networks (e.g., to choose the service with the lower price) by using a dual-radio interface. Note that the above system model is different from that in [15]. In particular, churning of best-effort users between WiMAX and WiFi networks was not considered in [15].

Service Competition

User Utility and Bandwidth Demand — To quantify the bandwidth demand function, we consider a quadratic utility function for best-effort users (as in [16]). The bandwidth demand function can be obtained based on utility maximization. That is, the demand can be obtained as the optimal bandwidth that maximizes the utility of a best-effort user, given the qualities and the prices of the wireless access services, and the degree of substitutability among the services. Let \( p_i \) denote the price per unit of bandwidth offered by service provider \( i \), where \( i = \{m, f\} \) correspond to WiMAX and WiFi networks, respectively. The bandwidth demand function is defined as follows:

\[
D_i(p_i, p_j) = \frac{u_i (p_i - u_i)}{1 - v^2}
\]

where \( \gamma_i \) is the transmission quality for wireless access through the network of service provider \( i \), and \( u_i \) is a weighting (or normalization) parameter. Here, \( v \) is the degree of service substitutability (e.g., when \( v \) is close to one, a large fraction of best-effort users can switch between the WiMAX and the WiFi networks).

Note that the above bandwidth demand function can capture the effect of service substitutability and the quality of service. The bandwidth demand from a best-effort user for a particular wireless access service increases if the quality of transmission in the corresponding network becomes better. However, bandwidth demand decreases if the price becomes higher. The bandwidth demand is also affected by the qualities and prices corresponding to other wireless access services/networks. If the quality of transmission becomes better (e.g., a lower transmission error rate) or the price becomes
lower for an access network, some of the best-effort users will churn to the corresponding access network. The proportion of the churning best-effort users is controlled by the substitutability factor.

**Game Formulations and the Solutions** — We consider a simultaneous-play and a leader-follower game where the WiMAX and the WiFi service providers are the players. The strategy of a player is the price per unit of bandwidth (denoted by \( p_j \)). The payoff for each player is its profit denoted by \( \pi \). The profit of the WiMAX service provider is calculated based on the revenue obtained from the premium users, the cost due to the transmission delay of the premium users, and the revenue obtained from the best-effort users (i.e., price multiplied by the bandwidth demand). This is given by

\[
\pi_m(p_m, p_f, b) = \sum_{k=1}^{n_p} \frac{n_p}{n_v} \left( B - \beta_m(p_m, p_f) \right) - c_d \sum_{k=1}^{n_p} \frac{n_p}{n_v} \beta_m(p_m, p_f) + p_m \beta_m(p_m, p_f),
\]

where \( B \) is the total bandwidth, \( \beta_m(b) \) is the transmission delay of user \( k \) in the premium class with allocated bandwidth of amount \( b \), and \( c_d \) is a weighting parameter corresponding to the transmission delay performance. Similarly, the profit of the WiFi service provider is given by,

\[
\pi_f(p_m, p_f, b) = p_f \beta_f(p_m, p_f).
\]

The best response of the WiMAX service provider can be obtained from the optimal price \( p_m^* \) for which profit \( \pi_m(p_m^*, p_f) \) is maximized given the price \( p_f \) offered by the WiFi service provider. Similarly, the best response of the WiFi service provider is the optimal price \( p_f^* \) for which profit \( \pi_f(p_m, p_f^*) \) is maximized, given the price \( p_m \) offered by the WiMAX service provider. This best response is denoted by \( \beta_f(p_f) = \arg \max_{p_f} \pi_f(p_m, p_f) \).

When the WiMAX and the WiFi service providers offer their prices simultaneously, Nash equilibrium gives the set of prices such that none of the service providers can increase the profit by choosing a different price, given the price offered by the other service provider. This is the point where \( \pi_m(p_m) = p_m^* \) and \( \pi_f(p_f) = p_f^* \).

When the WiMAX service provider offers its price before the WiFi service provider, the WiMAX service provider will choose a strategy to maximize its profit based on the assumption that the WiFi service provider will set the price based on its best response, given the price that is offered by the WiMAX service provider. The price offered by the WiMAX service provider, which maximizes its profit, along with the best response price of the WiFi service provider constitutes the Stackelberg equilibrium — that is, \( p_m^* = \arg \max_{p_m} \pi_m(p_m, \beta_f(p_m)) \) and \( p_f^* = \beta_f(p_m^*) \).

**Numerical Results**

We assume that the transmission rate for WiMAX and WiFi networks is 20 Mb/s and 11 Mb/s, respectively. The number of users in the premium class of WiMAX service is five (i.e., \( n_p = 5 \)), and the traffic arrival rate for each of these users is 1 Mb/s. For the premium class users, we assume that \( P_E = 2 \) and \( c_d = 1 \). Here, the quality of a wireless access service is measured by the transmission quality (i.e., the bit-error rate, which is a function of the signal-to-noise ratio (SNR) at the receiver for a best-effort user). The service substitutability factor is assumed to be 0.8 (i.e., \( v = 0.8 \)). To obtain the equilibrium solutions, it is assumed that information about the competition is available (e.g., through a wireless service regulator).

We show the best responses of both the service providers, namely, the best price offered by a service provider to a best-effort user, given the price offered by the other service provider (Fig. 4). Clearly, when one service provider reduces its offering price, the best strategy for the other service provider is to increase the price so that it can gain higher profit. For example, when the WiMAX service provider increases the price, bandwidth demand for WiMAX service decreases while that for WiFi service increases. Consequently, the WiFi service provider can increase its offered price to fund the larger demand. The best responses of both WiMAX and WiFi providers are linear, and the Nash equilibrium is located at the point where the best responses intersect.

In the Nash equilibrium, none of the WiMAX and WiFi service providers has any motivation to deviate by increasing or decreasing its offered price. However, when the WiMAX service provider offers its price before the WiFi service provider, the equilibrium moves to the higher price for the WiMAX service provider whose profit becomes higher (i.e., due to the “first-move advantage”). This is defined as the Stackelberg equilibrium, which is always the best response of the follower (i.e., WiFi service provider), but not necessarily to be the best response of the leader (i.e., WiMAX service provider). That is, the WiMAX service provider can deviate from the Stackelberg equilibrium, for example, to point \( A \) in Fig. 4 to gain higher profit. However, because point \( A \) is not on the best response of the WiFi service provider, it will decrease its offered price (e.g., to point \( B \)) to generate a larger demand. This will result in a lower profit for the WiMAX service provider. If this step is repeated, the Nash equilibrium ultimately will be reached. However, the profit at the Nash equilibrium is smaller than that at the Stackelberg equilibrium. Therefore, if the WiMAX service provider can offer its price to the best-effort users before the WiFi service provider, it can gain higher profit by not deviating from the Stackelberg equilibrium. Note that a higher price may not always result in a larger profit because it reduces the bandwidth demand from the best-effort users. In this case, if the price offered by the WiMAX service provider is higher than that at point \( A \), its profit decreases.

Figure 5a and 5b show the variations in price and profit, respectively, under different channel qualities for a WiMAX service provider. When the transmission quality becomes better, the WiMAX service provider can increase its offered price (Fig. 5a) to gain a higher profit (Fig. 5b). Also, we observe that the prices and profits of both WiMAX and WiFi service...
providers at the Stackelberg equilibrium are higher than those at the Nash equilibrium. This confirms the result in Fig. 4 that the Stackelberg equilibrium is always on the right top of the Nash equilibrium (i.e., corresponds to higher prices offered by both WiMAX and WiFi providers).

The substitutability factor $v$ affects both the Nash and the Stackelberg equilibrium. When $v$ is close to zero (i.e., a best-effort user cannot switch between WiMAX and WiFi services), the prices are higher because a best-effort user has limitations in choosing any one of the available service providers. Consequently, WiMAX and WiFi service providers can charge a higher price. In contrast, when $v$ is close to one (i.e., a best-effort user can freely switch between WiMAX and WiFi service providers), the level of competition between WiMAX and WiFi service providers is higher because a user can choose the service with the lower offered price. Consequently, the prices offered by the service providers become lower.

Figure 6 shows the variation in the total bandwidth demand from a best-effort user (in Mb/s). When the quality of transmission in the WiMAX network becomes better, the bandwidth demand for WiMAX service increases. However, this decreases the bandwidth demand from the WiFi network because best-effort users may churn to the WiMAX network. In the Stackelberg game, because the WiMAX service provider can offer its service before the WiFi service provider does, the WiMAX service provider can set a higher price (Fig. 5a) so that the highest profit can be achieved. Consequently, the bandwidth demand of the WiMAX network decreases (Fig. 6).

Note that in the case of more than two service providers, a similar formulation can be used to obtain the solution of service competition in a heterogeneous wireless network. In such a case, the demand function for an arbitrary number of service providers as in [16] can be applied to obtain the best responses and the solution of the competition. Because there are more choices for the mobile users when the number of service providers increases, and hence, a higher level of competition exists among service providers, the service price will decrease.

**Conclusion**

Pricing is an important issue not only to maximize the revenue of the service providers, but also to allocate the radio resource efficiently. In this article, we discussed the challenges in designing resource allocation and pricing in heterogeneous wireless networks. Also, we proposed competitive pricing models for a WiMAX and WiFi-based heterogeneous wireless network. The competition between the WiMAX and WiFi service providers was modeled by using non-cooperative game models. However, the distributed implementation of the pricing models and the corresponding stability conditions were not addressed. Also, competition and cooperation among the users have not been considered in the presented pricing models. The pricing of the core network elements connecting the different radio access networks from different service providers also must be considered.

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References


Additional Reading


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