An Econometric Model for Resource Management in Competitive Wireless Data Networks

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Abstract

This article investigates the role and importance of the economic aspects that are vital to the success of wireless services deployment and provider selection by users in a competitive environment. We show how some of the econometric measures can meaningfully capture the user decisions/actions (e.g., churning) that can potentially be utilized by the providers in managing radio resources (e.g., bandwidth) in wireless data networks. In particular, by modeling the interaction between a service provider and its customers (or users) as a non-cooperative game, we propose a novel cross-layer resource management framework for integrated admission and rate control in CDMA networks. Analytical and simulation results demonstrate how the proposed framework can help minimize customer churning and maximize revenue for the wireless operators, yet optimizing customer satisfaction by providing differentiated quality of service to different classes of users.

The tremendous advancement in wireless communications technology, such as the third generation (3G) cellular systems as well as IEEE-802.11-based wireless LANs, and efforts toward seamless mobility management have created a global mobile network today. Alongside, the growing demand for wireless Internet access has prompted rapid growth of a wireless data services market. This also implies that a scarce resource like radio spectrum or wireless bandwidth has to be managed more efficiently in order to support a wide variety of (multimedia) data services.

Traditionally, telecommunication networks in most countries were monopolistically operated by the government or a regulated industry. However, the telecommunication deregulation decision in the 1980s was instrumental in making the wireless services quite competitive from the very beginning, thus allowing for faster deployment of infrastructure with competitive services and pricing. Due to this deregulation, multiple wireless service providers can operate in the same region, which means the customers (or users) have the freedom to select their providers as well as the opportunity to seamlessly roam across heterogeneous network interfaces that offer voice and data services at competitive prices.

Such flexibility, coupled with the recent mandate by the Federal Communication Commission (FCC) on wireless local number portability (WLNP) [1], has led to an unprecedented phenomenon called *churning*. This accounts for the migration of users from one service provider to another, mostly due to dissatisfaction with perceived quality of service (QoS) and competitive offerings of new services by other providers. Figure 1 illustrates an abstraction of the churning dynamics. The transformation from a monopolistic to a *competitive* market brings forth significant research issues and challenges in the design of architectures, algorithms, and protocols for wireless data networks. Even with lucrative offerings, providers are finding it difficult to control the churn rate (i.e., the rate at which existing customers leave their providers). Let us discuss next the impact of churning on service providers as well as on end users.

The Impact of Churn

Churning is a continuous process that manifests itself in the perception of user utility as an important aspect of the network design and operation. There are many factors that influence customer churning. They include marketing advertisement and promotional packages offered by the service providers, resource management policies, network coverage and reliability, pricing, service features offered, QoS, and so on. Thus, effective design of architectures, algorithms, and protocols for wireless data networks must include all these factors to keep the churn rate under control. The current network design paradigm is still based on a static set of rules that were primarily meant for a monopolistic environment. These network-centric rules comprising architectures, algorithms, and protocols are not suitable for efficiently managing resources in a competitive environment. Therefore, a new paradigm for wireless network design is required that can incorporate user utility functions to drive technological advancement with a goal of efficient network resource management.

The statistics from 2003 show that most wireless providers experienced an average churn rate of 2–3 percent/month, translating to about 30 percent/year. With the implementation of WLNP and higher competition, the churn rate is bound to rise even more sharply. This offers significant challenges to providers to retain a steady customer base. Moreover, the cost of churn to a provider is reported to be as high as $300 [2], which may include incentive plans (among other management costs) to attract new customers in order to maintain a nonde-

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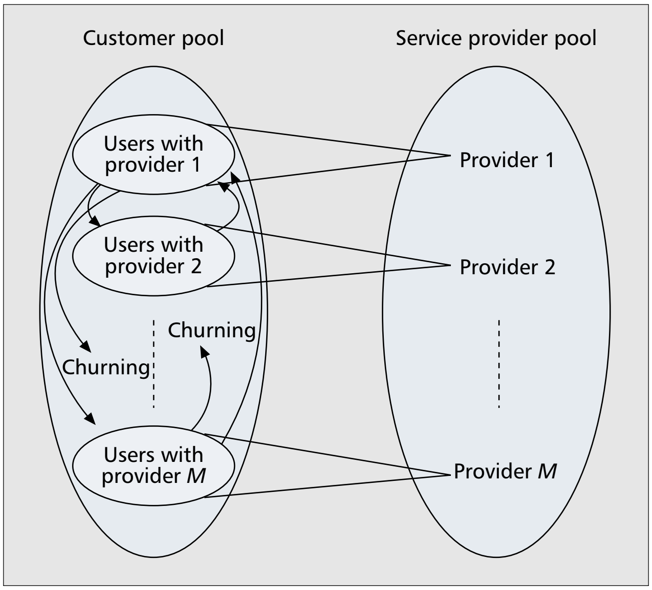


■ Figure 1. *Churning: migration of users from one service provider to another.*

creasing customer pool. With a churn rate of 33 percent, then, for a provider with a customer base of 1 million, the above translates into a loss of about $100 million. With such a high cost of churn, service providers must do everything possible to keep their churn rates as low as possible. Hence, we need to understand the complex relationship between user churn behavior and wireless network design, and its management and operations, especially managing the scarce bandwidth. This motivates our work.

Contributions of This Article

The essence of this article is to bring out the nexus between wireless network technology (e.g., resource management policies) and economics, often ignored by researchers. We demonstrate how the use of various economic factors can help enhance customer satisfaction, reduce churn rate, and improve the provider's revenue. For example, the utility of wireless data services to various classes of users plays a significant role in efficiently allocating resources among users. By modeling the relationship between a service provider and its customers as a non-cooperative game, we devise novel algorithms for network layer admission control at the session level and link/medium access control (MAC) layer rate control at the packet level, with a goal to efficiently manage the resources in code-division multiple access (CDMA) networks. In this cross-layer framework, the allocation of resources is adapted according to the flexibility of QoS tolerance in user utility. Conditions are also derived under which our game theoretic formulation leads to equilibrium solutions. Experimental results show that the proposed framework improves the provider's revenue, yet optimizing customer satisfaction and providing differentiated QoS for different classes of users.

The rest of the article is organized as follows. First, the role of economics and the effect of various econometric factors on user actions/decisions are explained. We highlight the need for a new paradigm for wireless network design and identify game theory as a potential candidate for this paradigm shift. Then we formulate the associated games and describe the resource management algorithms, admission control and rate control, for a CDMA-based system. Simulation experiments that capture the interactions between users and providers are also presented. Conclusions are drawn in the last section.

Econometric Considerations

The success of a technology or business is directly related to its economic viability. A well established technology might lose its stake for new customers to a competitor stepping up in the market. An industry can meet the customer challenges by defining subscriber values, determining a target prospect's propensity to be acquired, or determining a current subscriber's inclination to purchase additional services. When the customers are better understood and actions taken according to their buying preferences, not only is valuable data added, but also the profit margin of the service provider is improved.

In the case of wireless data services, as technology evolves and customer demands rise, providers will continue to encounter the life-cycle management challenges of customer acquisition, customer retention/loyalty, and service cost reductions. Increasing market penetration levels and declining average revenue per customer amplify these challenges.

Many service providers (or operators) have invested in the infrastructure development to support wireless data services as a means of differentiation and generating additional revenue. Moreover, billions of dollars have been paid to acquire portions of 3G spectrum. However, there is still skepticism about the successful deployment of 3G networks that would allow "anytime anywhere" access to the wireless Internet. This kind of debates and criticisms have created challenging problems for 3G wireless vendors and service providers, and there is little indication that they know how to solve them. Today, as we stand amidst all such confusion about 3G wireless systems and their deployment, there are already research efforts toward 4G mobile systems [3].

With all the chaos in the background, the natural question arises: "Is there any hope?" Hopefully, the answer is yes. The marriage between the Internet and wireless networks is paving the way to broadband wireless Internet access. Over the next few years, we can expect wireless LANs (WLANs) based on IEEE 802.11 technology to be omnipresent. These high-speed WLANs will interwork with 3G cellular networks to allow abundant opportunity for roaming across heterogeneous networks and service providers, and still offering true broadband services. Even though wireless data is a key focus, it brings forth increased risks associated with return on costly spectrum and infrastructure investments. The addition of wireless data to the customer care equation increases the number of customer interactions as well as the complexity of those interactions. The end result is escalating customer care challenges, specifically in the areas of cost per call and total call volume.

The Role of Economics

To retain its customer base, a service provider must make sure that customers are satisfied with the QoS they receive for the premium they pay. The level of customer satisfaction received from the system can be represented by *utility*-based functions due to the fact that each customer spends his/her disposable income in the way that yields the greatest amount of satisfaction or utility [4]. In the future, new wireless data services with better utility may be introduced to substitute for some existing services. These new services, however, may not necessarily provide additional revenue to the providers. This is because users will almost always attempt to replace old services with newer ones without exceeding their budget. This gradual replacement of services will allow new services to diffuse into the market as more and more users accept them. By understanding how new services diffuse, service providers can define the demand function, which is then used to derive the real network demand. Thus, a sound econometric model is required to determine the impact of demand on the resources in wireless data networks such as the wireless Internet.

Consistent economic models should guide the creation of demand on content, services, and applications. This approach would require new algorithms and protocols, the development of which must combine ideas from economics and networking research. It has been well accepted that the current wireless data network models are flawed, in the sense that they fail to capture:

- The utility of the services and network from the users' perspective
- The impact of user demands on revenue utility from the service providers' perspective

The deployment of new wireless Internet services is also impeded by the lack of market incentives to improve network services and applications along with their efficient use by the common people. Recent history has demonstrated that even with all the technological successes, perhaps the bottleneck for better services still lies in economics. The failure of Motorola's satellite-based Iridium system and Metricom Ricochet's high-speed data services in wide area wireless networks are two concrete examples corroborating this fact. Finally, wireless service providers are not too keen on implementing the Internet Engineering Task Force (IETF) defined protocols due to lack of economic incentives.

In the rush to provide quick solutions for immediate market returns, we believe the algorithms and protocols being developed are often short-sighted in nature. Careful consideration of user demands for technology and the extent to which they are willing to adopt these technologies must be taken into account. In other words, the development of algorithms and protocols should address not only the issues related to stability, convergence, and scalability, but also factors such as unpredictable user requirements, revenue distribution, and economic incentives.

Careful analysis reveals that most research on resource management in wireless networks mainly focuses on QoS provisioning and traffic management to optimize an objective function like overall system throughput or resource utilization. However, such an objective function in most cases is too generic and fails to capture the true utility from both the users' and provider's viewpoints.

Paradigm Shift: From Control Theory to Game Theory

As mentioned earlier, prior to deregulation of the telecommunications industry, most networks were monopolistically operated, with only one provider controlling the network and making resource management decisions independently based on available information. In such a scenario, most deployed resource sharing algorithms were based on the control theory approach.

With the market environment changing from monopolistic to competitive, service providers must continuously play with and manipulate different parameters so they can retain a steady customer base and also generate revenue. Given that one of the major driving forces behind the success of a new technology is the market economy, it is necessary to consider the technological aspects as well as the broader economic impact of the technology on society.

Game theory has been recognized as a cornerstone of micro-economics that can be applied to analyze problems with conflicting objectives among interacting decision makers. In any competitive market, customers may operate as a pool wherein they agree to pay for services that in a way also determine the value of the commodity. Thus, game theory offers a powerful mathematical tool to study different problems in science and engineering from an econometric point of view. It has been extensively applied to various competitive environments including the energy market, airlines industry, and Internet services. Recently, it has also been successfully used to deal with problems in the field of networking and communications [5–7]. This is because the service quality each user receives in a competitive environment is often affected by the action of other users trying to gain access to the same network resources.

Basics of Game Theory

Let us first understand the basics of game theory as widely used in the economics domain to model interactions among parties with conflicting interests, where each party is called a *player*. In a game, each player's strategy has impact not only on his/her own payoff, but also on other players' payoffs. Depending on whether cooperation is allowed among players, games can be divided into *cooperative* and *non-cooperative* categories.

The most basic form of non-cooperative games is a two-player game in which each player has a set of *strategies* with associated *payoff* values; each player makes an independent decision on a strategy so as to get the most out of the game on the basis that the other player is not *cooperating*. Thus, the outcome of the game is to find a pair of strategies, one for each player, that optimizes the payoffs of both players. Games can be played in two forms [8]:

- *Normal form* where each player makes a strategy decision without knowing the decision of the other player
- *Extensive form* where at least one player has partial information about the other player's decision

Mathematically, a two-player non-cooperative game consisting of players P_1 and P_2 is defined by payoff matrices A and B, respectively. Assume P_1 has m strategies denoted $s_1, s_2, \ldots, s_m$ and P_2 has n strategies denoted as $t_1, t_2, \ldots, t_n$. Thus, the rows in the payoff matrices represent P_1's strategies, while the columns represent P_2's strategies. More precisely, the element a_{ij} of matrix A defines P_1's payoff when P_1 chooses strategy s_i and P_2 chooses strategy t_j. The element b_{ij} of matrix B is P_2's payoff when P_1 chooses s_i and P_2 chooses t_j. Since this type of game is defined by two payoff matrices, it is also called a *bimatrix game*.

Games can be divided into *zero-sum* and *non-zero-sum*. For a two-player game, if $a_{ij} + b_{ij} = 0$ for $1 \le i \le m$ and $1 \le j \le n$, it is a zero-sum game; otherwise, it is a non-zero-sum game. In a zero-sum game, a player's gain in payoff results in loss in the other player's payoffs; in non-zero-sum games, a certain strategy change could result in gain for both players.

In a bimatrix game defined by the payoff matrices $A = [a_{ij}]_{m\times n}$ and $B = [b_{ij}]_{m\times n}$, a pair of strategies $\{s_i^*, t_j^*\}$ is said to constitute a *non-cooperative (Nash) equilibrium solution* [9] to the game if the following pair of inequalities is satisfied:

$$\begin{cases} a_{i^*j^*} \le a_{ij^*} \\ b_{i^*j^*} \le b_{i^*j} \end{cases} \text{for all } i = 1,\ldots,m \text{ and all } j = 1,\ldots,n.$$

Intuitively, the Nash equilibrium is the point where no player in the game can improve his/her payoff by changing his/her own strategy, if all other players' strategies remain unchanged. In other words, the Nash equilibrium is the point where there is no incentive for players to change their strategies if there is no cooperation among them.

Game Theory for Internet Pricing

There has been a lot of effort to understand the pricing of Internet services from both the economics and engineering perspectives. Internet pricing is important because it has a profound impact on cost recovery, maintaining a competitive market, and regulating user traffic. The application of game theory in the Internet domain has been based primarily on the "leader-follower" framework in which the Internet service providers (ISPs) publish the price and customers react to that price. The task of the ISP is to strike a balance between the price and demand to maximize the provider's revenue.

Cooperative game theory has been used to obtain a Nash bargaining framework to address issues like network efficiency, fairness, revenue maximization, and pricing [10]. Repeated non-cooperative games have also been used for market-based modeling for network resource management [11]. In most cases, the existence of a unique Nash equilibrium and its reachability using a decentralized approach has been studied. Game theory has also been used to study the pricing structure of a network service. To recover cost, network providers must understand user behavior and demands to offer different service plans. It has been shown how the network can behave as an active player in order to maximize its revenue. The network solely decides on the favorable operating point and forces the users accordingly. Similar approaches using game theory have been used to determine the Internet pricing model. For example, a pricing model proposed in [12] is for differentiated network services with one seller, one broker, and multiple users. The existence of a Nash equilibrium with two Internet service providers (ISPs) is studied in [13]. It has been shown that cooperation between two ISPs benefits both of them as well as users. Indeed, a lot of progress has been made on Internet pricing since the relationship between congestion control and pricing was first introduced in [14].

Wireless Resource Management

We are now ready to develop an econometric model, based on game theory, to capture the relationship (with conflicting interests) between a wireless service provider and its customers, and then use this model to efficiently manage resources in competitive wireless data networks. In particular, we demonstrate that the proposed framework significantly improves the service provider's revenue over traditional wireless cellular systems, and also provides differentiated QoS for different classes of users [15]. Our approach leads to a novel cross-layer framework for resource management that involves admission control in the network layer and rate control in the link/MAC layer.

For our subsequent presentation, we consider a wireless CDMA cellular network capable of both voice and data communications. Since such systems are interference limited, there is no hard limit on the number of voice channels that can be supported. However, admitting a new user into a saturated CDMA network results in either an infeasible power assignment (for voice calls) or higher delay for ongoing data sessions. This is because the admission of an additional voice call in a CDMA system reduces the power assignment of each existing call by some proportion, thus leading to graceful degradation in overall performance. On the other hand, admission of a new data session will increase the queuing delay of non-real-time data packets.

The Rationale

Let us justify why the admission control game in a competitive wireless data network is indeed non-cooperative and non-zero-sum in nature.

The service provider, on one hand, wants to maximize its own revenue. (Note that the service provider's incentive-based attempt to maximize user satisfaction or system utilization is merely a way to achieve this ultimate goal of revenue maximization). So the service provider's revenue is modeled as its payoff from this game. Users, on the other hand, want to maximize their own QoS satisfaction at minimum expense, given that they have the freedom to leave the current service provider and subscribe to a better one in a competitive market. Thus, the user's overall satisfaction is modeled as his/her payoff from the admission control game. Since these two goals are different and often conflict with each other, the service provider and a customer have no apparent motivation to cooperate with each other to achieve a single optimal goal. It is worth mentioning that the single goal optimization so far undertaken by most existing approaches does not justify the effectiveness of the service provider's strategy for resource management that, in our opinion, should include both admission control and rate control schemes in an integrated manner.

Second, the game is also non-zero-sum. In order to justify this, let us assume that the game is zero-sum in the sense that an increase in one player's payoff implies a decrease in the other player's payoff. However, this may not be true for the relationship between the payoffs of a wireless service provider and customer. For instance, when the system is underutilized, admitting a new request that does not affect the QoS of other ongoing sessions would increase the service provider's revenue as well as the customer's satisfaction. Thus, the payoffs of both the service provider and user are increased, which conflicts with the zero-sum assumption. Thus, this game has to be modeled as non-zero-sum.

Game Formulation

Let us assume that the service provider has two strategies: (SS_1), admit the request or (SS_2), reject the request. The customer seeking admission also has two strategies: (CS_1) leave the current provider, or (CS_2) stay with the provider. The payoffs of these two players are expressed in the form of matrices $A = [a_{ij}]_{2\times2}$ and $B = [b_{ij}]_{2\times2}$, where a_{ij} and b_{ij}, $i \in \{1,2\}$ and $j \in \{1,2\}$, respectively, denote the provider's and customer's payoffs if the provider chooses strategy SS_i and the customer chooses strategy CS_j.

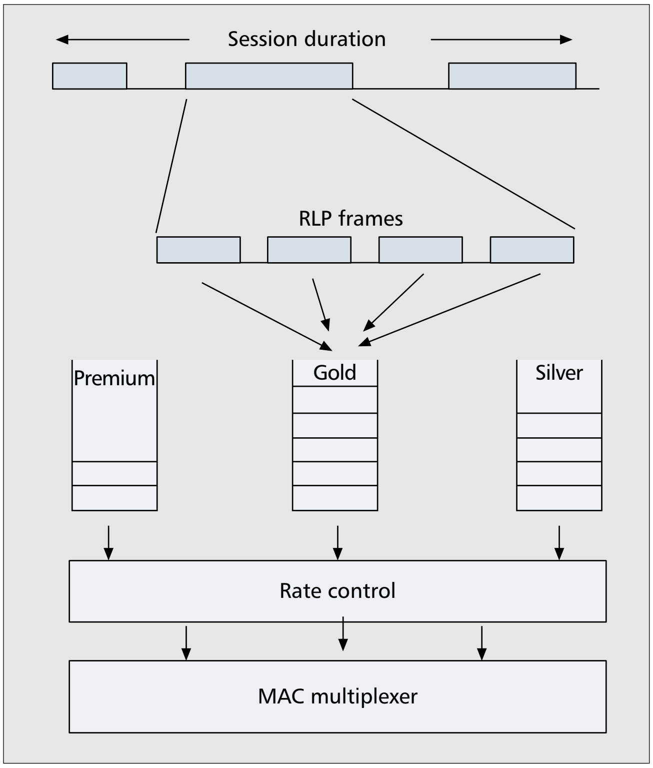
Depending on the particular strategies chosen by the service provider and customer, the payoff of the service provider will be a combination of one or more of the following components:

- The revenue earned from all ongoing sessions
- The revenue gain if the new session request is admitted
- The revenue loss due to churn of the user seeking admission (if rejected)
- The revenue loss because of the possible churn of other users

The first three components in the above payoff are straightforward. To explain the fourth component, let us consider a fully loaded CDMA system. In such a system, admitting a new customer would result in either an infeasible power assignment for voice calls or delay of ongoing data sessions. Either of these cases may prompt churning of customers whose ongoing sessions are being affected, hence incurring revenue loss for the provider.

Admission Control

The admission control game is invoked when a new session request is received by the system, which then decides whether to accept this request by allocating a certain amount of resource, or reject it due to lack of resource. This decision making process is carried out by the network resource management scheme on behalf of the service



■ Figure 2. *Controlling aggregated flows.*

provider. We formulate such a process as a two-player non-zero-sum non-cooperative game. Admission control can be done in *one-by-one* mode, processing the requests one by one. In other words, one instance of the game is played every time a new session request comes into the system. In this two-player game, the players are the service provider (or the system processing the new session request) and the customer currently requesting a session establishment. Admission control can also be performed in *batch* mode in which multiple session requests are processed at a time, leading to an *n*-player game.

The payoff of the user seeking session admission is composed of the following components:
- The user utility corresponding to whether he/she is admitted or rejected
- The user utility when he/she chooses to stay with the service provider or churn out

As an outcome of our game formulation, the final decision on the admission control scheme is the *equilibrium* generally considered as the "stable" solution to this type of non-cooperative game.

In [16] we proved that for both underloaded systems (in which admitting a new session does not affect ongoing sessions) and fully loaded systems (in which admitting a new session affects the QoS of some ongoing sessions), there exist Nash equilibria in the game as defined above. Intuitively, if the system is underloaded, a win-win strategy pair will be one in which the service provider chooses to admit the session and the user also chooses to stay with the current provider. When the system is fully loaded, the equilibrium is decided by the relative values of revenue gain (denoted F) in admitting the new user and the potential revenue loss (denoted L) from other users whose services are affected by the newly admitted session. More precisely, if $F > L$, the service provider is better off admitting the request; otherwise, rejecting the request is a better option. The service provider can directly use such equilibrium results for making the admission control decision.

Dynamic Rate Control

Since the admission control scheme does not force a hard limit on the number of simultaneous sessions that could be admitted into a CDMA system, it is possible that not all sessions can get feasible power assignment to support their full-rate transmissions. Here we propose a simple rate control mechanism between the link and MAC layers so that the packets from certain sessions are buffered, and consequently their transmission rates can be reduced such that the allowed power limit is not exceeded. The econometric rate control algorithm is also based on games where the system tries to exploit the tolerance level of users and accordingly assigns power such that the churn rate is low. It can be noted that if an ongoing session is deprived of adequate power, the user may not decide to churn out of the network instantly. However, if he/she continues to experience degraded services, eventually the probability of churn increases significantly.

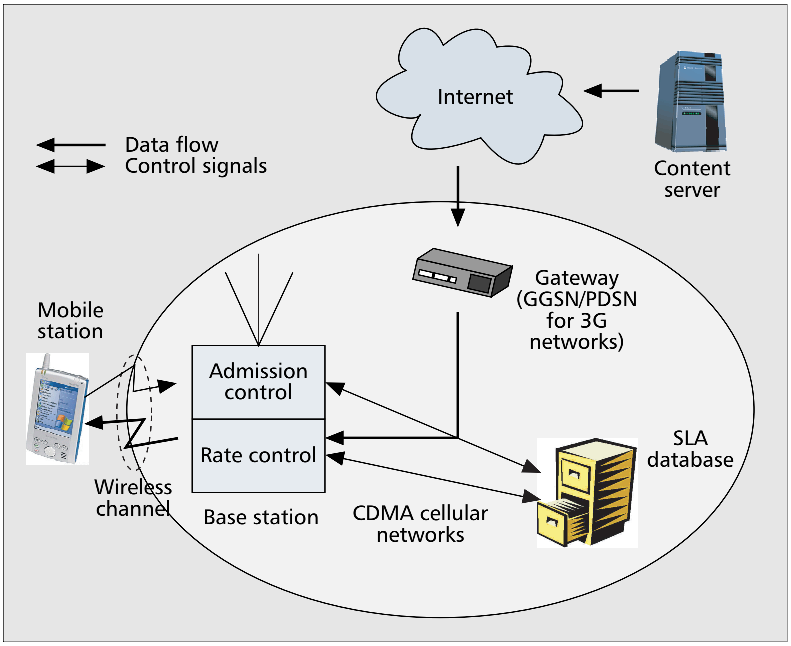
The goal of our rate control algorithm is to provide a differentiated data rate to each class of users — the higher the priority class, the higher is the data rate. Regarding the power control, any standard algorithm [17] can be used to find the power allocated vector $P = [p_1, p_2, \ldots, p_N, p_{N+1}]$ after admitting the new user, where p_i is the power assigned to the ith user and N is the total number of users in the system before the new user arrived. Let P_{max} be the total maximum power a base station can transmit. If $\Sigma_{i=1}^{N+1} p_i > P_{max}$, the rate control algorithm is initiated to ensure that no more data than the system can transmit is fed into the MAC layer multiplexer (mux). The main objective is to provide a bound on the delay a user class is willing to tolerate. Thus, the proposed scheme takes into account the flexibility of delay tolerance among user classes in order to manipulate their power assignment. The smaller the delay bound, the lesser the blocking probability of packets of that user class at the MAC layer mux.

Figure 2 illustrates how the rate control can be accomplished for three classes of users: premium (class 1), gold (class 2), and silver (class 3). In each base station of the proposed framework (Fig. 3), the aggregated forward link traffic flows corresponding to these classes are controlled through a gating mechanism. Upper layer segments from each data session are fragmented by the radio link protocol (RLP) to form RLP frames. The rate at which the rate controller feeds these frames to the MAC layer mux depends on the user class that generated the frames.

The rate control scheme has the capability to continuously measure the signal-to-interference ratio (SIR), which indicates the average power (or energy) per bit required by the forward link to optimize the flow rate. Based on these measurements, the rate control is activated on a frame-by-frame basis. The rate control logic makes use of the frame-level SIR measurements and determines how many packets can be transmitted to the MAC mux using optimal power per bit. The power control algorithm at the MAC layer is not affected by this rate control mechanism. The MAC layer receives the number of frames that maximizes the throughput of the system. In summary, the basic idea of our rate control scheme is to reduce the transmission rate of users in the same class as well as lower classes so that the power budget is not exceeded.

Experimental Results

The game-theory-based integrated admission and rate control framework is simulated to evaluate its performance. The architecture of the CDMA network is shown in Fig. 3. A mobile station communicates through a wireless channel to the base station, which executes the admission control algo-



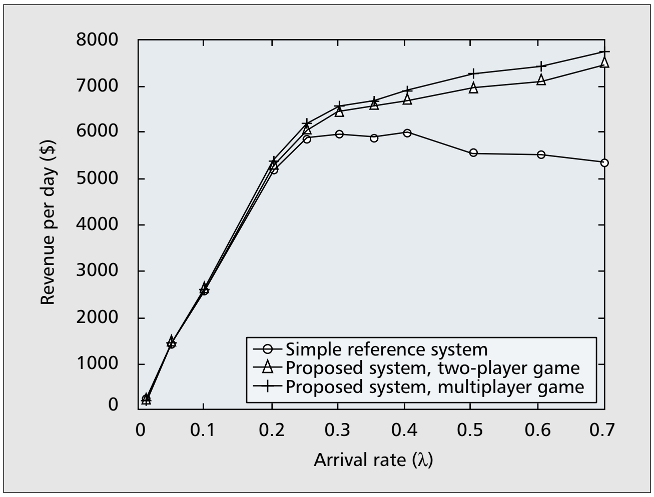
■ Figure 3. *The architecture of the proposed framework.*

rithm at the session level and the rate control algorithm at the packet level, in consultation with the service level agreement (SLA) database, which maintains the user profiles. The base station is connected to the backbone Internet via a gateway. With respect to such performance metrics as the revenue generated and its percentage improvement, our experimental results demonstrate that the proposed framework can provide differentiated services to different classes of users [15]. More important, we show it is able to allocate resources so that the service provider's revenue is maximized. In order to illustrate this, we have compared the performance of the proposed framework with a *reference* system with a simple admission control scheme but no rate control. The reference system admits a request as long as the total number of users (of all classes) after admitting the new request does not exceed the capacity of the system. The comparison is based on the average revenue generated by both the reference and proposed systems for each 24-hour period. The total revenue is calculated by summing all the revenue gathered from the sessions admitted into the system minus the revenue loss caused by user churning due to unsatisfied or degraded service. Figure 4 shows the variation of revenue generated against the session arrival rate (λ) by the reference system and two variants of the proposed econometric-based system in a 24-hour period.

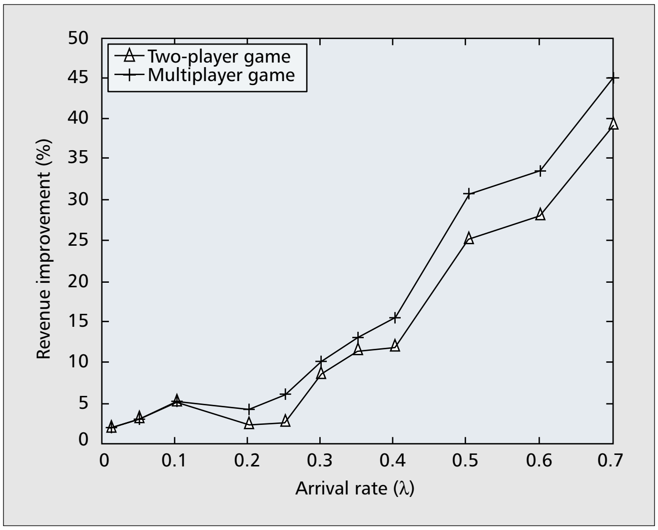
When the session arrival rate λ approaches or exceeds the full capacity of the system (i.e., λ ≥ 0.3), the proposed system generates much more revenue than the reference system. Moreover, as shown in Fig. 5, the multiplayer game admission control (batch) mode produces higher revenue than the two-player game (one-by-one) mode. Here the improvement is with respect to the reference system. The gain for the multiplayer game comes from the fact that the service provider has more candidate strategies in each instance of the game, and hence more potential for selecting the mix of users that can result in higher revenue. The price paid for such revenue gain is a longer admission request processing time, since requests are buffered before processing. Our results show that the proposed system is capable of identifying the pros and cons of selectively accepting requests to generate more revenue.

Conclusion

Communication on the move has become an integral part of our everyday life. Indeed, wireless communications and networking have greatly impacted the very way people interact with technology, devices, and human beings. However, the fact remains, in many cases, that incumbents have spent vast amounts of money acquiring (through auctions) new spectrum on which to offer service. The technology-driven economic burden of new services is forcing the providers to look for new application avenues, business models, and opportunities for survivability. In parallel, researchers are addressing various technical issues and challenges with a goal to develop better architectures, algorithms, and protocols. Only recently has the dependence on econometric factors been recognized as being so important that they are being slowly brought into mainstream research in this area. Better understanding of economic constraints can help us change the wireless network design philosophy, leading to further innovations in the field of wireless communications and networking that will prompt new ser-



■ Figure 4. *Revenues of the reference and proposed systems.*



■ Figure 5. *Revenue improvement of the proposed system.*

vice domains. Over the next several years, we can expect not only the commercial success of complementary deployment of both 3G wireless networks and IEEE-802.11-based WLANs, but also their economic viability. As the next-generation wireless technologies (3G and beyond) become reality, users will have the unprecedented opportunity to roam seamlessly across competitive service providers and technologies, and also shop for services as and when required. This will open up new challenges for wireless providers who will focus on ensuring the absolute quality of their own service offerings (data rates, QoS guarantees, price, etc.) in addition to their relative advantages over alternative providers.

To this end, this article has attempted to formulate for the first time such competition among service providers with the help of non-cooperative games and derived some interesting results, including Nash equilibria conditions. Further work is needed to extend the game model to accommodate more involved (multiple-threshold-based) strategies for both users and service providers in the admission and/or rate control scheme(s). Note that the framework presented here deals with only one cell (or base station) in a CDMA system. As the user moves from cell to cell, session handoff needs to be incorporated, thus leading to mobility-aware resource management. Finally, a more sophisticated game theoretic power control algorithm can be designed that should be integrated with admission and rate control schemes such that our cross-layer resource management framework addresses all three layers (physical, link, and network).

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