To subscribe, or not to subscribe: The analysis of new service paradigms in cellular markets

FORTH-ICS TR 424, AUGUST 2011

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***Abstract*—Traditionally customers subscribe to specific operators/providers and are served by accessing base stations (BSs) of the network of their operator. Often subscribers with relatively "high" usage pattern and data-rate requirements are subsidized by the ones with lower usage and data-rates. As the cognitive radio technology advances, an even more diverse set of services will be available. This paper introduces a novel service paradigm the flexi-card or card that allows a customer with a cognitive radio to dynamically access base stations (BSs) of different infrastructures and operators based on various criteria, such as its profile, network conditions, and offered prices. Card customers can select the appropriate operator and BS on a per-call basis. This work considers a diverse customer population based on their demand, their preference on data-rate over price, their tolerance on the blocking probabilities of their calls, and their willingness to pay for certain services. Customers could dynamically decide to buy a long-term subscription or become card users. In this paper, we develop a modeling of this market and analyze its evolution, focusing on whether this new paradigm can improve the quality of service, social welfare, flexibility and further enhance the competition among providers. The main contribution of this paper is a detailed modeling and an in-depth performance analysis of a complex market, in which various parameters manifest in different spatial and temporal scales, with a diverse customer population, from the perspective of clients, operators, and regulators, demonstrating the benefits of the card service paradigm, and comparing it to markets that offer only subscription contracts.**

I. INTRODUCTION

The expectation that the commercial deployment of cognitive radio networks (CRNs) will lead to improved network services has triggered numerous research and industrial activities and discussions about the dynamic spectrum access and sharing mechanisms. Traditionally, cellular wireless networks are managed by operators, which offer a fixed part of the spectrum to their customers via subscription mechanisms. Subscribers and pre-paid card users are associated with a certain operator to access the spectrum. However, new paradigms in both the wholesale and retail spectrum market and service models are being formed. Unlike the traditional cellular-based markets, these spectrum markets have larger sizes (in terms of number of potential providers), are more heterogeneous (in terms of services, clients, and providers), and potentially can offer an improved set of services (e.g., higher multiplexing gains and a reduction of costs due to the higher utilization of existing infrastructure).

As the wireless access and use increases, customers are differentiated even more by their usage and data-rate requirement profile. Often subscribers with relatively high usage pattern are subsidized by the ones with lower usage demand. As the cognitive radio technology advances, an even more diverse set of services will be available. To this end, we proposed the novel paradigm of a card client that is not associated with a specific operator and can dynamically access base stations (BSs) of different infrastructures and operators based on various criteria, such as its profile, the network conditions, and the offered prices. Specifically, card users are flexible to select the appropriate operator on a per-call basis. This "flexi-card" paradigm, which has been assumed as a typical access paradigm in wireless LANs, could be a new type of service offered in spectrum markets. A similar concept is the "soft" (or virtual) SIMs cards.

This work models a cellular market, its providers and a population of clients, highlighting the impact on the new service paradigms of card users on the evolution of the market and the welfare. Customers could dynamically decide to buy a *long-term subscription* or become *card* users. As card users, they can decide about their provider on a per-call basis, while as subscribers they are associated with a specific provider for the entire duration of their contract. The decision making processes of a client for selecting the appropriate service paradigm take into consideration the constraints, demand, and QoE criteria of that client. We use the terms customers, clients, and users interchangeably throughout the paper.

The analysis considers different customer populations and the perspective of regulators, users, and operators, possibly with conflicting objectives. A primary role of regulators is to promote competition and social welfare, a fair inclusive treatment of various user populations with respect to services and access, e.g., by minimizing the number of disconnected customers. Clients target to improve their access (e.g., by reducing their blocking probability) and satisfy their demand, according to their profile. On the other hand, the revenue maximization is the primary objective of providers.

Several questions drive this research: Will this additional service paradigm improve the social welfare by providing more options to customers? What is the impact on the benefit of customers, revenue of providers and market share? Are more or less users excluded from the wireless access due to the market prices offered? Would card service be a viable option for operators and a way to differentiate their services and attain more revenue? How does the traffic demand and customer profile shape the decision making mechanism and market share of customers? Would subscriptions “die out” and card users dominate the customer population? How does the market “treat” the different customer populations? What are the related pricing decisions of the operators and how they affect the outcome?

The detailed modeling of the paper allows us to perform an in-depth performance analysis of a cellular duopoly market where providers compete for a *diverse* population of customers who can access *two different services*. This is an important contribution of this work since most related papers focus on just one good. It is important to note that claims on optimality made on various related papers (e.g. [1], [2], [3]), with respect to the revenue of providers, the social welfare, and market efficiency, though valid in their context where providers compete for selling one good for a certain price, may not hold in our setting. In general, product differentiation allows for a finer market segmentation and can further increase the revenue of providers. In our model, there are two goods to be offered to the market, and thus, two different prices to be offered for those goods: the pricing decisions of the network operators are more complicated but at the same time allow for a finer partitioning of the market and possibly higher participation for users and revenue for the operators. That is, users that may have been “excluded” in a market where only long-term contracts are offered, due to the fact that their communication needs and respective willingness to pay do not justify entering this market, could now consider beneficial the good of “cards”, thus increasing the overall market pie. This market exhibits several complexities due to the interplay of several parameters (e.g., the dynamic decisions of clients, their multiple options, the competition among providers, the diverse customer profiles) both in time and space. This paper develops a rich modeling framework and simulation platform that allows the analysis of the evolution of such markets. It demonstrates the benefits of the card service paradigm and offers important insights to regulators, customers and providers.

Section II overviews the related work. In Section III, we present the modeling framework and the main features of the simulation platform that instantiates it. Section IV-A describes the simulation scenarios and Section IV-B discusses the main results. Finally, in Section V, we summarize our main conclusions and future work plans.

II. Related work

A part of the game-theoretical research on spectrum markets explores competitive pricing in which providers are aware of their competitors and aim to maximize their own utility function (e.g., [4], [5]), while other papers consider providers that cooperate to maximize a common utility function (e.g., [6]). In addition to the type of interaction across entities in the market, the available information is another critical parameter. For example, some studies consider complete knowledge, i.e., each entity knows the utility functions and the strategies of all others (e.g., [5], [6]), while other studies assume partial knowledge, in which each entity is aware only of its own utility function and strategy [7]. In general, pricing issues in spectrum markets have received considerable attention in the literature. However, most of the papers have addressed these issues in a somewhat narrow scope and with simplistic models. In particular, Al Daoud *et al.* [1] consider a single provider of a CDMA-based cellular wireless network, who leases to a single lessee a part of his network, thus attaining revenue from both the leased part and the remaining part. The authors use a reduced load approximation to compute the blocking probabilities in the network and assess the lessor’s optimization tradeoff stemming from the revenue attained due to the exercised price of the region versus the cost due to the reduced spatial coverage of its network and the possible interference from the leased region. Both this paper and the earlier work [8] lack a realistic model of the users and their demand; calls and users are assumed to be identical, user mobility is not taken into account and both the microscopic and mesoscopic model are abstracted by means of functions that attempt to approximate end user demand. Most importantly, this model does not allow for users to choose a certain provider given the price policy employed; instead an “exogenous” demand function is used to depict demand. Overall, this paper and many similar ones, though providing some insight to the pricing issue, fail to provide a complete and realistic model of the market and the network as a whole, including user incentives and behavior.

Paschalidis and Liu [9] establish an asymptotically optimal static pricing scheme for calls, that does not depend on system state, assuming that traffic load and system capacity tend to infinity. Their assumptions are somewhat restrictive for the currently underutilized cellular networks. Unlike that paper, our work focuses on the evolution of the market, highlighting various complex dynamics and transient phenomena, and aims to provide insights for a multitude of settings regarding the customer population, preferences, mobility, demand, and network load. Mutlu *et al.* [2] also consider a wireless provider who caters to two classes of customers, namely primary and secondary users and attempt to solve the provider’s profit maximization problem under unknown demand function and call length distribution. The authors show that occupancy-based policies are insensitive to the call length distribution, except through the mean. Maillè *et al.* [3] derive a model where two operators compete for end users and one of the networks is also a customer of the other since it purchases a part of its spectrum. They investigate whether and when the leasing of spectrum is indeed beneficial for the primary operator and also investigate the resulting market phenomena. However they do not consider any product differentiation and their assumption that the secondary operator is by definition more efficient in terms of spectrum usage compared to the primary is not necessarily realistic. In addition, their microscopic layer modeling does not consider user distributions, mobility, and spatial reuse.

Finally, the agent-based economies and pricing issues is the focus of [10] (part of the infoecon activity [11]), which provides insights about several interesting phenomena, such as price wars, niche markets, market oscillations. In our work, we also investigate and explain such phenomena as the proposed cellular markets evolve.

This paper builds on our earlier work [12], [13], and extends it in several ways: it provides new price setting algorithms for subscriptions and card rates, a model for the blocking probability that providers can use, a richer model of the cellular market (e.g., customer profiles, populations), and performs an extensive analysis of the interactions between customers and providers when there is the choice of the card service. Furthermore, it investigates an entire new set of metrics (e.g., social welfare) and dynamics.

III. Modeling framework and simulation platform

The modeling framework is fully configurable and parameterized based on the channel, infrastructure and network topology, type of users (e.g., service, demand, mobility, constraints, preferences, decision making processes), providers (e.g., price estimation, services), and available information. We have developed a detailed simulation environment of this framework, which is modular, in that, it can instantiate and implement different models for these parameters.

A. Cellular topologies

Each provider has deployed a cellular topology that offers wireless access via its BSs to clients in a small city. The providers divide their channels into time-frequency slots according to a TDMA scheme. To simulate the channel quality, we employed the *Okumura Hata* path-loss model for small cities considering the contribution of shadowing to the channel gain [14], [15]. The interference power at a BS during a time frequency slot is computed considering the contribution of all interfering devices at cochannel BSs.

B. Clients

Client demand Clients generate requests to connect to a BS to start a *call* (i.e., flow). The duration of calls and *off durations* (i.e., time interval between the end of a call and the start of the immediately next one of the same customer) are given by appropriate distributions. Specifically, the *call duration* follows a Pareto distribution, while the *off duration* is generated according to a Lognormal distribution (as were modeled in our empirical-based modeling work [16]). We assume that each client knows the parameters of these two distributions. To perform a call, the client needs to select a BS.

Service types A client needs to select a *service type* or remain *disconnected* (during a disconnection, the client does not make calls). Two customer types are considered, namely, the subscribers and card users, with their corresponding service types of subscription and flexi-card, respectively.

As mentioned earlier, for a call, a client needs to select a BS. A card user may select a BS of *any* provider, while a *subscriber* of a certain provider connects *only* to BSs of *that provider*. A subscription lasts for an *epoch*, a fixed time period for all subscriptions.

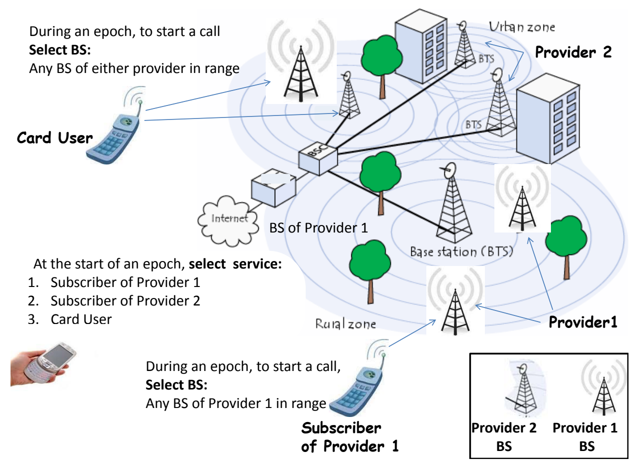

Fig. 1: An example of a cellular-based duopoly with a card user and a subscriber.

Customer profile The profile of a user includes the *constraints, demand*, and *preferences* of that user. The constraints of a user are quantified by four thresholds: two thresholds for the service selection and two thresholds for the BS selection. The constraints of a user (u) for the service selection are expressed by its *willingness to pay for a service* (e.g., $T(u)$) and its call *blocking probability* tolerance threshold ($B(u)$). Moreover, the constraints of a user u for the BS selection are, its *willingness to pay for that call* and the *minimum acceptable data-rate*. On the other hand, the preferences indicate the selection criterion, which can be either based on the monetary cost of the service or the QoS (e.g., the data-rate, call blocking probability). The preferences criteria are used for *selecting a service type* as well as *selecting a BS*.

Service type selection A client selects the service that optimizes the metric that reflects its preference with respect to the blocking probability or the cost. Specifically, in the case of a cost-conscious customer, the client selects the service that minimizes its cost spending, while a QoE-conscious customer selects the service that minimizes the blocking probability.

BS selection During an epoch, subscribers and card users make calls. For each call, a client selects the BS of their wireless range based either on the data-rate or price criterion. Specifically, a price-conscious client selects the BS that *minimizes its cost spending*, while QoE-conscious clients select the BS that *maximizes their achievable data-rate*. For the service selection, a client expresses its preference with respect to cost and blocking probability, while for the BS selection, the preference is over cost and data-rate. For example, a client may select its service type based on the blocking probability criterion and the BS based on the price criterion.

u-map The market assumes the presence of a user-centric data repository that maintains information about the customer population. The u-map is a data structure that corresponds to a grid-based representation of a region. At the end of an epoch, each client reports the percentage of blocked calls and its service type at the u-map. The call duration, status, customer id, and provider id are recorded at the u-map. Statistics on the mean, median, and maximum blocking probabilities across all subscribers of the same provider are computed and reported at the u-map, taking into consideration the values reported by clients at the end of an epoch. Providers report their subscription and card-rates at the u-map. Furthermore, each client reports information about its constraints, demand, and preferences at the u-map.

Decision-making processes of clients The decision-making process of a user involves *long-term* decisions made at the beginning of each epoch for selecting the service type for that epoch and *short-term* decisions for selecting the appropriate BS at *a per call basis*. For each of the three service options, namely, to become subscriber of the Provider 1, subscriber of the Provider 2, or card-user, *the service constraints need to be satisfied*. Specifically, a client first checks whether the total cost for that service is under its willingness to pay threshold *as well as* the estimated blocking probability with that service is under the blocking probability threshold.

A client needs to estimates the blocking probability for each of the above services. Specifically, the blocking probability of subscribers of a certain provider is estimated as the average blocking probability as reported by all subscribers of that provider during a last time period (of multiple epochs) at the u-map. The blocking probability for the card service is estimated as the average blocking probability of all card users during the last time period (of multiple epochs) as reported at the u-map.

The client selects the service that optimizes the metric that reflects its preference (e.g., blocking probability or price preference). Specifically, in the case of a cost-conscious customer, the client selects the service that minimizes its cost spending, while for blocking-conscious customer, the client will select the service that minimizes the blocking probability.

After the service-type selection, during an epoch, clients make calls and, for each call, a client selects the BS of its wireless range based either on data-rate or price. Specifically, the price-conscious clients will select the BS that minimizes their cost spendings, while data-rate conscious clients select the BS that maximizes their achievable data-rate. Note that in both the service and BS selection process, a customer has predefined preferences. Specifically, for the service selection, the preference is over cost and blocking probability, while for the BS selection, the preference is over cost and data-rate.

The transmission rate is computed based on the Shannon capacity theorem, although more sophisticated models that take into consideration the modulation schemes can also be incorporated easily [17].

Client and call status A client becomes *disconnected* when *any* of its constraints for the *service* selection can *not* be satisfied. Otherwise, the user chooses a service type (subscriber with one of the two providers or card user) according to its preference. A call can be *successful* or *blocked*. An unsuccessful selection or association process with a BS results to a blocked call. Specifically, a call is blocked when *any* of the client constraints for the *BS selection* can *not* be satisfied by any BS in the wireless range of the client or *all* the channels of these BSs have been serving other calls.

Client mobility Clients move with pedestrian speed according to a random waypoint like model.

C. Providers

Decision making processes of providers Providers perform two decision making processes, namely, (a) the estimation of their subscription rate at the start of each epoch, and (b) the estimation of the card rate that takes place multiple times during an epoch. The subscription rate is decided at the start of an epoch and remains fixed during that epoch, while the card rate is updated multiple times during the epoch. A provider does not apply any priority or reservation algorithm for serving the calls in its cellular infrastructure.

Tariffs/charging schemes The subscription charging scheme is a two-parameter tariff that includes a *flat-rate* (e.g., p) for an *up to a certain total call duration* (e.g., D_{flat}) and a *fixed per-minute per watt of transmission power cost* p_0 that charges for any extra call duration. The flat-rate price p is determined at the subscription rate estimation process. For example, the cost of a subscriber u with demand $D(u)$ that buys a subscription with a rate p, will pay p if $D(u) \leq D_{flat}$, whereas, if its total call duration exceeds the D_{flat} threshold, it will be charged of $p_0 * \tau * d$, for each extra call of duration d, during which, it invests transmission power of τ. The card charging scheme is a simple *linear* tariff which charges the calls per minute and Watt of transmission power. These pricing schemes that charge the clients proportionally to the transmission power they invest aim to penalize an aggressive increase of the transmission power.

Subscription rate estimation The objective of a provider is to maximize its revenue. We assume that each provider knows the distribution of the demand, constraints and preferences of all clients, as provided by the u-map. The approach is myopically greedy, in the sense that it determines the price that maximize its revenue for the upcoming epoch, assuming a fixed price of its competitors, an average card rate (based on the card rates announced during the previous epochs by all providers) $\hat{p}_c$, and knowledge of the demand, preferences, and constraints of all clients (via the u-map).

At the beginning of each epoch, a provider performs the following novel algorithm to determine the subscription rate that it will offer at that epoch which maximizes its profit. Subsequently, it announces the subscription rate and each client can make its service selection.

To estimate its revenue, each provider *emulates the market offline* and the decision making process of all clients (based on their profile recorded at the u-map). Specifically, the provider knows the demand distribution of each client, its constraints, and emulates the service selection process of this client. As mentioned earlier, the constraints of a client (namely, its blocking probability and willingness to pay) need to be satisfied. For the estimation of the blocking probability, the provider employs a novel sigmoid-based model that will be described in the next paragraph. The provider estimates the expected charge for each client based on its demand and for each potential service choice that this client can make (e.g., subscriber with one of the two providers or card user). Specifically, to compute the extra charge (over the flat rate fee) for the subscription service, the provider considers the average price that all customers of each provider paid during the last epochs. Similarly, the average charge of card users is computed. Based on the offered subscription rates and the average card rates, the provider estimates its revenue. After exploring the space of the possible prices, the algorithm reports as the subscription rate of the provider, the price p^* that maximizes its revenue, (given the announced subscription rate for its competitor).

Blocking probability model A provider forecasts the blocking probability that will be observed at its network when it offers a subscription rate p_1 given that its competitor offers the subscription rate p_2 during that epoch. Specifically, it models the blocking probability $B(p_1, p_2)$, based on the following sigmoid function:

$$B(p_1, p_2) = \frac{1}{1 + e^{a_1 p_1 + a_2 p_2 + b}} \qquad (1)$$

The a_1, a_2 and b are the parameters of the function that each provider separately estimates using fitting during a training phase. The training takes place dynamically as the market evolves. Specifically, each provider uses the average blocking probabilities for its network recorded at the u-map by its subscribers during a large time period of multiple epochs to fit the parameters a_1, a_2, and b. The provider will consider this specific blocking probability $B(p_1, p_2)$ for its subscription rate estimation process.

Card rate estimation The price estimation for card rates runs multiple times during an epoch, motivating the design of a more efficient algorithm. It is a novel algorithm based on the concept of *representative users*: Instead of considering the detailed characteristics of each individual customer/entity in our population, something impractical and unrealistic, we model the customer population using a *relatively small number of representative users*.

To determine the characteristics of "representative users", we consider that the city consists of a number of regions $R_k, k = 1, ..., K$. We also divide the duration of the experiment T into a number of non-overlapping intervals $T_m, m = 1, ..., M$. Finally, we denote the set of all calls that are performed during the experiment as H. A specific call $h \in H$ can be written as a triplet (h_u, h_a, h_τ) where h_u are the characteristics of the user that performed the call (willingness to pay and data-rate threshold) and h_a, h_τ are the location and the time instance at which the call was initiated. The characteristics of the "representative users" of a specific region R_k at a given time interval T_m are determined based on the dataset of calls that were performed at the same region during the previous time interval $H(k, m-1) = \{h \in H | h_a \in R_k, h_\tau \in T_{m-1}\}$. Specifically, the characteristics of the "representative users" are determined by applying a clustering algorithm on the dataset $H(k, m-1)$ (e.g., the K-means in this case).

To estimate the revenue of a provider at a particular time instance, the price of its competitor is assumed to remain fixed. The positions of the "representative users" of each region are according to a uniform distribution on the area of the region. The "representative users" take their decisions at a random order. Subsequently, the decision making of the "representative users" is simulated and the revenue of each provider is computed. This process is repeated for all prices that could be offered by the providers. We also employ multiple random realizations of the "representative-user" positions and order of their decision process (corresponding to multiple Monte Carlo runs) to increase the accuracy of our results. The prices are adapted by applying the best response algorithm.

IV. Performance evaluation

A. Simulation scenarios

Wireless network infrastructure The simulation platform considers a small city, represented by a grid of 3 Km x 2.3 Km. Each provider has a cellular network that consists of 4 BSs placed on the sites of a triangular grid, with a distance between two neighboring sites of 1.6 Km. Moreover, each provider owns bandwidth of 5.6 MHz, that is divided into 28 channels of 0.2 MHz width. These channels are allocated to BSs according to a frequency reuse scheme with spatial reuse factors of 4 and 7, for Provider 1 and Provider 2, respectively. Each channel is further divided into three time-frequency slots in a TDMA scheme, resulting in 21 time-frequency slots per BS of Provider 1 and 12 slots per BS of Provider 2. Note that a single time-frequency slot of a given BS can be offered to only one client. Each client is associated with one BS during a given call. The maximum allowable transmission power that a client can invest is 2 Watts.

Client population There are 2000 clients in total, distributed according to a uniform distribution in the simulated region of this small city.

Client profile The constraints of clients namely the willingness to pay and the blocking probability threshold for the service selection as well as the data-rate and the price tolerance threshold for the BS selection, follow Gaussian distributions (their parameters are shown in Table I). The name convention "X-Y" indicates with "X" the service type selection criterion and with "Y" the BS selection criterion (as shown in Table II).

Client demand A client generates a sequence of call requests. The call duration follows a Pareto distribution ($x_s = 3.89$, $a = 4.5$) of mean 5 min, while the disconnection period follows a Log-normal distribution with different parameters for each user (μ is uniformly distributed in the interval $[4.0679\ 6.2150]$ and σ is equal to 5.5584) resulting in client

TABLE I: **The thresholds of the client constraints follow Gaussian distributions**

Threshold	Mean	Standard deviation
Willingness to pay (service selection)	0.17	0.0374
Blocking probability	0.2	0.05
Willingness to pay (BS selection)	0.15	0.0374
Data-rate (Mbps)	0.1	0.01

demand varying from 33 to 267 minutes per epoch. We assume that during disconnection periods, clients move with pedestrian speed of maximum value 1 m/sec, while they remain stationary during calls. Furthermore, during a call, the client remains connected at the same BS for the entire duration of the call.

We implemented the simulation platform and this market in Matlab. 10 Monte Carlo runs were performed for each scenario. The preferences and constraints of a client remain *unaltered throughout the simulation*. Each run represents the evolution of the market during a period of 160 epochs, each lasting 5 days (a 27-month period in total). This long duration is required in order to better observe the evolution of providers, their interaction with clients in this simulated small-city environment, and identify transient and steady-state phenomena.

To highlight the impact of the flexi-card service, two market types were simulated: an *only-subscriber market* (baseline case), in which each customer has only the choice of becoming a subscriber with one of the providers or remain disconnected, and a *mixed market*, in which customers have the additional service option of becoming card users.

TABLE II: **Simulated scenarios**

Scenario	Service criterion	BS criterion
B-R	Blocking probability	Data-rate
B-P	Blocking probability	Price
P-R	Price	Data-rate
P-P	Price	Price

B. Analysis

This analysis evaluates the impact of service paradigms on the evolution of the market, using metrics that can provide insights to regulators, customers, and providers. The performance of a provider is characterized by its revenue, while the performance of a client is indicated by the blocking probability of its calls. Furthermore, we quantify the overall satisfaction of the society by computing the percentages of blocked calls, social welfare, market share, and percentage of disconnected users for the only subscribers and mixed markets. The *percentage of blocked calls of a client* is the ratio of its successful calls over the total number of call requests. The social welfare is defined as the sum of the net benefit of all users and providers. The net benefit of a provider is its revenue while the net benefit of a user is the difference of what the user was willing to pay and what the user actually paid for his/her calls. Our reported results are average statistics over all epochs and Monte Carlo runs.

We comparatively analyze the only-subscribers and mixed markets. We speculated that the presence of the card service will have the following impact: (a) reduce the blocking probability (compared to the baseline case), and thus encouraging more clients to remain connected, (b) increase the competition among providers, which will help in offering relatively lower rates (compared to the baseline case), and thus, encouraging more customers to remain connected. Indeed, the presence of card service becomes a catalyst in the market! There is a dramatic decline of the number of disconnected users, a prominent reduction in the blocking probability in all scenarios, and an increase in the social welfare (as shown in Figs. 2b, 2a, and 2c, respectively). Note that due to the larger participation in the market, the social welfare attained is substantially improved, thus comprising further evidence of the merits of having the multiple service offerings in the market. We also observe that card users exhibit significantly lower blocking probabilities than subscribers in all scenarios.

TABLE III: **Customer Populations**

Type	Willingness to pay	Blocking Probability	Demand
High-business	$>$ 80% percentile	$<$ 20% percentile	all range
Bargain-finders	$<$ 20% percentile	$<$ 80% percentile	all range
Low-profile	$<$ 50% percentile	all range	$<$ 20% percentile

We distinguished three customer populations, namely the *high-business, bargain-finder*, and *low-profile customers* (Table III) and observed their performance in the context of the two markets. From the perspective of regulators, an important implication to the social welfare is the exclusion effect. To highlight how an only subscribers market excludes certain customer populations (e.g., the ones of low demand and willingness to pay), we computed the percentage of such users that remain disconnected, and found that in the only-subscriber market this percentage is very high (90%), while in the mixed market this percentage is about 57 % in the B-R and P-R scenarios, and close to 0 in the B-P and P-P scenarios (as shown in Fig. 2d). The percentage of the high-business disconnected users is close to 0 in all scenarios! More statistics about the percentage of disconnected users of other customer profiles are shown in Figs. 2d, 2e, and 2f. We will now focus on the specific scenarios:

1) Blocking probability criterion: The first part of this analysis focuses on the blocking probability as the criterion for selecting the service. For the BS selection, clients select the BS based on the data-rate or price criterion. The only subscribers market shows very high percentages of disconnected users (e.g., up to 52%) and relatively high blocking probabilities (e.g., up to 0.14). In general, due to the higher channel availability of the first provider compared to the second one, that directly affects the observed blocking probabilities, the revenue of the first provider is larger. This difference is prominent especially in the B-R scenario.

Interestingly though, a different charging behavior of the providers depending on the BS selection criteria (rate prefer-

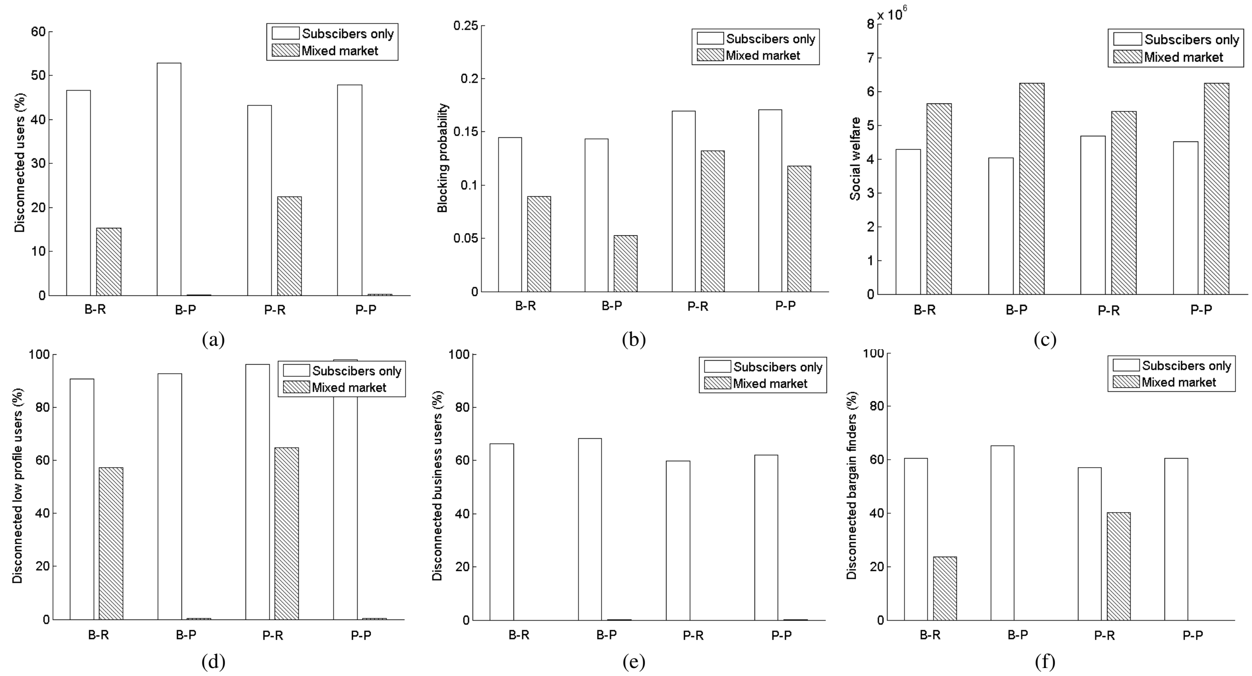

Fig. 2: (a) Percentage of disconnected users. (b) Blocking probability. (c) Social welfare. (d), (e), and (f) Percentage of disconnected low-profile, high-business, and bargain-finder users, respectively.

ence vs. price preference) can be observed: in rate preference, clients invest higher transmission power which will affect their total monetary spending, and of course, the revenue of the provider. On the other hand, in the B-P scenario, the price preference forces the providers to keep their offered prices relatively low, and thus, their revenue is lower than in B-R.

What is also interesting, and not necessarily expected, is that in the mixed market with rate preference (B-R as shown in Figs. 3a and 3b), not only the percentage of disconnected users and the blocking probability are lower but also the revenue of the providers has increased substantially. This is prominent especially for the second provider (with the lower channel resources). This means that the prices allow low- and high-consumption users to self select the most suitable product that matches their type, thus increasing participation in the market.

Customers as subscribers tend to select the first provider that has the lower blocking probability (due to its larger channel availability). Although the difference in the offered prices of the two providers is small, the blocking probability selection criterion for selecting the provider gives a distinct advantage to the first provider.

The card becomes the preferable service for customers sensitive to the blocking probability and data-rate and with higher willingness to pay threshold, which results to relatively higher card rates. The high-business customers in the mixed market always prefer the card service option, given that it offers them the lowest blocking probability. As mentioned earlier, unlike the only-subscribers market, in the mixed market, there are no disconnected high-business customers.

In the B-R scenario, in both the only-subscribers and mixed market, the first provider attracts more bargain-finder and low-profile users (than the second one) due to its lower blocking probability and lower subscription rate. In addition, the percentage of card-users from these populations is significantly lower than in the case of high-business customers, given the relatively higher rates of the card service. Due to the lack of space the corresponding plots are not included.

When the BS selection uses the price preference (i.e., B-P), the difference in the percentage of disconnected users in the mixed market compared to the only subscribers is even more dramatic (0.15% vs. 53%, respectively). Similar reductions are observed in the per user and per call blocking probabilities (e.g., 0.05 compared to 0.14, for the mixed and only subscribers markets, respectively). Moreover, the price criterion intensifies the competition, which has as a result, a more prominent reduction in the offered prices, causing a steep decrease in the revenue of the first provider. Even more interestingly, the population of subscribers dies out! Note that the price preference at the BS selection affects dramatically *the card rates*: the competition between providers results in a card rate reduction which encourages all customers to become card users.

2) Price criterion: The second part of this analysis focuses on the price as the criterion for selecting the service. For the BS selection, clients select the BS based on their preference, i.e., data-rate and price (P-R and P-P, respectively). The mixed markets still exhibit a very low percentage of disconnected users. At the same time, the enhanced competition among

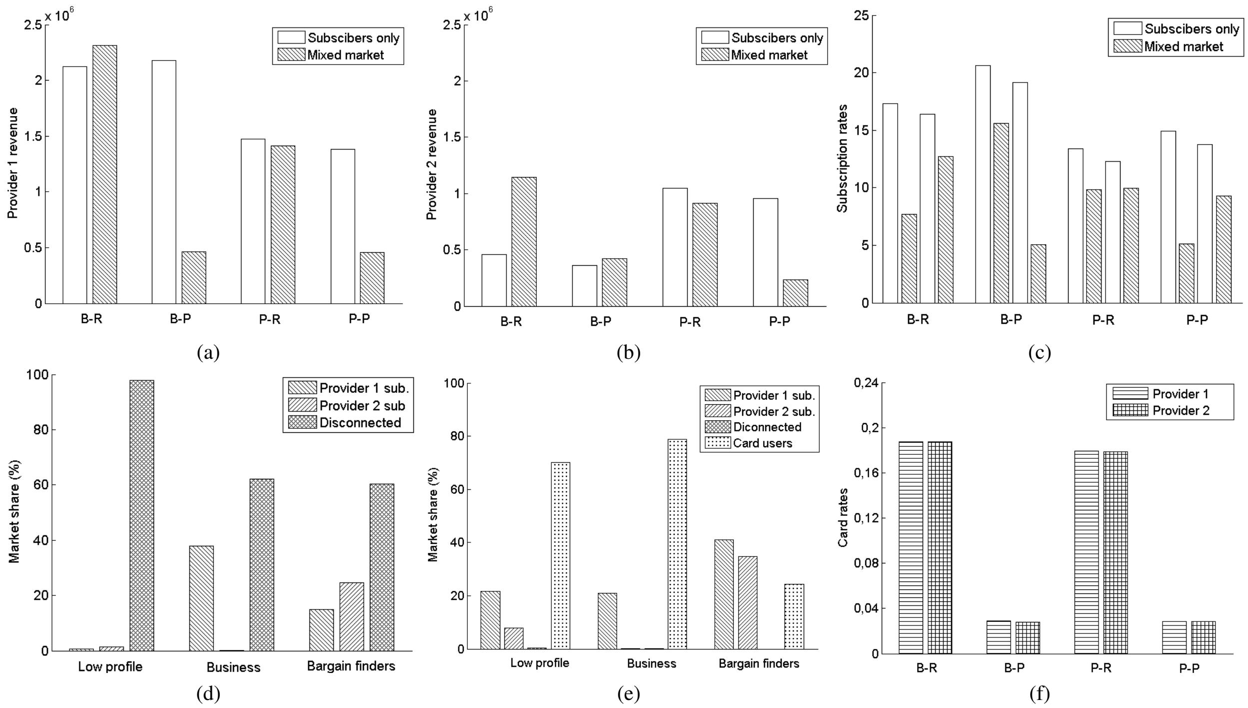

Fig. 3: (a) The revenue of Provider 1. (b) The revenue of Provider 2. (c) The subscription rates. For each scenario, the left column corresponds to the Provider 1 and the right column to the Provider 2 of that market, respectively. (d) Market share in the only-subscriber market for the P-P scenario. (e) Market share in the mixed market for the P-P scenario. (f) Card rates in the mixed market.

providers on the offered rates reduces their revenue. In addition, the reduced offered prices both in subscription and card services encourage more customers to become subscribers compared to the markets in which the blocking probability was the service selection criterion. The preference of users for lower prices over the blocking probability further increases the blocking probability.

In P-P, in the only-subscribers market, the Provider 2 has an advantage over Provider 1 in the market share of bargain-finder and low-profile users due to its lower subscription rate (as indicated in Fig. 3d).

C. Additional discussion on price dynamics

A general trend in the mixed markets is that the difference of the card rates of the two providers is very small (as shown in Fig. 3f). This can be explained by the symmetry in the deployments of the two providers and the uniform distribution of clients in the region. As mentioned earlier, the card rates are determined and are affected by the BS selection mechanism, in which the position of the clients and the BS deployments play an important role. The card product market is actually a commodity market with an almost identical "market price" across all competing providers (same with price for any kind of commodity goods ranging from crude oil to Internet transit prices) [18].

In the cases of blocking probability and rate preferences, the card rates are relatively increased, compared to the subscription rates. On the other hand, in the case of price preference, the price criterion forces the providers to keep their offered card rates at relatively lower levels.

Notice that in the subscribers-only market, the Provider 2 offers a smaller subscription rate compared to the Provider 1 (as shown in Fig. 3c). The Provider 1 does not react by lowering further its prices, which could result potentially in price wars. This is due to the blocking probability awareness "embedded" in the sigmoid blocking probability forecasting model: Specifically, it expects that a reduction in the subscription rate would have an adverse impact on the blocking probability. However, the presence of card users (in the mixed market) introduces further complexities to the subscription rate estimation algorithm and to the blocking probability forecasting model.

Another related phenomenon with respect to the performance of the Provider 2 (the one with the smaller number of channels) is the following: Although, in general, the demand is smaller than the number of channels, in some cases the call durations and off periods (given by a Pareto and Lognormal distribution, respectively) are such that the demand exceeds the availability of that provider, causing an increase in the blocking probability. This disadvantage of that provider will be exacerbated when the selection criteria are based on the blocking probability and date-rate. In an effort to increase the revenue, the myopically greedy pricing setting algorithm of that provider will result in a relatively poor performance.

Specifically, the Provider 2 increases its subscription rate, hoping to reduce further the blocking probability and attract more customers. However the first provider still maintains its advantage over the blocking probability, due its larger number of channels, and thus, the second provider cannot gain any substantial revenue by simply increasing its prices in order to further reduce its blocking probability. On the other hand, in the subscriber-only market, the sigmoid function of the blocking probability model can capture well the behavior of the users and the dynamics of the market, resulting to a certain degree of "stability" in the subscription rates (as shown in Fig. 3c the rates of both providers are very close). Such cases motivate the design of more sophisticated blocking prediction models, and a larger set of options/strategies for providers.

V. Conclusions and future work

This paper introduces the card service in a cellular-based market, which becomes a catalyst, providing significant benefits, compared to traditional markets with only subscribers. We developed a modular modeling framework and simulation platform that takes into consideration client mobility, demand, a diverse set of customer profiles and various performance metrics, analyzes the evolution of a complex market and can offer insights to regulators, customers and operators. The analysis demonstrates that the duopoly that offers the card services in addition to subscriptions alleviates the market exclusion effects, dramatically reduces the percentage of disconnected users, decreases substantially the blocking probabilities, and improves the social welfare! Furthermore, due to the larger participation in the market, the social welfare attained is also substantially improved, thus comprising further evidence of the merits of having the multiple product offerings in the market. The benefits are prominent also for specific customer populations, such as high-business, bargain-finders, and low-profile users. The diverse customer population can select the most suitable product that matches their type, thus increasing participation in the market. For example, the disconnected high-business customers have been eliminated. Also, the card service offers lower blocking probability, becoming the preferable service for high-business customers. In some cases, the revenue of both providers increases, though the gains are more noticeable for the provider with the less spectrum resources (in terms of number of channels). The successful price setting also justifies the increased revenue attained by both providers. In cases in which the customer population is QoS-sensitive (e.g., sensitive to blocking probability and data-rate), the card service can improve the revenue of both operators. The price criterion intensifies the competition and results in more prominent reduction in the offered prices, causing a decrease in the profit of providers.

We plan to experiment with tit-for-tat price adaptation strategies and investigate whether the two providers can implicitly cooperate to offer prices that yield higher revenue to both, instead of constantly competing against each other. The analysis will be extended to include a sensitivity analysis of the various thresholds and multiple degrees of asymmetry of the two providers (in terms of deployment and resources). We are in the process of integrating a richer set of customer profiles shaped from real-world data and QoE-based metrics.

A longer-term research direction is to enhance the price setting algorithm with longer-term objectives, with more sophisticated blocking probabilities, and reservation policies that can be superior to myopically greedy approaches. Specifically, we will explore a longer time scale prediction of the users' reaction to the posted prices and more importantly the competitor's reaction curve. Furthermore, we will employ state-of-the-art "trunk reservation" policies for reserving a part of the network for the high-value high-business users, thus offering competitive prices and attractive blocking probabilities. This paper shows that the complementary service of flexi-card in cellular markets is highly beneficial, setting the foundations for exploring further such services in spectrum markets.

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