Deployment Strategies in Competitive Wireless Access Networks

Pamela González Sánchez [1,2], Jens Zander [1]
[1]The Royal Institute of Technology KTH, Radio Communication Systems, 164 40 Kista, Sweden
[2]National University of Engineering UNI, P.O. Box5595, Managua, Nicaragua
Emails: dpgs@kth.se, jenz@kth.se

***Abstract*—The rapid growth of mobile internet traffic has forced wireless service providers to deploy increasingly higher capacity in their wireless broadband access systems. The flat rate revenue streams in combination with the rapidly growing costs associated with conventional access deployment is usually referred to as the "revenue gap". In this context, various schemes for infrastructure sharing to reduce unnecessary duplication of infrastructure present an interesting solution. Besides explicit cooperation, competitive sharing ("coopetition") where various access providers provide partially overlapping coverage is one interesting sharing mechanism. In this paper, we analyze such a scheme and study how the operator should deploy their networks, striking a balance between areas of exclusive coverage, where each provider has a monopoly situation, and overlap areas with provider competition, to achieve maximal profitability. The competition is based on the proportionally fair auction scheme. The users behave selfishly as they bid for the various access providers. The access providers compete with each other by selecting the so called reservation price. Results are expressed in terms of Nash equilibrium solutions, which are numerically derived for some sample scenarios. Results indicate that the fraction of coverage overlap does play an important role for both the performance of the system and the profitability of the service providers. As the level of overlap between the two networks increases the revenue that each base station gets decreases significantly. In addition, the user experienced throughput degrades considerably for low demand but the cost per transferred Megabyte is not greatly affected. Further, we conclude that a win-win situation for both users and access providers can be achieved with a suitable overlap coverage by two networks.**

***Index Terms*—Wireless access markets; coverage overlap; competition; resource allocation; Nash equilibrium**

I. INTRODUCTION

A. Overview

The rapid increase of mobile internet traffic has put the spotlight on how the future wireless broadband access systems should be deployed and operated at significant lower costs per transmitted bit than today. The flat rate revenue streams in combination with the rapidly growing costs associated with conventional access deployment is usually referred to as the "revenue gap. Nowadays, closing this "gap" is on top of the priority list of wireless mobile service providers. Low cost deployment and more efficient utilization of existing resources are key solutions to be investigated.

The traditional way of infrastructure deployment has been that every service provider offers his own access system in all locations, i.e., achieving "full" coverage by himself. This has been possible in most mobile phone systems due to the relatively low costs and high profit margins. As the increasing data rates require a much denser (and more expensive) network of base stations, full coverage is no longer an option to most service providers. Instead *Infrastructure sharing*, where providers share infrastructure in low user density areas is one possible alternative to offer better coverage and quality of service (QoS) in a cost efficient manner [1].

The sharing of wireless infrastructure, however, raises the question of how resources and revenues should be divided when multiple subsystems, managed by potentially competing actors, are involved in delivering the access service. An alternative would be to share the infrastructure implicitly by establishing an open wireless access market wherein networks not only compete for users on a long-term time-scale, but also on a much shorter time-base. This could be realized with an architecture where autonomous trade-agents, that reside in terminals and access points (APs) or base stations (BSs), manage the resources through negotiations [2]–[5].

In competitive multi-user networks, services are provided to users that are assumed to be rational, choosing strategies in order to maximize their own utility. This resource management problem can be expressed as a noncooperative game and the system performance can be analyzed in terms of the Nash equilibrium, i.e., a set of optimal bids such that no single user wishes to deviate from its bid given that the bids of the other users remain the same and cannot further improve their utility [6]–[8].

B. Prior Work

In [2], the authors developed a framework for studying demand-responsive pricing in contexts where access points (APs) with fully overlapping coverage compete for users. Resources are partitioned through a proportional fair divisible auction and they investigated if, and when, an open market for wireless access can be self-sustained. They showed that in scenario where access providers (APs) compete an open access market results in better services at lower price, compared to a case where APs cooperate. They utilized an architecture where autonomous trade-agents manage the resources through negotiations.

In [4], a market-based framework for decentralized radio resource management in environments populated by multiple,

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possibly heterogeneous, APs and the service provided to the users is of file transfers, was introduced. The problem addressed for the user is to determine how much resources it should purchase from the different APs in order to maximize its utility ("value for money").

In [7], Maheswaran et al. introduced a bidding mechanism for allocation of network resources among competing agents, and study it from a game-theoretic perspective. Although they proved the existence and the uniqueness of Nash equilibrium in a decentralized manner, the user's performance (QoS) and service providers' revenue have not been studied.

C. *Our problem*

In this work we study how competitive sharing ("coopetition"), where various access providers provide partially overlapping coverage in a competitive fashion, can reduce cost.

The scenarios studied can be illustrated as in Figure 1. We analyze how the balance between areas of exclusive coverage, where the provider has a monopoly situation, and overlap areas with provider competition affects the profitability of the access providers. We also analyze how the user's QoS is affected by this level of overlap among networks and by traffic load variation. A game-theoretic approach and the proportionally fair auction mechanism [9]–[11] are used aiming to answer the following questions:

- *How is the operator revenue affected by the level of overlap and the traffic load variations in the system?*
- *Is the user quality of service, QoS, in terms of available data rate and cost per Megabyte affected by these two parameters?*

The rest of the paper is organized as follows. In Section II, we introduce our basic assumptions and describe the wireless architecture-scenario, resource allocation mechanism, and user demand model. Section III gives a thorough overview of the user game. Section IV outlines the service providers' strategy. In Section V we show the numeral results from simulation and in Section VI we present out the conclusion.

II. SYSTEM MODEL

The system model with the basic assumptions, a description of the scenario under consideration and the resource allocation mechanism applied in this work are introduced in the following.

A. *Basic Assumptions - Scenario*

Given the network deployment illustrated in Figure 1, the problem for each BS is to select a reservation price, ϵ, so that its expected revenue is maximized. When the user is in a nonoverlapping area, this user can only bid for resources from the single BS that provides coverage of this area. This user faces a monopolistic market, since the BS can charge any price due to the absence of a competitor. Both, in overlapping and nonoverlapping coverage the users may choose not to utilize a specific BS if the price is too high.

Figure 1 illustrates the basic scenario under investigation, where $s_{i,j}^{m}$ denotes the bid, in *monetary units*, that user j places in auction i at BS m, in order to get a portion of the available transmission time $x_{i,j}$ for a file transfer (Note that we have assumed a purely time division multiplexed link). The link $user{-}SP$ indicates the link provided by access provider who dominates the market in this area (i.e., the access providers who provide coverage) and it is to this BS that users should send a positive bid in order to be served.

We model a file download service, specifically, the download time in a wireless TDMA system with N selfish competing users and m BSs with overlapping coverage areas. The BSs are assumed to be identical in transmit power, system bandwidth, minimum received signal to noise ratio requirement, etc.

The resources that we focus on are downlink transmission slots. These slots are allocated to different users in order to share the downlink throughput among them. Allocation of the resource is done through a proportional fair divisible auction. We assume that the resource is infinitesimally divisible and that the cost associated with the file transfer depends on the total time-duration and the monetary expenditure required for the complete file download.

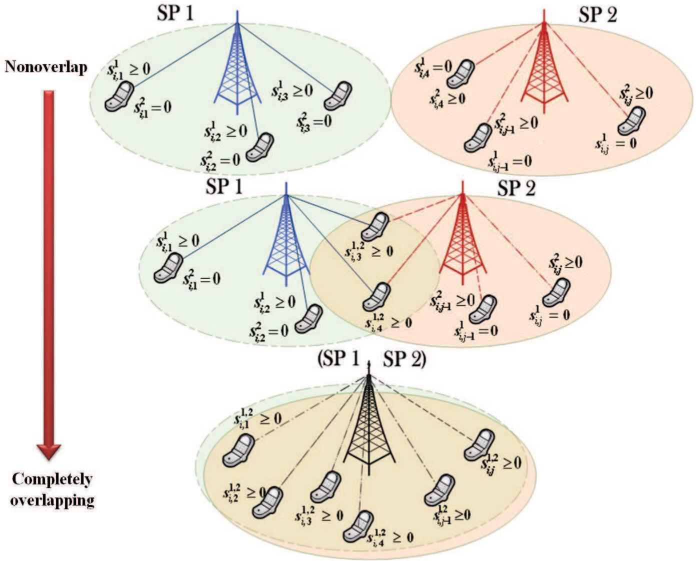

Fig. 1. Basic scenario - Illustration of a wireless network architecture with different percentages of overlap, which represents a system with different levels of competition

As in [2] [4], we investigate a trade-agent-based model for the auction bidding process.The trade-agents are entities located in the BSs, who act selfishly on behalf of their users. The main objective of each trade-agent is to maximize its user's utility (here computed as *value for money*). The portion of the transmission time allocated to user j can be expressed as follows:

$$x_{i,j}(s) \quad = \quad \frac{s_{i,j}}{s_{i,j} + S_{i,-j}} \in [0, 1), \qquad (1)$$

where $S_{i,-j}$ represents the strategies (bids) of all the opponents' trade-agents and it is equal to $\sum_{k \neq j} s_{i,k} + \epsilon$ where the reservation price $\epsilon \in [0, \epsilon_{max})$. The reservation price is a nonzero price floor below which the resource will not be sold. Note that by definition the price floor must be nonzero as if it were zero, then there would be no price floor.

Assuming that the peak data-rate of a single user j on whose behalf the trade-agent j is acting, remains unchanged during the entire file transfer and that this applies for all the users, i.e., $R_{i,j}$=$R_{z,j}$ $\forall$ i, z, the total demand associated with the other trade-agents, thus $\sum_{k \neq j} s_{i,k}$=$\sum_{k \neq j} s_{z,k}$ $\forall$ i, z.

Note that z is the last round of the auction. Due to these assumptions, each trade-agent will place identical bids in all the auctions.

B. Resource Allocation Mechanism - Proportionally Fair Divisible Auction

As described in the previous section, the total transmission time is divided via employing a proportional fair divisible auction . In a proportional share allocation scheme each user is characterized by a parameter that expresses the relative share or amount of the resource that it should receive. Hereafter, the bid that the user submits to the BS is used to express the user's share. In this work a dynamic system has been modeled in which users are assumed to dynamically join and leave the competition (game). Therefore, the portion of the resource depends on both the number of users that enter the game and the level of competition at different times. On light of this, this mechanism allows flexibility, since the users can decide when to join or leave the competition, and ensures fairness, which follows from the fact that the users always get a share of the resource proportionally to their bids (as expressed in Equation 1).

The auction process is held by an auctioneer located in the BS (thus since the users' trade-agents are also allocated in the BS all the communication between the trade-agents and the auctioneer is strictly local to the BS). This concept was introduced in [9] and analyzed later in competitive environments for networks with fully overlapping coverage in [2], [4]. We examine the case where the file transfer requires z auctions to complete, i.e., $i = \{1, ..., z\}$ (see Figure 2).

Figure 2 illustrates the auction procedure associated with a file transfer [4]. In this example trade-agent j initiates a file transfer in auction 1.

Since, at the beginning of each allocation cycle, an interrupt is generated in the system, too short a cycle may cause a large overhead in the system, in the long run (i.e., in Operating Systems each allocation cycle is in the order of milliseconds). On the other hand, a cycle of too long duration (i.e., cycles of one minute) may induce a large delay for the file download, thus, a degradation in the user QoS.

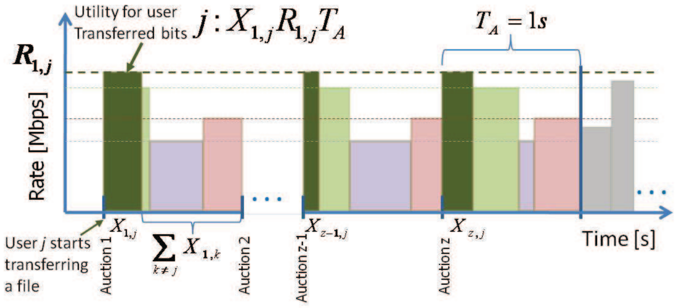

Fig. 2. Illustration of auction procedure associated with a file transfer

In our analysis, we assume that each auction is carried out every one second [2], [4]. This means that each auction determines the allocation of resources for the time after the conclusion of the auction and that a new auction starts every second. Note that the auction can proceed in parallel with the usage of the link resources for downloading, but this usage is according to the resource allocation determined by the last auction. For simplicity of the analysis, we neglected the overhead that can occur in a real system application.

In a proportional fair resource allocation mechanism, a user knows exactly how much it has to "pay" over any interval of time while this is active, considering that they choose how much they will bid for the resource. The user cannot, however, predict how much service time it will actually receive. This is because the fraction of the resource, and therefore the service time the user will receive, may change at any time depending on the level of competition for the resource [10].

In each auction, user j is allocated a portion $x_{i,j}$ of the total available transmission time during each auction T_A (where $T_A = 1$ second), and depending on its peak data-rate $R_{i,j}$ the agent will be able to transfer a total of $x_{i,j} R_{i,j} T_A$ bits. After participating in z auctions the file transfer is completed and the trade-agent j awaits for a new request from its user to enter the competition again.

C. User Demand Model

A demand function that consists of files with an expected size q in Megabits is considered. Each file arrives to the system of BSs according to a Poisson process characterized by an intensity, λ.

D_0 represents the potentially offered load, which can be defined as D_0=$q\lambda$, and it is assumed that the aggregate demand is perfectly known for all BSs [2].

III. USER GAME - UTILITY MAXIMIZATION

We focus in finding the Nash Equilibrium Point (NEP) for the reservation price of the resource, ϵ, considering the two games (competition among users for resources and among BSs for users) in the competition area for different levels of coverage overlap. This NEP is related to the Best Response from the trade-agents (acting on behalf of the users). In the monopolist area (non-overlapping coverage) only competition among users is observed.

By obtaining the NEP we are able to analyze the BS's expected revenue with different levels of competition. These results enable us to predict the users' performance (in terms of throughput and monetary expenditure per transferred file).

The users compete against each other for resources - while trying to maximize their utility function in order to transfer a file. This game is expressed later in Equation (2). For our analysis, we assume that the file size is finite (and identical), $q = 1$ Megabyte.

$$\begin{aligned} \varphi(s_{-j}) &= \arg\max_{s_j} U_{i,j}(s_j, S_{-j}) \\ &\forall \quad j \in \{1, ..., N\}, m \in \{1, 2\}. \end{aligned} \tag{2}$$

In the above equation $U_{i,j}(s_j, s_{-j})$ is related to the throughput, $x_{i,j}R_{i,j}$, associated with user j and is defined as:

$$U_{i,j} = \sum_{m=1}^{2} \max\left[0,\ x_{i,j}R_{i,j}^{m} - s_{i,j}^{m}\right]. \tag{3}$$

Deriving the first order solution (i.e., as a linear equation) of Equation (3) with respect to $s_{i,j}^{m}$ we can obtain the best response (BR), which describes how trade-agent j should react to the strategies (optimal bid that the trade-agent should submit the BSs) of all the other trade-agents in order to maximize its user's utility. This would be expressed as follows:

$$s_{i,j}^{m} = \sqrt{R_{i,j}^{m}(\sum_{k\neq j} s_{i,k}^{m} + \epsilon_m)} - \sum_{k\neq j} s_{i,k}^{m} + \epsilon_m. \tag{4}$$

Since the peak transfer rate for all of the users is the same over all auctions, and they all have to transfer the same size file, then giving each user the whole channel (i.e., all of the time slots) enables this user to complete and leave the system, hence leaving all of the remaining resources for the *remaining* users.

The monetary expenditure, E^m, incurred by user j is given by the summation of the bids submitted in all the auctions, z_j, required to download the file, as indicated in:

$$E_j^m = \sum_{i=1}^{z_j} s_{i,j}^{m} \tag{5}$$

IV. BASE STATION STRATEGY-REVENUE MAXIMIZATION

A. *Open Access Market-Competing BSs*

This game take place among BSs, who selfishly, try to maximize their own expected revenue per second, as defined in Equation (6).

$$\phi_m(\epsilon_{-m}) = \arg\max_{\epsilon_m} \Phi(\epsilon_m, \epsilon_{-m}), \tag{6}$$

where $\phi_m(\epsilon_{-m})$ represents the best response (BR) function associated with BS m. Equation (7) describes the NEP, which is the solution to the competitive game among BSs.

$$\epsilon_m^* = \phi_m(\epsilon_{-m}^*) \quad \forall m \in M. \tag{7}$$

The stability and uniqueness of the NEP for the games have been calculated through successive iterations (negotiation) between the BSs and users via mean of simulation. It has been proved that symmetric wireless systems with proportional share resource allocation mechanism converge to the NEP reaching the nearest optimal performance [2]–[4], [6], [12].

V. NUMERICAL RESULTS

The requests of the files to be downloaded by the users arrive according to a Poisson process and the resources are allocated once per second based on the NEP. In this work we characterize the user's performance (QoS) by using the average user throughput and monetary expenditure per Megabyte. The BSs' performance is quantified by the average revenue per second. The pathloss has been modeled as expressed bellow:

$$L(d) = 35.3 + 38\log_{10}(d) \quad in\ units\ of\ dB, \tag{8}$$

where d denotes the distance between the BS and the mobile terminal. In our experiment we have neglected shadow fading and modeled interference as coming from constantly transmitting BSs. As in [2], we use a truncated version of the Shannon bound that has been adjusted to include efficiency losses, leading to the peak data-rate:

$$R_{i,j} = \min\left(W\log_2\left(1 + \frac{\Gamma_{i,j}}{2}\right), R_{max}\right), \tag{9}$$

where $W = 3.84$ MHz is the channel bandwidth, $\Gamma_{i,j}$ represents the signal to interference and noise ratio and R_{max} denotes the maximum bit-rate that can be achieve by the user.

A. *Simulation Settings*

Extensive simulations in MATLAB were carried out with a granularity of one second (auction cycle) for two wireless access providers. Table. I summarizes the simulation parameters that were used. These values have been taking from the prior analysis introduced in [2].

TABLE I
SIMULATION PARAMETERS VALUES

Parameters - with units in square brackets	Value
BS Transmit Power (P) [W]	20
Users distribution	Uniform
Cell Radius [meters]	440
Number of Competing BSs (M)	2
File size (q) [Megabyte]	1
Maximum bite-rate (R_{max}) [Mbit/s]	7

B. Simulation Results

Figure 3 shows the BR function for the non-cooperative game under different levels of competition where there, in average, 0.4 packets/BS/s enter the system. In this figure A represents the percentage of overlap of the two wireless access networks coverage.

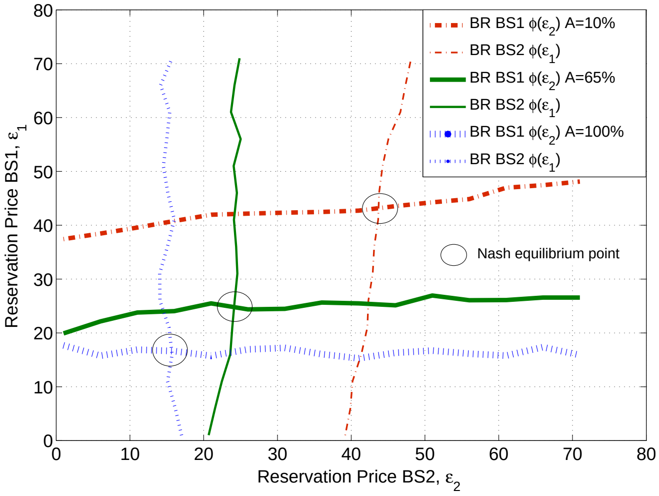

Fig. 3. Average revenue per BS as a function of the reservation price, ϵ.

Based on the results in Figure 3 we observe that there exist at least one NEP in the system.

1. User Performance The experienced users' QoS in terms of throughput and average price per transferred file as a function of the potentially offered load, D_0, is shown in Figure 4. These depend on the load demand density and are affected by the level of competition introduced with the coverage overlap between networks (representing different levels of competition).

It can be observed that for low load demand, the throughput experienced by users degrades considerably as the level of competition increases. This is due to the fact that the fraction of the resource that each user gets decreases as more users fall in the competition area (in the overlapping coverage).

When the load density increases (2.4 Megabits/second and higher, from λ=0.3 files/s) the throughput degradation is slightly smaller leading to less negative impact on the user's experienced QoS, compared to fully overlapping coverage.

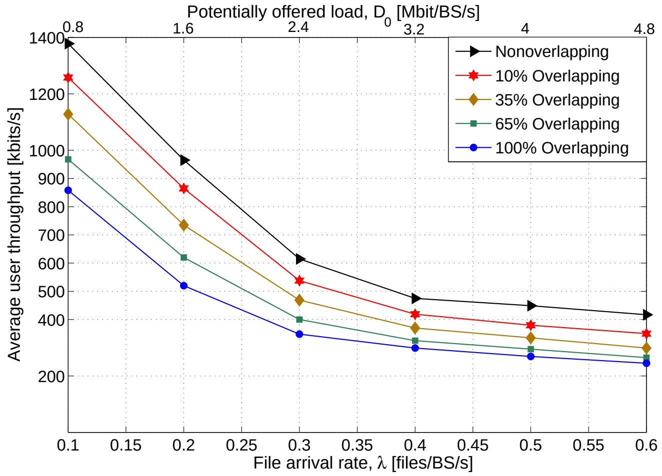

Fig. 4. Average throughput experienced by users for different levels of overlapping coverage as a function of the potentially offered load, D_0, (file arrival rate λ).

Figure 5 shows the average price per transferred Megabyte experienced by users. We observe that an architecture where BSs compete and share their resources implicitly, combined with autonomous trade-agents acting on behalf of the users, has the potential to reduce price. For networks with low demand density the average price per transferred Megabyte is affected (small increment) in a low scale.

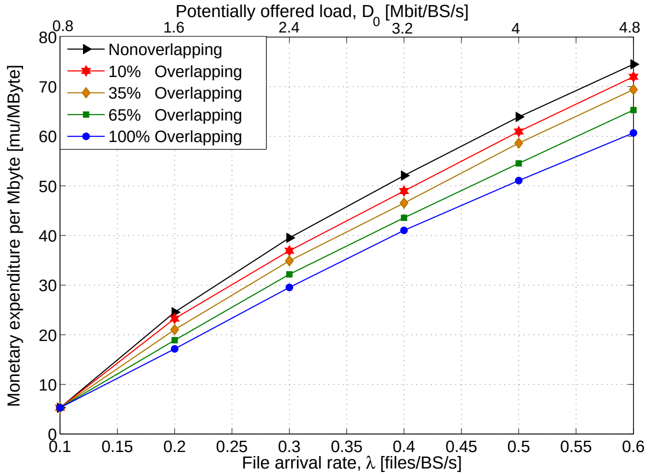

Fig. 5. Average price, p, per transferred Megabyte of data for different levels of overlapping coverage as a function of the potentially offered load, D_0, (file arrival rate λ).

As illustrated in Figure 5, the resulting user's monetary expenditure per Megabyte increases rapidly as a function of the potentially offered load, D_0, and on a slightly basis as the level of overlap (competition) is reduced.

2. Base Station's Revenue; The average revenue associated with the BS game for different levels of coverage overlap can be observed in Figure 6. As the overlapping area by the two wireless networks increases so does the level of competition and more users experience an *open access market*. The reservation price for the resource decreases as a consequence of the competition leading to lower BS's revenue.

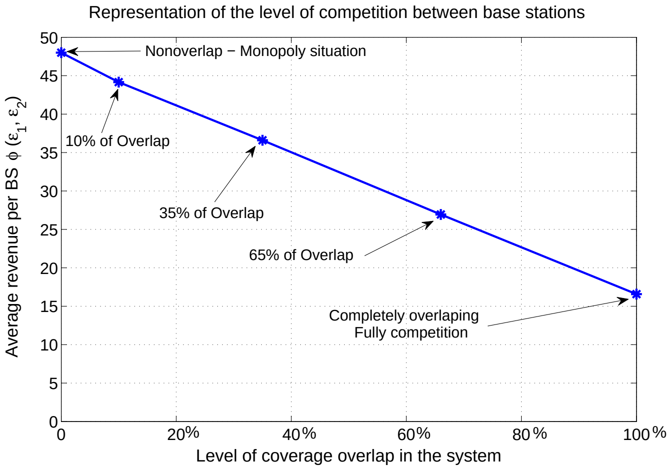

Fig. 6. Average base station's revenue per second and slot associated with the BS game as a function of the level of coverage overlap. On average 0.4 files/s arrive to each BS, each file is of size q = 8 Megabits.

Figures 4 and 5 show that the experienced user's QoS is affected for low demand density. However, we can notice that for load density higher than 3.2 Megabits/second (λ=0.4 files/s) the degradation is slightly smaller leading to less impact on the user's experienced QoS and providing a great gain (more than 50%) in the BS's revenue.

Generally, our results indicate that both users and access providers can benefit when a suitable overlap coverage by two networks is achieved. According to our results a proper percentage of overlap might be approximately 35% based on the interest or objective function of all the involved parties. We investigated the behavior of the system by considering only two wireless networks in order to get insight on to which extent competition can be beneficial for both providers and users.

VI. CONCLUSION

In this paper, we analyzed a competitive sharing scheme ("coopetition") where two access providers provide partially overlapping coverage in a competitive fashion as an option to maximize their revenue. We study how the balance between areas of exclusive coverage and overlap areas with provider competition affects the profitability of the access providers.

Access providers with symmetric wireless networks that overlap partially in coverage compete with each other by selecting a reservation price. It has been shown that, under our assumptions, the system converges to a unique Nash equilibrium point. Results indicate that the fraction of coverage overlap does play an important role for both the performance of the system and the profitability of the access providers.

We observe that as the level of overlap increases the revenue that each base station decreases significantly. In addition, the user's experienced throughput degrades considerably for low demand density meanwhile the cost per transferred Megabyte is affected in a low scale. Further, we conclude that a win-win situation for both users and access providers can be achieved with a suitable coverage overlap by two networks.

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REFERENCES

[1] J. Markemdahl, Östen Mäkitalo, J. Werding, and B. G. Mölleryd, "Business innovation strategies to reduce the revenue gap for wireless broadband services," *Communications and Strategies Journal*, vol. 1, no. 75, 2009. [Online]. Available: http://econpapers.repec.org/RePEc:idt:journl:cs7502

[2] M. Blomgren and J. Hultell, "Demand-responsive pricing in open wireless access markets," in *Proceedings of the IEEE Vehicular Technology Conference VTC-Spring*, 2007.

[3] R. T. Maheswaran and T. Baçar, "Nash equilibrium and decentralized negotiation in auctioning divisible resources," *Group Decision and Negotiation Journal*, vol. 12, no. 5, 2003.

[4] M. Blomgren and J. Hultell, "Decentralized market-based radio resource management in multi-network environments," in *Proceedings of the IEEE Vehicular Technology Conference VTC-Spring*, 2007.

[5] R. T. Maheswaran and T. Baçar, "Coalition formation in proportionally fair divisible auctions," 2003.

[6] D. Fudenberg and J. Tirole, *Game Theory*, 1991.

[7] R. T. Maheswaran and T. Baçar, "Decentralized network resource allocation as a repeated noncooperative market game," in *Proceedings of the* 40^{th} *IEEE Conference on Decision and Control*, vol. 5, 2001.

[8] D. Niyato and E. Hossain, "Radio resource management games in wireless networks: an approach to bandwidth allocation and admission control for polling service in ieee 802.16," *Wireless Communications, IEEE Journal*, vol. 14, no. 1, 2007.

[9] I. Stoica, H. Abdel-Wahab, K. Jeffay, S. Baruah, J. Gehrke, and C. Plaxton, "A proportional share resource allocation algorithm for real-time, time-shared systems," in *Proceedings of the* 17^{th} *IEEE Real-Time Systems Symposium*, 1996.

[10] I. S. Hussein, H. Abdel-wahab, and K. Jeffay, "On the duality between resource reservation and proportional share resource allocation," in *Proceedings of Multimedia Computing and Networking*, 1997.

[11] L. Abeni, G. Lipari, and G. Buttazzo, "Constant bandwidth vs. proportional share resource allocation," vol. 2, 1999.

[12] J. Hultell, "Access selection in multi-system architectures: cooperative and competitive contexts," *Licentiate Thesis in Telecommunications*, Kungliga Tekniska Högskolan KTH, Sweden 2007.