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SPECTRUM AND INFRASTRUCTURE SHARING IN WIRELESS MOBILE NETWORKS: ADVANTAGES AND RISKS

ABSTRACT

In recent time the spectrum and infrastructure sharing has been gaining more and more on importance due to high spectrum license costs and expensive infrastructure needed for modern high-bandwidth wireless communications. In this paper the advantages and disadvantages of spectrum and infrastructure sharing by analytical models and simulations are analyzed. Results show that operators could significantly reduce their costs, increase capacity and improve network quality by sharing their infrastructure and spectrum. Using Game Theory it is shown how operators could "protect themselves" against non-cooperative behaviour of other operators.

KEY WORDS

infrastructure sharing, spectrum sharing, Game Theory

1. INTRODUCTION

Future wireless systems should offer significant capacity increase over existing systems in order to provide the required Quality of Service (QoS) for new demanding services and an increasing number of users. This requires large investment in spectrum licenses and in the infrastructure: base station, sites, switches, trunks etc.

An efficient method for reducing the costs is the spectrum and infrastructure sharing (resource sharing). By sharing their infrastructure (mostly base stations) and spectrum, operators could substantially reduce the costs without decreasing either the number of served users or the quality experienced by the users. That is why it is clear that resource sharing is an attractive option for operators.

This paper investigates analytically and by means of simulations the benefits of resource sharing regarding operators' costs and service quality provided by the operators. Further, the possible problems are addressed that might arise in resource sharing like "free rider" problem i.e. possible non-cooperative behaviour of other operator(s). Some strategies based on the Game theory to cope with these problems are provided.

The sequel of the paper is organized as follows. First, an analytical model for estimating benefits from resource sharing is provided. Then, by simulations the benefits of resource sharing are shown. Finally, the strategies are proposed based on the Game theory for "protection" from non-cooperative behaviour of other operators.

2. ANALYTICAL CONSIDERATIONS

This section contains some analytical results that underline the simulation results in the following subsections.

2.1 Infrastructure sharing

We assume that the deployment costs of a wireless network linearly increase with the number of base stations and system bandwidth [1] and obtain the following equations for operator costs:

$$Cost_{sys} = c_1 + c_2 N_{bs} + c_3 W_{sys} \tag{1}$$

where $Cost_{sys}$ are total system costs, N_{bs} the number of Base Stations (BS), W_{sys} total bandwidth used in the system. c_1, c_2 and c_3 are parameters reflecting the fixed costs, costs per BS and cost per unit bandwidth, respectively.

The required number of BS N_{bs} can be estimated according to the required coverage area and users' bandwidth by using the following equation [2]:

$$N_{bs} = \max\left\{\frac{A_{service}}{\pi R_{\max}^2}, \frac{N_{user} W_{user}}{W_{\max}}\right\} \tag{2}$$

where $A_{service}$ is the desired coverage area, $R_{\max}$ maximal radius of BS, N_{user} the number of users per BS, W_{user} bandwidth needed per user and $W_{\max}$ the maximal bandwidth available per BS.

From (1) and (2) we can immediately see the benefits of infrastructure and spectrum sharing i.e. operators can reduce their costs by providing only a part of the required number of BS and spectrum. The other part of BS and spectrum needed for covering a certain area is then provided by other operator(s).

According to (2) the number of BS needed to cover certain area is proportional to the size of area $A_{service}$. If the operators share the infrastructure i.e. a part of required BS is provided by one operator and the rest by the other operator, then cost saving is proportional to the number of BS installed by other operator according to equation (1).

Furthermore, we investigate other advantages from resource sharing like reducing spectrum costs, multiplexing and diversity gains.

2.2 Spectrum sharing and multiplexing gain

We can now estimate the effect of the spectrum sharing on the cost structure. Spectrum sharing means that the operator has more effective bandwidth available than it pays for i.e. ($W_{\max} > W_{sys}$). This means that costs are reduced, since on the one side the operator can effectively use more bandwidth than it pays for, on the other side the number of needed BS (N_{bs}) is reduced according to (2). Consequently, the infrastructure costs are also reduced, since the costs are proportional to N_{bs} according to (1).

However, spectrum sharing brings also the multiplexing gain i.e. gain of using more bandwidth (more channels) increases non-linearly with the number of channels [3].

Usually, the communications systems are designed so that the Blocking probability i.e. probability that all channels are occupied, lies below predefined limit (1-5% typically). Blocking probability P_b can be calculated using Erlang B formula from the Queuing Theory [3]:

$$P_b = \frac{\frac{\rho^N}{N!}}{\sum_{k=0}^{N} \frac{\rho^k}{k!}} \tag{3}$$

where ρ is the total offered load (measured in Erlangs) in the system (cell) and N is the number of channels in the system (cell). According to (3) an operator could also explore the multiplexing gain i.e. the fact that for the same blocking probability one needs less channel per unit load the higher the number of channels [3]. This means that according to (3) the ratio ρ/N increases with N for the same P_b. For example, channel usage is approximately twice greater with 100 channels than with 10 chanels for the same blocking probability of 1%.

Consequently, by spectrum sharing and multiplexing gain the number of users that an operator could serve increases not linearly but almost exponentially.

2.3 Diversity gain

Diversity gain can be obtained in areas where several operators have overlapping coverage and share their network infrastructure i.e. base stations. Diversity gain comes from the fact that a mobile can select one out of N (>1) base stations. Consequently, the probability of having a bad channel is lower than if only one BS from one operator were available.

If N Rayleigh distributed signals are received and the strongest signal is selected (selection diversity), the expected diversity gain DG has been shown to be [4]:

$$DG = \sum_{i=1}^{N} \frac{1}{i} \tag{4}$$

Since usually a mobile receives a good signal from no more than 3 base stations at the same time, DG is typically in the range of 2-3 dB.

3. SIMULATION MODEL AND ASSUMPTIONS

For our simulations a MATLAB-based simulator RUNE (Rudimentary Network Emulator) provided and described in [5] was used. RUNE is a snapshot simulator i.e. simulations consists of discrete time steps (snapshots) of the system. It means that a system is studied at specific, regularly spaced, time instants. In general, th e system changes between each time instant i.e. mobiles may have moved, new calls may have been created and others may have been terminated. The advantage of the discrete time steps model is that the whole system can be handled at the same time. The state of the system can be represented by vectors and matrices and treated efficiently with mathematical software like MATLAB. The implementation of a snapshot simulator is in general simpler and simulations can run faster than in the event-based simulators where each event must be treated separately. The disadvantage is lower accuracy in comparison with the event-based dynamical simulators i.e. the relative order of the events is not alays the same as it would be in real systems.

Traffic was generated according to Poisson distribution approximated by a binomial distribution. The number of the mobiles who should have left the system was calculated assuming the exponential service time. The mobiles that should have left the system were then selected randomly. The new mobiles were added according to Poisson distribution to keep the average number of agents in the system constant.

In order to model mobility in the system with each mobile a velocity vector (magnitude and direction) and position ((x, y) coordinates) were associated. In each time step the mobiles were moved according to the current velocity and the size of the time step. The velocities of the mobiles were also changed randomly a little bit so that the mobiles accelerate, slow down and change their directions with certain probability.

The propagation loss was modelled as a sum of the antenna pattern, the distance dependent fading, log-normal shadowing and Rayleigh fading. The distance dependent fading was modelled according to the following formula:

$$G=\frac{C}{r^{\alpha}}$$

where C is path gain at a distance of one meter from the transmitter antenna and α is a parameter which determines how power decays as a function of the distance from the base station. For free space propagation α is 2 and in a typical urban environment α ranges from 3 and 4 (3.5 in our case).

The log-normal shadowing was modelled as $G=10^{X}$, where X is normal distributed with mean 0 and variance (typically 8-10 dB). With each geographical point in the system, a specific amount of shadow fading was associated. In this way it was ensured that the shadowing was correlated in space and that the amount of shadow fading will always be the same in the same position. In order to keep implementation expenditure moderate, a smaller shadowing map was repeated many times over the system area.

In a similar manner a map was used to define Rayleigh fading for each geographical point within the simulation area. Because of fast changes of Rayleigh fading, two maps were used and the fading in a point was obtained as the sum of both maps. In this way the memory requirement for storing the map was reduced.

In the RUNE simulator random channel allocation and path-loss-based HO was used. We use Carrier-to-Interference (CIR) based power control (PC), where users increase/decrease their powers in the time step n+1 if their CIR was below/above the required CIR-threshold in the time step n.

An overview of RUNE parameters is provided in Table 1.

For further details regarding RUNE simulator see [5].

I - Simulation Results

Combining the equations (1) and (2) and assuming that the operators' revenue increases with the number of users and decreases with the number of base stations (BS) we obtain Figure 1.

Table 1 - Some Parameters of the Rune Simulator

Parameter	Value
Number of clusters	36
Cell Radius [m]	100
Reuse factor	3
Channels per Cell	5
Offered traffic (Erlangs/cell)	3
Gain at 1 meter [dB]	-31
Noise [dBm]	-118
Distance attenuation coefficient (α)	3.5
Standard deviation lognormal fading [dB]	8
Down link correlation [m]	0.5
Correlation distance [m]	110
Step size of CIR-based PC [dB]	1
Maximum power [dBm]	30

According to Figure 1 relative profit (revenue minus costs) of the operator decreases with the users' bandwidth and the number of BS needed to cover a certain area. Consequently, if operators need to cover a large rural area (low user density) with high bandwidth services (like video streaming), they would need a large number of BS and the profit would be low.

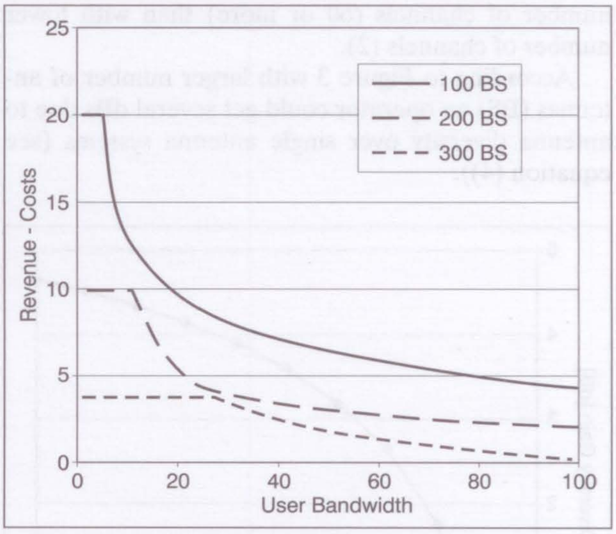

Figure 1 - Relative profit of the operator (revenue minus costs) in dependence on the user bandwidth and number of base stations (BS) according to [5]

Therefore, the profit maximizing strategy of operators would be to provide full coverage in hot-spots (with high user density) and only a partial coverage in rural areas. In order to fulfil the regulator coverage requirements (say 95% national-wide coverage), the operators should share their infrastructure with other operators in rural (low user density) environment.

However, the gain from providing the required coverage is not the only gain from sharing the resources. From Figure 2 we can see the multiplexing gain and from Figure 3 the diversity gain that could be obtained by resource sharing.

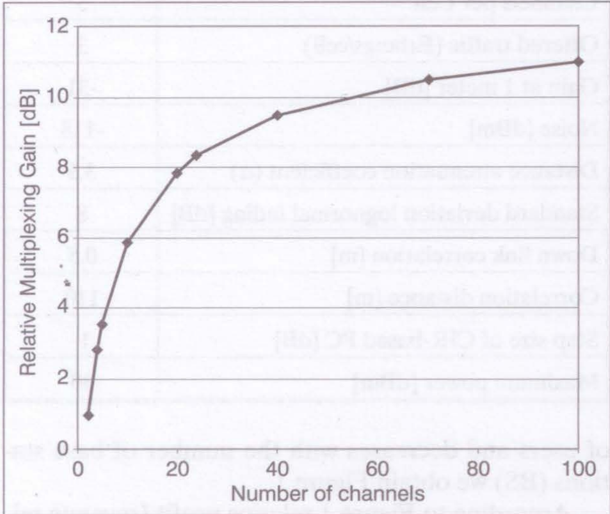

Figure 2 - Multiplexing gain in Erlangs/channels (relative to the gain in case of 2 channels) for the case of 1% blocking probability according to equation (3)

According to Figure 2 and equation (3) an operator could serve about 10 times more traffic per channel for the same blocking probability (1%) with larger number of channels (60 or more) than with lower number of channels (2).

According to Figure 3 with larger number of antennas (BS) an operator could get several dBs due to antenna diversity over single antenna systems (see equation (4)).

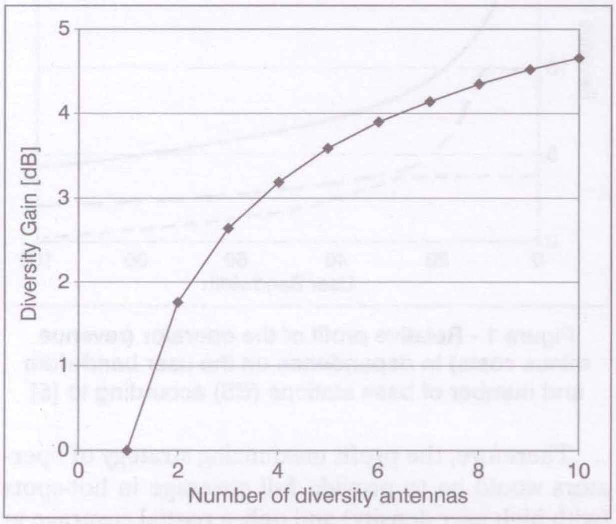

Figure 3 - Diversity gain in dependence on the number of diversity antennas (or BS) according to equation (4)

The diversity gain can be then used to increase the percentage of satisfied users i.e. the higher diversity gain, the lower required CIR at a single antenna and the higher the percentage of satisfied users (see Figure 4).

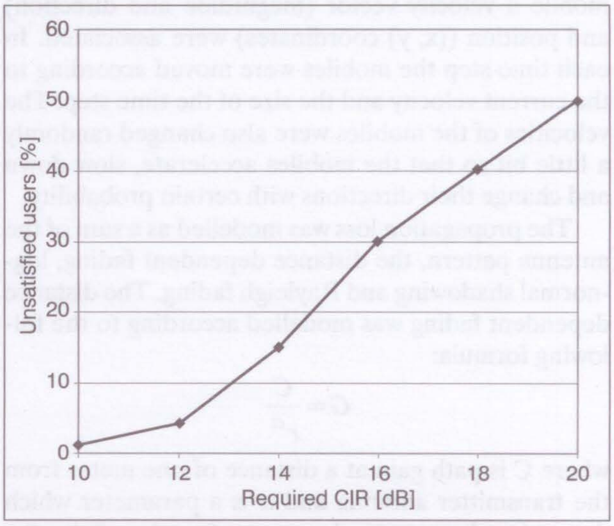

Figure 4 - Percentage of unsatisfied users in dependence on the required CIR according to RUNE simulator from [5]

We can see from Figure 4, for example, that decreasing the required Carrier-to-interference Ratio (CIR) from 14 dB to 12 dB due to diversity gain of using two antennas (BS) instead of one (see Figure 3), brings almost 4-fold decrease in the percentage of satisfied users (from 16% to 4%).

4. PROTECTION AGAINST CHEATING

In previous sections we showed that the operators could significantly increase their profit by infrastructure and spectrum sharing. This is a clear example of "Win-Win" situation, provided that both (all) operators cooperate i.e. deploy and allow the usage of their infrastructure to other operators according to previously achieved agreement.

The question is: What to do if the operator(s) do not cooperate? This is a typical "free-rider" problem, where one partner could be let to provide (almost) alone common good, from which all partners have benefits [6]. Unless keeping the contract cannot be guaranteed by the law, there are at least two possibilities how operators can protect hemselves against non-cooperative behaviour:

- Operators can charge the usage of their infrastructure and spectrum according to real costs. In this way all operators can still benefit at least from multiplexing and diversity gain as shown in previous section.

- The issue of resource sharing among operators can be also modelling according to the Game Theory as the "Prisoner Dilemma" game [7]. In "Prisoner Dilemma" Nash equilibrium outcome of a single-shot game is for both partners not to cooperate because an operator could exploit the resources of the other operator without paying for it. This is a bad outcome for both, since both operators would be better off if they cooperated, as shown in the previous section. However, the good news is that in the repeated "Prisoner Dilemma" when the number of game "shots" is not limited, cooperation might be the best strategy. This is the case with operator resource sharing: each time the users from one operator use the network of the other operator a "new shot of the game is played". In case of the repeated "Prisoner Dilemma" "TIT-for-TAT" ha s been proved as an efficient strategy [7] i.e. "cooperate as long as the other player cooperates, if the other player cheats then do not cooperate". "Pnishment" phase should last for at least several "shots" in order to enforce cooperation.

Operators can also enforce the cooperation in resource sharing game by sharing their resources only with those operators, which were cooperative in the past.

5. CONCLUSION

We showed that significant savings for mobile network operators are possible by sharing their infrastructure and spectrum. We also proposed a model based on the Game Theory how operators should "protect" themselves against exploitation by non-cooperative partners.

Our results could help operators making their decisions about infrastructure and spectrum investment taking into account possible cooperation with other operators.

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SAŽETAK

ZAJEDNIČKO KORIŠTENJE SPEKTRA I INFRASTRUKTURE U BEŽIČNIM MOBILNIM MREŽAMA: PREDNOSTI I OPASNOSTI

U posljednje vrijeme zajedničko korištenje spektra i infrastrukture postaje sve važnije zbog visokih troškova frekvencijskih licence i skupe infrastrukture koja je potrebna za modernu bežičnu vezu širokih pojasnih frekvencija. Ovaj rad analizira prednosti i nedostatke zajedničkog korištenja spektra i infrastrukture pomoću analitičkih modela i simulacija. Rezultati pokazuju da bi operateri mogli znatno smanjiti svoje troškove, povećati kapacitet i poboljšati kvalitetu mreže zajedničkim korištenjem infrastrukture i spektra. Prikazano je pomoću teorije igara kako bi se operateri mogli "zaštititi" od ostalih operatera koji nisu spremni na suradnju.

KLJUČNE RIJEČI

zajedničko korištenje infrastrukture, zajedničko korištenje spektra, teorija igara

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