On The Performance Of Coexisting Spread Spectrum Systems

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ABSTRACT

Wireless communication services may in the future be provided by a larger number of operators than provide the services today. A key enabling factor is the possibility to automatically share the radio spectrum. Bandwidth efficiency is defined as the number of users that can be supported by a basestation in a given spectrum. The bandwidth efficiency in a DS-CDMA and a frequency hopping system is studied when two operators share the same spectrum. The influence of base station location is also studied. The results indicate a substantial loss for the DS-CDMA system and a lower loss for the frequency hopping system.

INTRODUCTION

On the telecom market ten years into the future we expect numerous new operators as well as new services [1]. We can expect that not only the traditional mobile phone operators will provide communication services but also owners of buildings (shopping malls, railway stations, campuses etc.) or private persons may provide communication services. With more operators on the scene a problem of sharing the available radio spectrum will arise.

Today a piece of spectrum is shared by means of regulation. One operator is given the exclusive use of a piece of spectrum in a specific geographical area. Various methods for giving out licenses to operators are described in [2]. When many operators share a piece of spectrum the traditional method has several drawbacks. A large number of operators create a large administrative overhead. If a resource (spectrum) is split into smaller parts the total available capacity is smaller than if the resource had not been split, this is known as trunking losses. Finally the traditional method for allocating spectrum is static in nature. A typical license may be issued for five or ten years. Markets and customer demands change more rapidly which means that the spectrum allocation rarely reflects the actual demand situation.

In order to make future telecommunication systems successful we believe that these systems must be easy to deploy, i.e. they should be possible to install by the end user. Preferably no planning should be required. If planning cannot be avoided it should be possible to do by people who are not trained radio engineers. In addition future systems should require less administration from the regulatory bodies. Key factors for the success of future wireless systems are methods for automatic planning and for allowing different systems to coexist in the same spectrum. If we can find tools for allowing operators to use the same spectrum that don’t require a licensing procedure competition will be promoted. The chosen technology for a standard tends to quickly become obsolete. By avoiding standardization it becomes easier to utilise technological advances since the technology choice is not locked by a standard.

Recently a number of spectrum allocations have been opened for unlicensed operation. Typically devices that operate in these must follow a set of etiquette rules that control maximum output power and how to prevent devices from consuming all available bandwidth [5]. Certain systems that don’t require a license to operate provide telephony services, e.g. DECT. The methods that allow coexistence are typically based on DCA algorithms, the performance of various DCA algorithms are studied in [3]. These generally rely on statistics to determine where there are available channels. The problem with using these algorithms for data communication is the burstiness of the traffic, which tends to make statistics unreliable.

By understanding the mechanisms that underlie the behaviour of systems that operate in the same spectrum it will be easier to design methods for coexistence. In this paper we investigate the effects of using spread spectrum techniques in a shared environment. We consider both direct sequence CDMA and frequency hopping.

In future systems we expect the access point locations to be less planned than today. Therefore we will also study the location influence on the properties of the shared system. Finally the amount of available spectrum influences the coexistence properties of a system and we study this influence as well.

The rest of the paper outlines the system model used in our analysis. We then move on to mathematically analysing coexisting DS-CDMA systems for a special case. In order to study other cases we have performed a set of computational experiments. The paper concludes with the results and we draw some conclusions.

SYSTEM MODEL

We study two cellular systems that coexist in the same geographical area. Each system corresponds to one operator. In the area there are a number of users spread out that are serviced by one of the operators. We assume that all users have the same datarate.

Our channel model includes distance dependent fading and a lognormal shadow fading. This model gives us a short term average C/I. Fast fading, multipath propagation etc. is ignored in these experiments since it is assumed that such channel variations are taken care of by other means, e.g. coding or diversity techniques.

Mobiles and base stations are scattered over a rhombic service area and a wraparound technique is used to emulate an infinitely large system.

In these experiments three different base station placement schemes have been studied.

- Co-located base stations. Both operators have put their base stations at the same geographical location.
- Superimposed hexagons. Each operator has his base stations arranged in a hexagonal pattern. These are shifted by half a cell size in relation to each other so that one operators base station is as far from the other operator's basestations as possible.
- Random location. The base stations are randomly located with a constant probability distribution over the service area. This models the locations of user deployed base stations.

The total number of mobiles is poisson distributed. The mobiles are randomly located over the service area. Mobiles belong to one operator and do not switch. Each mobile uses the same constant datarate.

Users are not handed over between operators. The reasoning behind this assumption is that we believe that the operators are reluctant to carry other operators' traffic. From a technical point of view handover may be difficult to implement since an extensive knowledge of the cells of another operator is necessary. This means that either it is necessary to perform extensive setup or have large standardized interfaces that allow the necessary information to be transferred. Finally for security reasons one operator may be reluctant to let another into their network.

In this paper the analysis focuses on the downlink, i.e. the link from the fixed infrastructure to the mobile user. The reason is that in future systems we expect a lot of data going to the user. As much as 90% of the traffic may be going to the user. Thus the critical link will be the downlink even if the uplink generally is considered to be the critical one. In this paper we assume that the spreading codes used in the DS-CDMA case are perfectly orthogonal when they are from the same base station. In the frequency hopping case there is no adjacent channel interference.

SHARING STRATEGIES

There are generally two ways that a piece of spectrum can be shared between two operators. Both operators can either use the whole spectrum or the spectrum can be split into two parts that are used by only one of the operators.

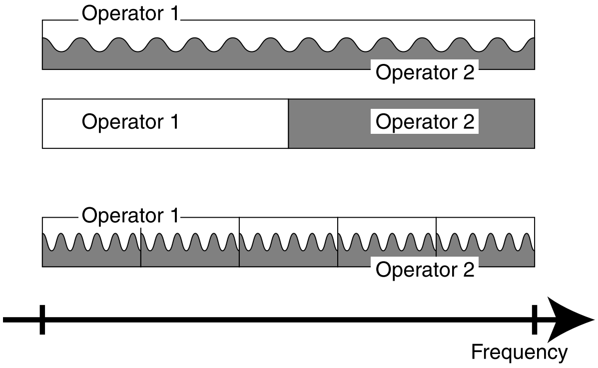

Figure 1 – Spectrum sharing can be done either by coexistence in the same spectrum or by dividing the spectrum between operators.

It is also possible that the spectrum can be split into smaller chunks. These chunks are then shared individually. The reason for doing that may be that the coexistence properties may be better for small systems than for large ones. However the bandwidth efficiency will be the same independent of how many chunks we study.

PERFORMANCE MEASURE

To evaluate the performance of the system we determine the maximum number of users that the system can handle. With handle we mean that 5% of the users in the system will not be given any service. Since the maximum number of users is a random variable we use the average as performance measure.

The number of users that can be supported is determined by increasing the system load until less than 95% of the users can communicate. Each load case is an independent experiment.

In the experiments where DS-CDMA is employed the power control scheme used is DCPC [4]. The C/I target used is 11 dB. If users have a C/I below 10.5 dB they are considered as unable to communicate. We run a number of DCPC iterations if there are users that have reached their maximum power one of them is randomly selected and removed. The DCPC algorithm is then run again to check if the remaining users can communicate.

In the frequency hopping case all transmitters use the same power. A mobile is considered able to communicate if he has a C/I above 7 dB at least 70% of the time.

A. Bandwidth Efficiency

We want to determine how many users that can be supported within a given frequency spectrum. The number of base stations each operator has in a given area will influence how many users that can be supported. If we define M as the average number of users per base station our result will not be influenced by the number of basestations an operator has. The number of users that can be supported is proportional to the number of base stations in the area. The modulation scheme, datarate, error control coding etc. will also influence the number of users that can be supported in a specific spectrum. We define B_0 as the bandwidth that an (unspread) carrier will occupy. By dividing the total bandwidth (B) with the bandwidth of one carrier (B_0) we obtain a measure of how many carrier bandwidths the system occupies. Then our measure becomes easy to use for different carrier bandwidths. The bandwidth efficiency can then be defined as:

$$\eta = \frac{M}{(B/B_0)} \qquad (1)$$

We thus get a number of how many users that on average can be supported per carrier bandwidth and per basestation.

MATHEMATICAL ANALYSIS

In this section we study the performance of two DS-CDMA systems that coexist in the same spectrum. First we outline the general expression for the performance of these systems. However this is difficult to analyse. Thus we study the special case where the pathloss only depends on the distance from a base station and the user. We also simplify by studying the case with a large bandwidth and many users.

Consider a system with unconstrained SIR balancing power control. For the signal to interference in the downlink we get the expression:

$$\Gamma_{ij} = \frac{P_{ij}G_{ijj}}{\frac{1}{N}\sum_{k\neq j}^{K}\sum_{l=1}^{M_k} P_{lk}G_{ijk} + \eta_{ij}} \qquad (2)$$

Where Γ_{ij} is the SIR in the downlink for user i in cell j, P_{ij} is the power transmitted by basestation to user i in cell j, G_{ijk} is the pathloss between user i in cell j and basestation k, N is the processing gain of the system, K is the total number of base stations in the system, M_k is the number of users in cell k and η_{ij} is the thermal noise for user i in cell j.

Analysing this is difficult since P_{ij}, G_{ijk} and M_k are random variables. However if the number of users is large we can simplify by using averages instead since $M_k \rightarrow E[M_k]$ for large M_k. If the number of users is large there will be the same number of users $M=M_k$ in each cell. The pathloss G can be simplified to only include distance dependence. We introduce r_{ijk} – the distance from user i in cell j to basestation k, α is the propagation loss parameter.

$$G_{ijk} = \frac{1}{r_{ijk}^{\alpha}} \qquad (3)$$

We introduce P_k to be the average power transmitted from basestation k to a user in that cell. Finally Γ_T is the target SIR for the power control algorithm. After some reorganisation we get:

$$P_{ij} = \Gamma_T r_{ijj}^{\alpha}\left(\frac{M}{N}\sum_{k\neq j}^{K}\frac{P_k}{r_{ijk}^{\alpha}} + \eta_{ij}\right) \qquad (4)$$

In a sir balancing power control scheme the SIR should be constant for all users. Thus we can find out the power that is necessary to transmit for one base station in order obtain a given SIR at a specific user at a specific location. Given that the interference power from the other base stations is constant.

It should be noted that if the user is very close to another base station the power necessary to obtain a specific SIR will tend to infinity. The reason is that $r_{ijk} \rightarrow 0$ close to an interfering basestation. We want to find the average power necessary to support one user, so we average over the whole cell area. In order to limit the average power we exclude a circular area around each interfering base station. It should be noted that excluding a circular area does not result in the lowest average power. The radius of the exclusion circle is set so that the exclusion circles cover 5% of the total cell area. The figure below outlines the area (A) that we serve.

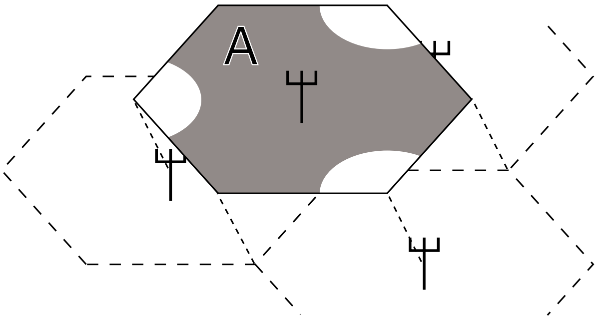

Figure 2 – The area (A) that is supported by the omnidirectional basestation in the middle. The cell is coexisting with another cellular system using the same frequency spectrum.

It is now possible to find the average power P_k that we assumed previously. By averaging over the area A we can determine the average transmission power in the cell we are studying.

$$P_k = \iint_A \Gamma_T r_{ijj}^{\alpha}\left(\frac{M}{N}\sum_{k\neq j}^{K}\frac{P_k}{r_{ijk}^{\alpha}} + \eta_{ij}\right)dxdy \qquad (5)$$

However since all cells have the same number of users the average interference power is equal to the average transmitted power is equal in all cells (P_k=P). From this we obtain:

$$PM = \frac{\frac{1}{A}\iint_A \Gamma_T r_{ijj}^{\alpha}\eta_{ij}\,dxdy}{1-\frac{M}{N}\frac{1}{A}\iint_A \Gamma_T r_{ijj}^{\alpha}\sum_{k\neq j}^{K}\frac{1}{r_{ijk}^{\alpha}}\,dxdy} \qquad (6)$$

Since the power must be positive we can obtain an upper bound on M/N. Namely:

$$\frac{M}{N} < \frac{1}{\frac{1}{A}\iint_A \Gamma_T r_{ijj}^{\alpha}\sum_{k\neq j}^{K}\frac{1}{r_{ijk}^{\alpha}}\,dxdy} \qquad (7)$$

The area we excluded corresponds to the users that cannot be supported. We note that by disallowing more users we can obtain higher spectrum efficiency. We also note that for the case of 5% lost users we obtain very low spectrum efficiency.

NUMERICAL RESULTS

A. DS-CDMA

In our first experiment we investigate the effects of processing gain on the coexistence properties. The figure shows the results. It should be noted that for systems that utilise the spectrum sharing the bandwidth efficiency of the shared system is only 30% of the bandwidth efficiency that can be obtained if the spectrum is given exclusively to one operator.

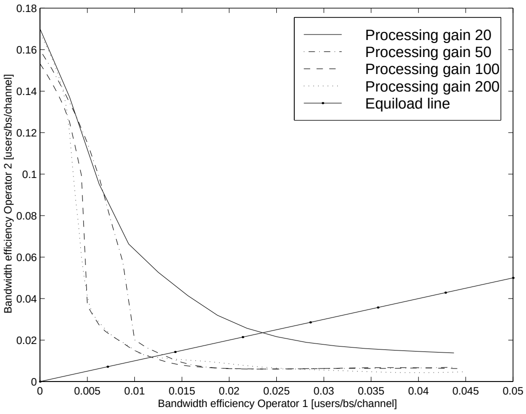

Figure 3 – Spectrum sharing using DS-CDMA. The figure shows the bandwidth efficiency for different processing gains. The cell layout is superimposed hexagons and outage probability is 5%.

Due to statistical variations the curves are a little bit shaky. More points are simulated around the equiload line which makes the curves. Note that the more bandwidth that is available the lower the bandwidth efficiency becomes. Finally it should be noted that it is possible to continue the curves by mirroring in the equiload line.

B. Location Influence

We expect future infrastructures to a large extent be deployed by the end user. We model the location of these base stations as randomly located base stations. When performing numerical experiments we get the results in figure 4.

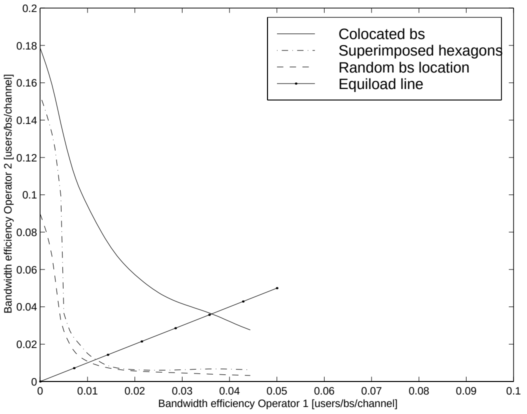

Figure 4 – The figure shows the bandwidth efficiency for various base station location strategies and 5% outage. Processing gain is 100.

We note that the random location of base stations results in lower bandwidth efficiency when only one operator has load. But when both operators has a traffic load the losses are not as severe as for the superimposed hexagons case. This may be explained by the fact that the near far effect is not as pronounced in the random case.

C. Frequency Hopping

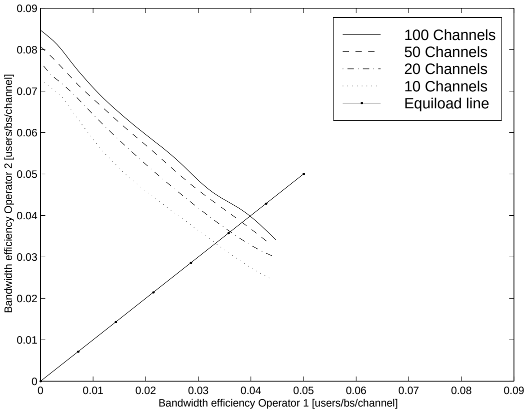

Figure 5 – Spectrum sharing using frequency hopping. The figure shows the bandwidth efficiency for different number of available channels. The cell layout is superimposed hexagons, outage probability 5%

Here we study what happens if frequency hopping is used as a multiple access method in a shared system.

Here we note that the total capacity in the system does not vary depending on the load distribution between the different operators.

CONCLUSIONS

DS-CDMA not suitable for future infrastructures from a coexistence perspective

We can see that the coexistence properties of DS-CDMA systems does discourage use in future communication systems where the radio spectrum is to be shared by many operators. We can see that we loose more than half of the available capacity in a network if we share the spectrum between two operators compared to splitting the spectrum, that means that the cost of building an infrastructure more than doubles for a given capacity. Clearly this is an undesirable property. We note that the losses are mainly due to the near-far effect. There may be ways to improve the performance. Remedies may be to allow handover between operators or by colocating the basestations of both operators.

Increased bandwidth in the DS-CDMA case gives worse coexistence properties

From figure 3 we see that by increasing the processing gain in a CDMA system the coexistence properties of a system becomes worse. When the processing gain is high each cell contains many users. That means that each of the base stations will transmit a fairly high power especially to support the users at the cell border. But in the superimposed hexagon placement scheme the base station for one operator is located on the border of the cell of another operator. If the base station transmits a high power that will effectively block out all the users of the other operator that are close to the base station of the first operator. Thus the capacity of the other operator is lowered.

Frequency hopping promises good coexistence properties

We see that the total capacity of two systems is approximately constant when using frequency hopping. This makes it better suited for coexisting systems. However we can note that the capacity of operator 1 drops when operator 2 increases his traffic. We also note that even though it is not done in this paper it is important to compare the absolute bandwidth efficiency when deciding on which access scheme to use.

Orthogonal channels preferable

The near-far problem has a large contribution to the losses when sharing the spectrum. By selecting an access scheme that is not influenced by the near far effect as much we may be able to improve the coexistence properties. Thus orthogonal access methods seems to be preferable.

Superimposed hexagons worst case

From figure 4 we can see that placement of the base stations influence the coexistence properties for the system. When we use the superimposed hexagons structure we see that the loss due to spectrum sharing is more pronounced compared to the colocated scheme. The loss for colocated base stations is due to the lack of synchronisation between the base stations. Thus interference is created within the cell. The loss in the superimposed hexagons case is due to near far effects. Finally we see that even though the random placement scheme has lower performance than the other schemes for each of the operators the coexistence loss is less.

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