REUSE-PARTITIONING COMBINED WITH TRAFFIC ADAPTIVE CHANNEL ASSIGNMENT FOR HIGHWAY MICROCELLULAR RADIO SYSTEMS

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Abstract

Dynamic channel assignment adapting both to traffic variations and to changing mobile locations is investigated for 1-dimensional cellular radio systems. In order to adapt the channel assignment to the mobile locations, the cells are divided into subcells. The special properties of 1-dimensional systems together with a simple propagation model are used to find the subcell configuration that minimize the reuse distance. To transform this shorter reuse distance to increased capacity it is essential that the channel assignment algorithm can adapt to traffic variations between the subcells. In the paper, this is obtained by using a slightly modified version of a previously proposed maximum-packing algorithm. Numerical results indicate that a channel assignment algorithm adaptive both to call traffic variations and to changing mobile locations may double the capacity compared to fixed channel assignment.

1. Introduction

The main limitation when providing mobile services to a large number of subscribers is the shortage of radio frequency spectrum. Subscribers to mobile telephone systems tend to concentrate along roads and streets. To achieve a sufficiently high capacity a very high base station density is needed along each heavily used road. Such systems will clearly exhibit a 1-dimensional structure. If the channels used in the overlaid macro-cell are not the same as those used in the microcells, the interference will originate from transmissions in other microcells in the 1-dimensional structure (fig. 1). It is thus possible to identify 1-dimensional subsystems which, to some extent, can be treated separately [1,4].

There are several other ways to increase the number of simultaneous users in the system, beside installing more base stations. The second generation cellular mobile communication systems will use digital transmission schemes together with error-correcting codes. Since these schemes are more tolerant to interference, they allow for a shorter reuse distance. It is also clear that the fixed channel assignment scheme, used in todays systems, is an inflexible and conservative design. To increase the flexibility and to reduce the unnecessary margins in signal-to-interference ratio Dynamic Channel Assignment (DCA) has been proposed.

In [2], a classification of different DCA-schemes was proposed. The DCA-schemes were subdivided into three categories, *traffic adaptive schemes, channel reusability schemes,* and *interference adaptive schemes.* The class of DCA-algorithms adaptive to traffic variations, increase the capacity through a more flexible use of the channels in the system. Instead of assigning all channels to the bases in a fixed manner, the number of channels assigned to each cell depends on the number of calls in progress in that cell. The DCA-algorithms that adapt to the received wanted signal power form the class of channel reusability schemes. It is easy to understand that in channels used by mobiles close to their respective base station the received signal level is, in general, higher than in channels used by more distant mobiles. In these channels (used by mobiles close to their respective base station) we can tolerate a higher interference level and are thus able to use a shorter reuse distance. The most straight-forward application of this concept is to divide the cell into subcells, each with a different reuse

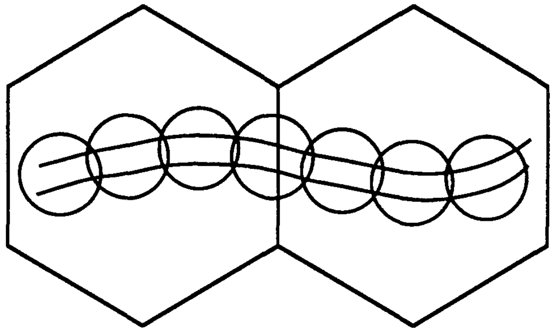

Figure 1: An example of a road covered by microcells. The microcells, illustrated with circles, form a 1-dimensional system. The hexagons correspond to the overlaid macro-cells.

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pattern. This method has been coined *reuse-partitioning*. Reuse-partitioning with two subcells (or zones) has been investigated in several papers [5,6]. In the final class we find the algorithms that adapt to the actual interference situation. The mobiles and the bases measure the interference on several channels. The interference adaptive DCA-scheme uses this information to assign channels to calls.

In this paper, we will focus on DCA-schemes that are combinations of traffic adaptive schemes and channel reusability schemes. The cells will be divided into subcells in such a way that no mobile will receive an unnecessary high signal-to-interference ratio, due to the varying location of the mobile. This will, in general, result in more than two subcells per cell. The special properties of 1-dimensional systems will be used in the design of a DCA-algorithm that adapts to traffic variations between subcells.

2. Basic assumptions

Throughout the paper we will assume that the base stations are placed at regular intervals along the road. The distance between two bases is normalized to 1 length unit. Each base is connected to an omnidirectional antenna covering the road on both sides of the base. All bases and mobiles are assumed to use the same transmitter power. Further, we assume that the signal strength is monotonously decreasing with the distance. We also assume that the mobiles are connected to the base with the strongest signal strength. The consequence is that the mobiles will be connected to the closest base. The region closest to each base is referred to as a *cell*. Each cell is then divided into *subcells* (section 3).

The communication resource is divided into M orthogonal channels. A channel corresponds either to a frequency band, a time slot, or a combination of these two alternatives. The channels are numbered from 1 to M and arranged in a list. We assume that the only restriction on the use of the channels is due to co-channel interference, i.e., we do not consider adjacent channel interference or thermal noise. Co-channel interference from users in other streets is assumed to be negligible. Denote the signal-to-interference ratio at the receiver by γ and the required signal-to-interference ratio γ_0. If $\gamma \geq \gamma_0$ the link is assumed to be usable and if $\gamma < \gamma_0$ the link is assumed to be unusable. Further, we assume that each base, if necessary, is able to use all M channels simultaneously.

To analyse the signal-to-interference ratio, γ, in each link we need to define a propagation model. We will assume that the received signal power P_r, at a mobile on distance r from the base, is described by

$$P_r = \frac{G \cdot P_t}{r^{\alpha}}, \tag{1}$$

where P_t is the transmitted power, G is a constant depending on the antenna gains, and α is a propagation constant. Using this propagation model it is possible to determine which pairs of subcells that are compatible in the sense that the same channel can be used in both subcells of that pair. The *extended compatibility matrix*, C, is defined as

$$c_{ij} = \begin{cases} 0 & \text{if a channel can be used simultaneously in subcells i and j} \\ 1 & \text{if a channel can not be used simultaneously in subcells i and j.} \end{cases} \tag{2}$$

A difficulty with the extended compatibility matrix is that it expresses a pair-wise compatibility between subcells, while in reality the compatibility between two subcells is affected by interference from other subcells not in that pair. This unknown interference can be compensated by including an extra margin, γ_I, in the required signal-to-interference ratio,

$$\gamma_0' = \gamma_0 \cdot \gamma_I. \tag{3}$$

In 1-dimensional systems the unknown interference will be dominated by the second closest interfering base. Typically, this base will be on approximately the same distance as the closest interfering base, implying an interference margin in the order of 3 dB.

3. Intra-cell borders

There exist infinitely many ways to divide the cells into subcells. Fortunately, we may note the key observation that the interference power at a given location only can take discrete values, since the interfering bases are at fixed locations. We will propose a subcell configuration, where all mobiles within a subcell can tolerate the interference from the same interfering base, but no mobile in the subcell can tolerate the interference from a closer base. In this way, we do not waste any "capacity" due to considering the worst mobile location. We will refer to the borders between the subcells as *intra-cell borders*.

Let us study the signal-to-interference ratio for a mobile on distance r from the base. The distance between the base in the studied link and the closest interfering base is called the reuse distance, denoted by D. If the closest interfering base is on the same side as the mobile, the distance between the mobile and the interfering base equals D-r and the signal-to-interference ratio is (1)

$$\gamma = \frac{\frac{P_0}{r^\alpha}}{\frac{P_0}{(D-r)^\alpha}} = \left(\frac{D-r}{r}\right)^\alpha \geq \gamma_0'. \tag{4}$$

If the closest interferer is on the opposite side compared to the mobile, the distance between the mobile and the interfering base equals D+r, and the signal-to-interference ratio is,

$$\gamma = \frac{\frac{P_0}{r^\alpha}}{\frac{P_0}{(D+r)^\alpha}} = \left(\frac{D+r}{r}\right)^\alpha \geq \gamma_0'. \tag{5}$$

Defining the *capture parameter* β as

$$\beta = (\gamma_0')^{1/\alpha}, \tag{6}$$

gives the following conditions on r for a sufficient signal-to-interference ratio (4-5),

$$r \leq \frac{D}{\beta + 1} \quad \text{(same side)}, \tag{7}$$

$$r \leq \frac{D}{\beta - 1} \quad \text{(opposite side)}. \tag{8}$$

The *intra-cell* borders are now chosen to the locations where a reuse distance D just barely can be used. For each D we obtain two intra-cell borders (7-8) on each side of the base. Starting with a reuse distance D=1, two intra-cell borders are obtained, then D is increased by one until the *inter-cell* border is reached. The intra-cell borders (fig. 2) on one side of the base stations is thus,

$$r_i = \begin{cases} \dfrac{\frac{i+1}{2}}{\beta + 1} & r_i < \frac{1}{2} \quad \text{i odd} \\ \dfrac{\frac{i}{2}}{\beta - 1} & r_i < \frac{1}{2} \quad \text{i even.} \end{cases} \tag{8}$$

The intra-cell borders and the number of subcells per cell will depend on the value of β. Changing the proposed borders implies that channels used by some mobiles has to use a larger reuse distance than prescribed by the propagation model (1). Therefore, in the proposed subcell configuration all mobiles can use channels with the shortest possible reuse distance.

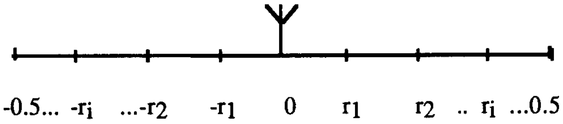
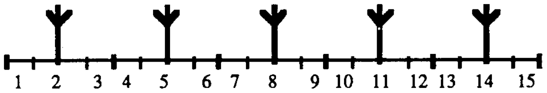


Figure 2: Intra-cell borders in one cell. The intra-cell borders are equal on both sides of the base station.

From the way the intra-cell borders are chosen the extended compatibility matrix follows directly. As un example, let us investigate the subcell configuration and the corresponding compatibility matrix for β=3. From (8) it follows that it is enough to divide each cell into 3 subcells. The resulting subcell configuration and corresponding compatibility matrix for a 5 cell system is shown in figure 3. We note, for example, that channels used in subcell 2 can be reused already in subcell 5, and that channels used in subcell 3 can be reused in subcell 7.

4. Performance measure

The traditional performance analysis for cellular radio systems assumes Poisson call arrivals and exponential call durations. Further, the cell sizes are assumed to be that large, that mobiles move only negligible distances during a call. The system is then modelled as a Markovian queueing system with blocking. In a small cell environment a mobile will move through several cells during a call. Using a DCA-algorithm will also require many channel reassignments within the cell. Taking these effects into account will make the traditional analysis intractable. The



$$C = \begin{bmatrix} 1&1&1&1&0&0&0&0&0&0&0&0&0&0&0 \\ 1&1&1&1&0&0&0&0&0&0&0&0&0&0&0 \\ 1&1&1&1&1&1&0&0&0&0&0&0&0&0&0 \\ 1&1&1&1&1&1&1&0&0&0&0&0&0&0&0 \\ 0&0&1&1&1&1&1&0&0&0&0&0&0&0&0 \\ 0&0&1&1&1&1&1&1&1&0&0&0&0&0&0 \\ 0&0&0&1&1&1&1&1&1&1&0&0&0&0&0 \\ 0&0&0&0&0&1&1&1&1&1&0&0&0&0&0 \\ 0&0&0&0&0&1&1&1&1&1&1&1&0&0&0 \\ 0&0&0&0&0&0&1&1&1&1&1&1&1&0&0 \\ 0&0&0&0&0&0&0&0&1&1&1&1&1&0&0 \\ 0&0&0&0&0&0&0&0&1&1&1&1&1&1&1 \\ 0&0&0&0&0&0&0&0&0&1&1&1&1&1&1 \\ 0&0&0&0&0&0&0&0&0&0&0&1&1&1&1 \\ 0&0&0&0&0&0&0&0&0&0&0&1&1&1&1 \end{bmatrix}$$

Figure 3: The compatibility matrix for a system with 5 cells. Each cell is divided into 3 subcells. The subcells are numbered from "left" to "right".

performance will also depend on, for example, the handover strategy. Therefore, we propose a simplified approach where the system in operation is studied at some randomly chosen instant of time. At this instant, we will determine how well the DCA-algorithm may accommodate the calls in progress.

We assume that the distances between the mobiles with calls in progress in the 1-dimensional system are exponentially distributed with mean $1/\lambda$ length units. This implies that the number of mobiles in a cell of 1 length unit is Poisson distributed with expectation λ (calls/cell). We normalize the traffic intensity with the total number of channels and define the *normalized traffic load*, ρ, as

$$\rho = \frac{\lambda}{M} \quad \text{(calls/cell/channel).} \tag{9}$$

Consider a system with V cells and let Z be the total number of calls that are not assigned a channel by the DCA-algorithm under investigation. Our performance measure will be the *assignment failure rate* defined as,

$$\nu = \frac{1}{\lambda V} E[Z] = \frac{1}{\rho M V} E[Z], \tag{10}$$

which is the "relative" number of calls that the DCA-algorithm fails to assign a channel at some given instant of time.

5. The channel assignment algorithm

The basic idea in the DCA-algorithm proposed below is that the channel assignments are done from "left" to "right" in the system. Given the traffic (number of calls) in each subcell and the extended compatibility matrix the algorithm assigns as many calls as possible, starting with the calls in subcell 1. When assigning channels to calls in subcell i, the algorithm has to check which channels are already in use in subcells not compatible with subcell i. The set of subcell, E_i, is defined as the subcells that has to be considered when assigning channels to calls in subcell i. These sets are given by,

$$E_i = \{ j \,;\, c_{ij} = 1 \text{ and } j<i \},\ i = [1 \ldots W], \tag{11}$$

where W is the total number of subcells in the system. This process can be formalized and we call it the Greedy-algorithm [8].

The Greedy-algorithm:

0. Set i=1.
1. Make a list of available channels in subcell i, by removing channels that are already used in the set E_i from the list of channels.
2. Assign channels from the remaining list of channels to as many calls as possible in subcell i.
3. i=i+1, go to step 1. ❑

We will investigate the assignment failure rate for two values of β. For β=3, the compatibility matrix consists of a diagonal band of ones (fig. 3). The property necessary for the Greedy-algorithm to minimize the assignment failure rate is that there are no "holes" (zeros within the field of ones) in the compatibility matrix [7]. Consequentially, the Greedy-algorithm will achieve an optimal channel assignment. We notice that the actual choice of channels from the list of remaining channels (step 2) is of no importance. For numerical results see section 6.

For β=5, each cell is divided into seven subcells (8) and the compatibility matrix will not have the properties necessary for the Greedy-algorithm to guarantee an optimal channel assignment. When the compatibility matrix contains "holes", which is the case for β=5, the explicit choice of channels becomes important [8]. We make the observation that the reason is that it is possible to remove the same channel twice from the list of available channels. This happens, for example, if the same channel is used in two adjacent "center" subcells and the algorithm is to assign channels in a subcell that are not compatible with either of the two center subcells. Therefore, we propose that the algorithm in step 2 chooses channels with as low numbers as possible when assigning calls in the subcells near the base and uses channels with as high channel numbers in the rest of the subcells. In this way we obtain a "soft" partitioning of the channels allowing for a traffic adaptation between the subcells. This ad hoc strategy turns out to have good performance, for numerical results see section 6. However, there may exist channel assignments with a lower number of not assigned calls.

6. Numerical results

In a fixed channel assignment scheme β=3 corresponds to a reuse distance D=2, and β=5 corresponds to D=3. In figure 4 the assignment failure rate as a function of ρ is plotted for a total of M=20 channels. For comparison, the performance of the Greedy-algorithm with "original" cells, and the performance of an optimum reuse-partitioning scheme [8] is included in the figure. The gain with the Greedy-algorithm using subcells is about 90%, compared to a fixed channel assignment scheme, for ν=0.01. In figure 5, the assignment failure rate for β=5 and a total of M=30 channels is plotted. The gain with the Greedy-algorithm using subcells is about 110%, compared to a fixed channel assignment scheme, for ν=0.01.

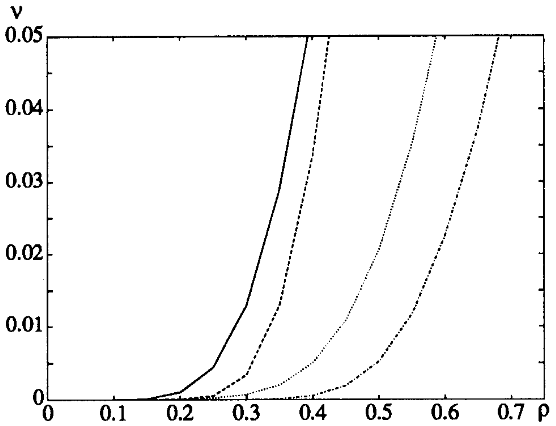


Figure 4: The assignment failure rate as a function of the normalized traffic load for $\beta=3$. Solid line: fixed channel assignment, dashed line: Greedy-algorithm with "original" cells, dotted line: reuse-partitioning, dashed-dotted line: Greedy-algorithm with subcells

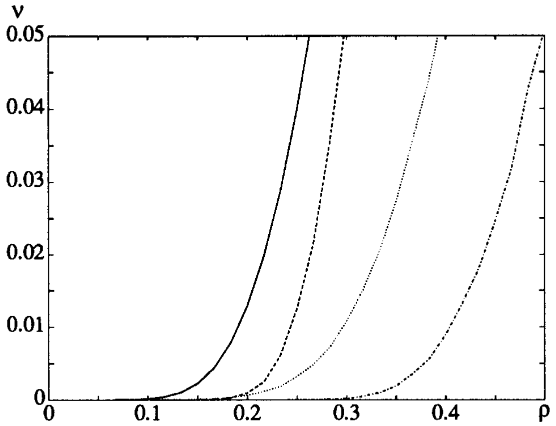


Figure 5: The assignment failure rate as a function of the normalized traffic load for $\beta=5$. Solid line: fixed channel assignment, dashed line: Greedy-algorithm with "original" cells, dotted line: reuse-partitioning, dashed-dotted line: Greedy-algorithm with subcells

7. Discussion

Assuming a monotonously decreasing signal strength it is shown that it is sufficient to divide the cells into a finite number of subcells to adapt fully to the mobile locations. In interference resistant systems there may be enough to divide each cell into three subcells per cell. The advantage of dividing the cells into subcells instead of dividing the cell into several new cells is that no additional base stations are required. The main cost associated with our schemes is instead the increased complexity of the pre-planning process, and the increased number of intra-cell handovers during operation of the system. To adapt to traffic variations between subcells a modified version of the Greedy-algorithm was proposed. We pointed out that the Greedy-algorithm for the case of three subcells per cell is the optimal algorithm in the class of Reuse-MP algorithms [2,3]. Using the modified Greedy-algorithm gains in the order of 100% compared to a fixed channel assignment scheme were obtained. We have only considered the down link in the paper, but similar gains should also be possible to obtain in the up link. In the up link, we would be forced to include an additional interference margin due to the variations in the location of the interfering mobiles.

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