Wireless Networks

-Catching the mobile future-

Edited by
Jos H.Weber
Jens C. Arnbak
Ramjee Prasad



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Influence of the User Mobility on the Spatial Multiplex Gain of an Adaptive SDMA System

M. Tangemann*

Alcatel SEL Research Centre
D-70430 Stuttgart
Tel: + 49 711 8304-121
Fax: + 49 711 8304-202
E-mail: mtangema@rcs.sel.de

Abstract: Adaptive SDMA (Space Division Multiple Access) is a new technology for mobile communication systems with which the capacity can be increased and cochannel interference can be reduced. It is based on the application of an adaptive array antenna at the base station site which is used to form multiple independent beams per traffic channel. Each of these beams is used to support a connection with a mobile station, i.e., multiple mobile users can be served in the same traffic channel, and the capacity of the base station is increased.

To evaluate the benefits of A-SDMA in terms of capacity increase, an analysis is presented which permits to analyse the spatial multiplex gain of an A-SDMA system taking into account the user mobility. Additionally, various other performance parameters of particular interest for the design of a cellular system with A-SDMA technology are derived. Furthermore, an example is given, where from a cellular scenario a user density distribution is derived which is then used as an input for the analysis derived in the first part of this paper.

1. Introduction

The ever increasing capacity demands in current cellular mobile communication systems will lead to a situation where the infrastructure installed is saturated during busy hours, leading to undesirably low quality of service. Two effects limit the capacity of these systems: The equipment limit is reached, if e.g. the number of carriers or call-handling devices installed is not sufficient to handle a given amount of offered traffic. On the other hand, even if there are resources available, the interference level caused by activating another carrier in a given cell might be too large, i.e. the system is interference-limited.

Both limits can be tackled using a new technique called A-SDMA [5,6]. It is based on the exploitation of the spatial dimension which has so far not been used for parallelism. Using adaptive array antennas [1] at the base station sites, multiple independent beams can be formed with which several mobile users can be served simultaneously in one traffic channel. This approach is an extension of the system in [4], where adaptive arrays are used for interference reduction, without exploiting the potential of spatial parallelism. An example of a typical A-SDMA scenario is depicted in Fig. 1, where seven mobile stations are served on only two carrier frequencies marked by bright and dark beams, respectively.

The purpose of this paper is to analyse the grade of spatial parallelism that can be achieved with A-SDMA by taking into account a given angular user density distribution which could be obtained from measurements or from scenarios describing the user mobility. The analysis is presented in Sec. 2. An example for the application of the analysis is given in Sec. 3, where a motorway scenario is assumed as a basis for the user mobility model and the call blocking probabilities as well as the achievable spatial multiplex gain are analysed. An extended version of this paper is available in [7].

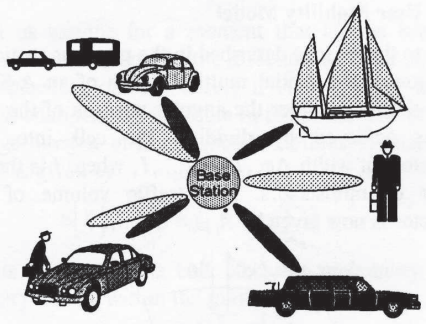


Fig. 1: Typical scenario for A-SDMA application

2. Analysis of the Spatial Multiplex Gain

2.1. Characterisation of the Problem

As A-SDMA aims at exploiting the spatial dimension of the radio resource, the spatial distribution of the users

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is critical to the effectiveness of A-SDMA and the benefits finally achieved. Even though a certain number of parallel beams per channel may be provided by the base station of a cell, they can be used for communication links only if the users to be served by these beams are located in different angular positions, far enough apart to be separated by different beams such that the C/I requirements are not violated.

An extreme case would evolve if all the users within a cell are grouped together in one place, e.g., a market place or a stadium. As seen from the base station, all these users have the same angular position, and they cannot be separated by different beams. In this case the application of an adaptive array antenna at the base station site would still help to reduce the interference in cochannel cells, but spatial multiplexing would be impossible.

On the other hand, a uniform user distribution is optimal for the application of A-SDMA since the spatial multiplex gain is only limited by the angular resolution of the direction finding and beam forming algorithms. Assuming a beamwidth of $2\pi/M$ with an M-element array, the theoretical maximum number of parallel beams is M. However, many direction finding algorithms limit the number of directions that can be detected to $M-1$. Taking into account several further limiting effects such as propagation effects and hardware restrictions, we frequently use $M/2$ as an estimate for the number of parallel beams N, which has been found to be a good compromise in a variety of situations. However, these considerations do not take into account the distribution of the mobile users in the cell which may further decrease the spatial multiplex gain in extreme situations.

2.2. A User Mobility Model

Due to the reasons described in the previous section, an evaluation of the spatial multiplex gain of an A-SDMA system should consider the angular position of the users. This is achieved by dividing the cell into small minisectors of width $\Delta\varphi_i$, $i=1,2,\ldots,I$, where I is the total number of minisectors. The traffic volume of each minisector is now given by A_i, $i=1,2,\ldots,I$.

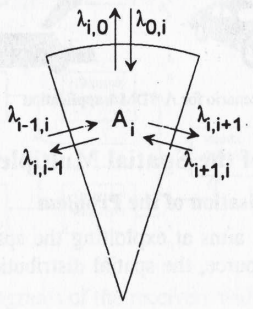


Fig. 2: Flow model for a minisector

A model of the flow of mobile stations into and out of the minisector is given in Fig. 2. The external arrival rate $\lambda_{0,i}$ includes active mobile stations entering the cell via handover as well as mobile stations inside the minisector becoming active by generating a call. Accordingly, the departure rate $\lambda_{i,0}$ includes active mobile stations leaving the cell via handover and active mobile station terminating their calls. In addition to that, transitions of mobiles into neighbouring minisectors are possible. They are characterised by the transition rates λ_{ij}, $|i-j|=1$.

2.3. Queueing Model for the Active Mobiles in a Cell

The queueing model of a cell for the purpose of description of the spatial distribution of the customers is based on a division of the cell into minisectors as described in the preceding section. Each minisector is modelled as a single queue with a service unit consisting of multiple servers (cf. Fig. 3). The service unit serves the mobiles before they are routed to another minisector or leave the cell.

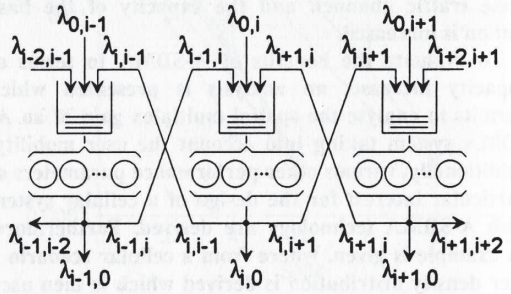


Fig. 3: Queueing model of a cell.

For the queueing model analysed here, the following assumptions are made:

1. External arrivals into the minisectors follow a Poisson process, i.e., the interarrival times are exponentially distributed. The arrival rate is

$$\lambda_i = \lambda_{0,i} + \lambda_{i-1,i} + \lambda_{i+1,i} \qquad (1)$$

2. The sojourn time of an active mobile in a minisector is exponentially distributed with a mean of $1/\varepsilon_i$.
3. The service unit of the queue consists of an infinite number of servers, i.e., each customer is served immediately after arrival, and no waiting phase in the queue is included. This assumption means that a) the physical space inside the minisector is enough for any number of customers which can be assumed to be true in practical scenarios, and that b) the number of traffic channels available inside a minisector is unlimited (Of course this latter assumption is not valid, and it will be removed in a later stage of the analysis using the results derived here as an approximation which is valid for small call blocking probabilities. For the moment, we concentrate only on the number of mobile stations that are

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willing to communicate without taking into account the number of channels available).

4. The branching probabilities for the departure process are independent of previous routing decisions, i.e., the branching process is memoryless.

From Burke's theorem [2] it can be concluded that as a consequence of the second assumption, the departure process from a service stage again is Poisson process given that the input process is a Poisson process. However, since memoryless branching and combining of Poisson streams again yields Poisson streams [3] the input process into each queue is Poisson, and finally an open queueing network consisting of $M/M/\infty$ queues is obtained. For this type of queueing network, the product form solution holds [2], i.e., the I-dimensional distribution of the cell state $(X_1,X_2,...,X_I)$ is given by

$$P\{(X_1,X_2,...,X_I)=(k_1,k_2,...,k_I)\}=\prod_{i=1}^{I}P\{X_i=k_i\} \quad . \quad (2)$$

This means that the distributions of the X_i are independent of each other. Therefore, it is sufficient to consider the minisectors in separation. Since the traffic load in a minisector i is

$$A_i=\frac{\lambda_i}{\varepsilon_i} \quad (3)$$

the stationary state distribution in an $M/M/\infty$ queue is given by

$$p_{i,k_i}=P\{X_i=k_i\}=\frac{A_i^{k_i}}{k_i!}\cdot e^{-A_i} \quad , \quad (4)$$

which is a Poisson distribution [2]. With eq. (2) now the distribution of the cell state is obtained as

$$P\{(X_1,X_2,...,X_I)=(k_1,k_2,...,k_I)\}=e^{-A}\cdot\prod_{i=1}^{I}\frac{A_i^{k_i}}{k_i!} \quad , \quad (5)$$

where

$$A=\sum_{i=1}^{I}A_i \quad (6)$$

is the total offered traffic of the cell.

An interesting characteristic of this solution is its additivity property. If, e.g., two adjacent minisectors are joined to form one, the number of active customers in the new minisector is

$$\tilde{X}_i=X_i+X_{i+1} \quad , \quad (7)$$

for which the state distribution

$$\tilde{p}_{i,k_i}=P\{\tilde{X}_i=k_i\}=\frac{\tilde{A}_i^{k_i}}{k_i!}\cdot e^{-\tilde{A}_i} \quad (8)$$

is obtained, which is again a Poisson distribution with a mean value of

$$\tilde{A}_i=E[\tilde{X}_i]=A_i+A_{i+1} \quad . \quad (9)$$

Consequently, with the above assumptions the stochastic behaviour of the traffic in a minisector is simply given by the average load A_i in the minisector. This property is independent of the manner in which the cell is divided into minisectors. For the special case $I=1$ the cell itself is covered by one minisector, and a Poisson distribution with a mean value of A according to eq. (6) is obtained.

On the whole, an I-dimensional compound Poisson distribution is obtained for the state distribution of the cell. Therefore, it is sufficient to characterise the cell by its traffic profile $A_i, i=1,2,...,I$, independently of the underlying traffic flow rates and service processes.

2.4. Traffic and Blocking within an A-SDMA Beam

To serve a customer which is located in minisector i a beam is formed in the direction φ_i of this minisector. Due to the fact that the minisector width is much smaller than the beamwidth β, the same channel cannot be reused in adjacent minisectors less than $\beta/2$ apart from minisector i. Vice versa, channels used in minisectors less than $\beta/2$ apart from minisector i cannot be reused in minisector i.

Therefore, within the range $(\varphi_i-\beta/2,\varphi_i+\beta/2)$ which corresponds to a beam directed to minisector i each of the C channels of the system can be used only once. To derive the blocking probability experienced by the users due to this limit, the distribution of the number of active mobiles in the beam is required. Due to the property of additivity of the state distribution, it is given by

$$\hat{p}_{i,k_i}=P\{\hat{X}_i=k_i\}=\frac{\hat{A}_i^{k_i}}{k_i!}\cdot e^{-\hat{A}_i} \quad , \quad (10)$$

with a mean value of

$$\hat{A}_i=E[\hat{X}_i]=\int_{\varphi_i-\beta/2}^{\varphi_i+\beta/2}a(\varphi)\,d\varphi \quad . \quad (11)$$

Let us assume for a moment that all the beams for these users are steered in the direction φ_i of minisector i. Then blocking of calls occurs if $\hat{X}_i>C$ since then not enough channels are available in the beam. Therefore, the average number of active mobile stations $\hat{Y}_i$ that can be served is given by

$$E[\hat{Y}_i]=\sum_{i=0}^{C}i\cdot\hat{p}_{i,k_i}+C\cdot\sum_{i=C+1}^{\infty}\hat{p}_{i,k_i} \quad . \quad (12)$$

This yields for the call blocking probability for an arbitrary mobile within the range of the beam

$$\hat{p}_{B,i}=\frac{E[\hat{X}_i]-E[\hat{Y}_i]}{E[\hat{X}_i]} \quad . \quad (13)$$

However, since only the beams for the mobile stations in minisector i are pointing in the direction of φ_i, this blocking probability is only valid for minisector i, and

$$p_{B,i}=\hat{p}_{B,i} \quad (14)$$

is obtained. For the other minisectors, the results may be changed due to user density fluctuations when the beam position is corrected.

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2.5. Performance of the Base Station

With eq. (14) the blocking probability in a minisector has already been derived. It permits to calculate the mean number of active mobiles that can be served as

$$E[Y_i] = A_i \cdot (1 - p_{B,i}) \ . \qquad (15)$$

By adding these values of all minisectors, the load actually served within the cell is obtained as

$$E[Y] = \sum_{i=1}^{I} E[Y_i] \ , \qquad (16)$$

and with the average total offered traffic of

$$E[X] = \sum_{i=1}^{I} E[X_i] = \sum_{i=1}^{I} A_i = A \qquad (17)$$

finally

$$p_B = \frac{E[X] - E[Y]}{E[X]} \qquad (18)$$

is obtained for the blocking probability of an arbitrary active mobile station within the cell.

3. Examples

3.1. A Scenario for User Mobility

A simplified scenario with which the results of the analysis of Sec. 3 can be demonstrated is depicted in Fig. 4. In this scenario a cell with an idealised circular coverage area serves a linear section of a motorway. The mobile stations are assumed to be equally distributed along the motorway section, and there are no mobiles elsewhere in the cell.

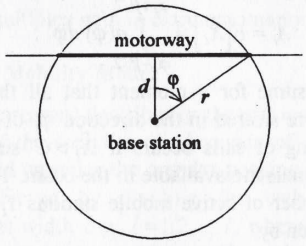


Fig. 4: Example of a scenario for the user mobility.

The cell radius is r, and the distance d of the base station from the motorway is varied. With traditional base station concepts with omnidirectional or fixed directional antennas it would be a rather natural choice to place the base station near the motorway, i.e., $d \approx 0$. For A-SDMA, however, this choice is not optimal. In the analysis in this section, the ratio d/r will be varied from 0 to 1, and an optimal value will be obtained for which the spatial multiplex gain of A-SDMA is maximised.

This yields the traffic profiles in Fig. 5, where the cell has been divided into $I = 100$ minisectors of 3.6° and the normalised values A_i/A have been depicted for different d/r ratios (the minisector numbering starts at $\varphi = -\pi$).

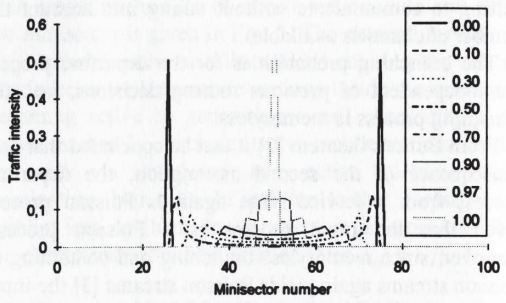


Fig. 5: Normalised traffic profiles for different d/r values

For $d/r = 0$, the base station antenna is located above the motorway, and mobile stations are seen only in two directions $\varphi = \pm\pi/2$ (minisectors 25 and 75). If, on the other hand, $d/r \to 1$, only a small piece of the motorway at $\varphi = 0$ (minisector 50) is covered. For values of d/r between these extremes, the angular traffic distribution has two maxima, and a minimum at $\varphi = 0$. This phenomenon is due to the fact that for larger values of $|\varphi|$ larger segments of the motorway are seen under the same angle.

3.2. Call Blocking Performance

The above traffic profiles have been used as input data for the analysis of Sec. 3. The base station is assumed to have $C = 8$ traffic channels and an antenna with a beamwidth of 45°. The blocking probability p_B according to eq. (18) finally obtained are depicted in Fig. 6 as a function of the total offered traffic A. It can be seen clearly that the d/r parameter has a significant influence on the performance of the base station. If the maximum load that can be carried is defined by an upper limit of the blocking probability, e.g., $p_{B,\max} = 0.01$, $d/r = 1.0$ permits a maximum of $A_{\max} \approx 4$ Erlangs, whereas with $d/r = 0.4$ an optimum value of $A_{\max} \approx 12$ Erlangs is obtained.

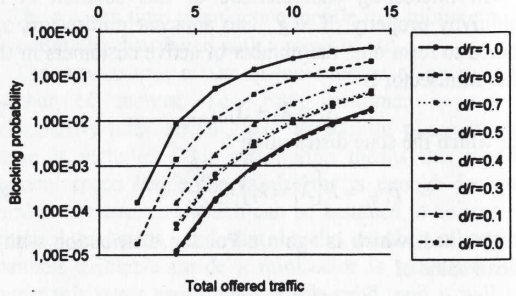


Fig. 6: Call blocking probability for different d/r values

Since in the case $d/r = 1.0$ no spatial multiplex gain can be achieved (all the beams are steered in the same

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direction $\varphi = 0$), this case yields the same results as a conventional system with an omnidirectional antenna. By comparison of the results to the case $d/r = 1.0$, the benefits of A-SDMA application can be evaluated.

3.3. Spatial Multiplex Gain

The most important performance figure to express the performance benefits of A-SDMA is the spatial multiplex gain. It is defined as the average number of parallel beams that can be achieved and is a direct measure for the capacity increase obtained by A-SDMA.

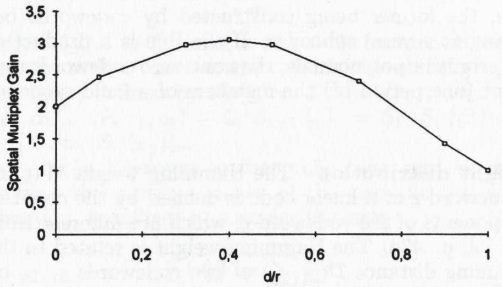


Fig. 7: Spatial multiplex gain vs. d/r ratio

To obtain the spatial multiplex gain for the scenario treated here, the ratio of the maximum offered traffic values under the constraint of $p_{B,\max} = 0.01$ between a system with A-SDMA and a traditional system is evaluated. Hence,

$$N = \frac{A_{\max,SDMA}}{A_{\max,trad.}} \qquad (19)$$

denotes the spatial multiplex gain or the average number of parallel beams. In Fig. 7, the results for N are presented. As mentioned before, with $d/r = 1.0$ no multiplex gain can be achieved, i.e. $N = 1$. For $d/r = 0$, exactly two parallel beams at $\varphi = \pm\pi/2$ can be used to serve the mobiles. Hence, $N = 2$ is obtained. Between these extremes, a maximum exists, which is $N \approx 3$ for $d/r = 0.4$. Consequently, it is possible to achieve a threefold capacity increase if the optimum d/r ratio is chosen.

To illustrate that this is even a rather pessimistic view of the benefits of A-SDMA, we would like to point out here that with the scenario according to Fig. 4 less than half the angular space of the cell is covered by the users. Assuming that additional users are located in the area $\pi/2 \le \varphi \le 3\pi/2$, i.e. in the lower half of the cell in Fig. 4, larger values of N can be obtained.

4. Conclusion

In this paper, an analysis of a new multiplex technique called A-SDMA (Adaptive Space Division Multiple Access) has been presented. A-SDMA has been designed to be implemented in current as well as future mobile communication systems to improve the spectrum efficiency by reducing the interference in cochannel cells and increasing the capacity. This increase of capacity is achieved with an adaptive array antenna at the base station site, with which multiple independent beams per traffic channel are created and hence more mobile users can be served.

The analysis in this paper is based on a queueing network approach and takes into account the angular user density distribution which is of critical importance for the performance of an A-SDMA system. The spatial multiplex gain of A-SDMA, i.e., the average number of parallel beams that can be supported as well as various other performance parameters such as blocking probabilities and carried load profiles have been derived.

An example has shown that the analysis is easily applicable to a large variety of scenarios. It therefore represents an ideal basis for new cell planning methods for cellular systems with A-SDMA. Cell planning with A-SDMA should consider the expected user density distribution. An appropriate selection of the base station sites will permit to increase the capacity of a single base station and hence the overall spectrum efficiency of the system.

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