SFDMA – SPATIAL FOCUS DIVISION MULTIPLE ACCESS

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1 Introduction

Currently we see a multitude of emerging ideas that aim to provide information and higher level services for mobile users. Starting with simple voice communications and information browsing they reach towards multi-component services like personal travel assistance comprising wireless communication, information technology and navigation. Provocatively, we could argue that the latter ones are likely to create a much higher demand for bandwidth than the agglomerate of concepts dubbed *multimedia*.
Knowledge of the user's position is desirable for various reasons. Services like personal travel assistance or local shopping guidance need this information to achieve user-friendliness. Apart from being user-friendly the amount of information transmitted can be reduced by preselecting the locally relevant.
The concept of Spatial Focus Division Multiple Access (SFDMA) facilitates these things that take place at the application layer by yielding the user's position as well as making use of it within the physical layer itself, in order to increase the system's capacity.
To perform this task SFDMA merely combines well-known techniques out of the wireless communication's toolbox.

1.1 Principle

A few thoughts lead directly towards the concept of SFDMA.

1. **The downlink is the critical part in terms of capacity.** Far less information is generated at the mobile terminal than is requested for downloading into the terminal. This leads to a strong asymmetry between load on uplink and downlink.

2. **Reduce injected power.** If capacity is limited by interference caused by the system itself, each component should inject as little power into the system as possible.

3. **Avoid omnidirectional antennas.** Omnidirectional antennas pollute the system with unaimed power. Sectorized antennas are better, but adaptive antennas pointing the power towards the desired target are better still.

4. **Control diversity.** A rake-receiver gathers the power arriving at the antenna with different delays due to multipath. This form of time-diversity improves transmission over fading channels. We rely on the surroundings to generate diversity for us. Of course this kind of diversity is to be exploited, but additionally we can obtain better control of the number of diversity paths by transmitting from more than one base station towards the mobile receiver.

5. **Smooth the handover process.** Handover between two base staions is prone to discontinuities. A soft handover with a multitude of base station sustaining the link is desirable.

In-depth research has been conducted by Kohno on matching a multi-antenna-element receiver on the spatio-temporal channel [Koh98]. For the time varying channel, matching the coefficients of the spatially and temporarily whitened matched filter (ST-WMF) to the transmission channel impulse response is a challenging task

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for digital signal processing.
Tarokh et al proposed space-time codes [TSC99] as a tailor-made channel coding scheme for systems comprised of multiple receive and transmit antennas.
In contrast to these very sophisticated approaches to increase capacity, SFDMA can be defined extremely easy: An estimation of the mobile's position is obtained. It may stem from measurements based on the wireless system itself, or other means like global navigation satellite systems (GNSS). As SFDMA has signals from more than one base station available, location determination methods described in Section (5) are well applicable. A variable number of base stations utilize adaptive antennas to steer their power simultanously towards the mobile's estimated position. No detailed channel information is needed. Adjusting the antennas' weights for emitting a beam with a certain width and azimuth is feasible. Fortunately, the time variance of these parameters is low.

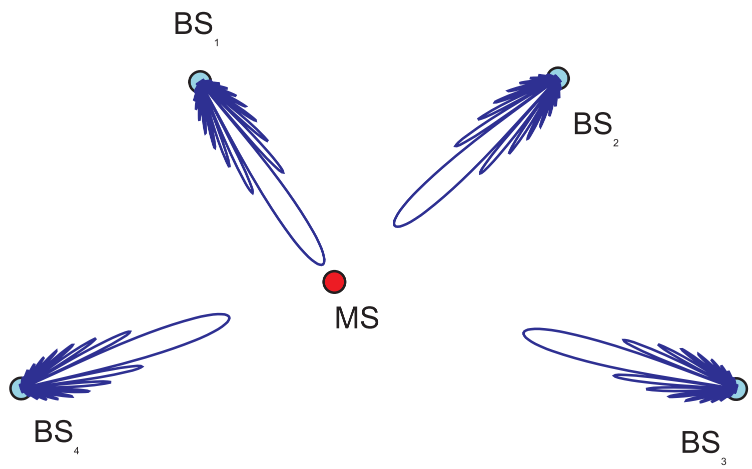

Figure 1: Base stations focussing on mobile

SFDMA spatially focusses the system's elecromagnetical power on the intended recipient. Each mobile terminal occupies its own focus in space. The signals of the base stations illuminating one mobile are divided using either frequency division multiple access (FDMA) or code division multiple access (CDMA). At the receiver the signals that arrive from the different base stations are combined by maximum ratio combining (MRC) or suboptimal methods like equal gain (EG) or selection diversity (SD) which work with less channel state information.
The number of base stations per mobile station N_{BS}/N_{MS} can be time variant. In this case the terms *cell* and *handover* no longer describe the situation well. The concept of soft handover usually implemented for two base stations [Vit95], is used for a larger number of base stations in SFDMA. If we allow N_{BS}/N_{MS} to vary, a station can enter the group of serving stations without an immediate need to remove another. Discontinuities known from hard handovers between individual cells are diminished.

2 Discussion

2.1 Multiple Access Interference

In CDMA systems every transmission is interference for all other receivers but the intended recipient. Like noise, interference causes errors. Interference therefore is a major limiting factor in CDMA. In order to increase the number of simultanously active mobiles in a given bandwidth we have to reduce the interference generated by one mobile upon all others.

2.2 Diversity and Combining Techniques

As the mobile channel inflicts fading on the signals, the bit error rate P_b is significantly higher than under pure Additive White Gaussion Noise (AWGN).
For comparison, we revisit the bit error rate P_b for transmission over AWGN and slow Rayleigh fading channels for coherent phase shift keying (PSK).

$$P_{b,AWGN,PSK} = \frac{1}{2} \cdot \text{erfc}\,\sqrt{\frac{E_s}{N_0}} \tag{1}$$

For characterization of the Rayleigh fading we use the average signal to noise ratio SNR $\gamma_0 = \frac{\overline{E_s}}{N_0}$.

$$P_{b,Rayleigh,PSK} = \frac{1}{2} \cdot \left(1 - \frac{1}{\sqrt{1 + 1/\gamma_0}}\right) \tag{2}$$

If we want to perform a fair comparison between different diversity combining methods, we have to keep the overall energy per bit constant. Therefore we introduce the energy per information bit γ_b, which takes the sum over all M branches' average SNR γ_{0i} into account.

$$\gamma_b = \sum_{i=1}^{M} \gamma_{0i} \tag{3}$$

This reference facilitates also a fair comparison with coding techniques.
If all M branches have the same average SNR $\gamma_{0i} = \text{const.}\ \forall\ i \in [1..M]$ this is equivalent to

$$\gamma_b = \frac{M \cdot \overline{E_s}}{N_0} \tag{4}$$

We can compute the bit error rate $P_{b,Rayleigh,PSK,MR}$ for phase shift keying and maximum ratio combining if we use the following expression [Lin64].

$$P_{b,Rayleigh,PSK,MR} = \frac{1}{2} \cdot \left(1 - \mu \cdot \sum_{r=0}^{M-1} \binom{2r}{r} \cdot \left(\frac{1-\mu^2}{4}\right)^r\right) \tag{5}$$

where

$$\mu = \sqrt{\frac{\gamma_b}{M + \gamma_b}} = \frac{1}{\sqrt{1 + \frac{1}{\gamma_b}}}$$

The resulting curves are shown in Fig. 2.2. From there we can see, that for a bit error rate of 10^{-3} the availability of 4 branches reduces the necessary energy per bit by approximately 14 dB. Under the optimal condition that 4 paths P_i between the 4 BS_i and the MS with the same mean attenuation $A_i\ \forall\ i \in [1..4]$ exist, we would have to inject 25 times less electromagnetical power into the overall system.

From a channel coding point of view, maximum ratio combining of the same signals transmitted via different channels can be interpreted as a kind of repetition code which is known to show very bad performance compared to other more sophisticated coding schemes. These schemes show good performance under the assumption of Rayleigh fading. Unfortunately, whenever the mobile unit stays "within a fade" without moving, they fail due to a lack of space diversity. Anyhow it is apparent that the introduction of sophisticated schemes like space-time coding (STC) into SFDMA is a promising field to investigate.
In addition to combatting the Rayleigh fading caused by the multipath propagation of the signals, SFDMA reduces the impact of the log-normal fading caused by shadowing. Due to the often largely different angle of arrival (AOA) (as a result of a suitable geometric constellation of base stations) of the M paths, the log-normal fading signals predominantly show little correlation.

3 Receiver Structure

Figure 3 illustrates a simplified channel and receiver structure. The information to be transmitted is spreaded at the M participating base stations with an individual spreading sequence $c_i(t)\ \forall\ i \in [1..M]$. Each spreaded signal is subject to change by its idividual channel with a set of N subpaths with delays τ_{ij} and complex channel factor z_{ij} with $j \in [1..N]$. They are summed up and white Gaussian noise is added. At the mobile station all spreaded signals are summed up and fed into a super-rake-receiver consisting of M rake receivers. Each rake-receiver works with one of the sequences $c_i(t)$. The rake-receiver outputs are again maximum ratio combined and upon the resulting value the decision in made.

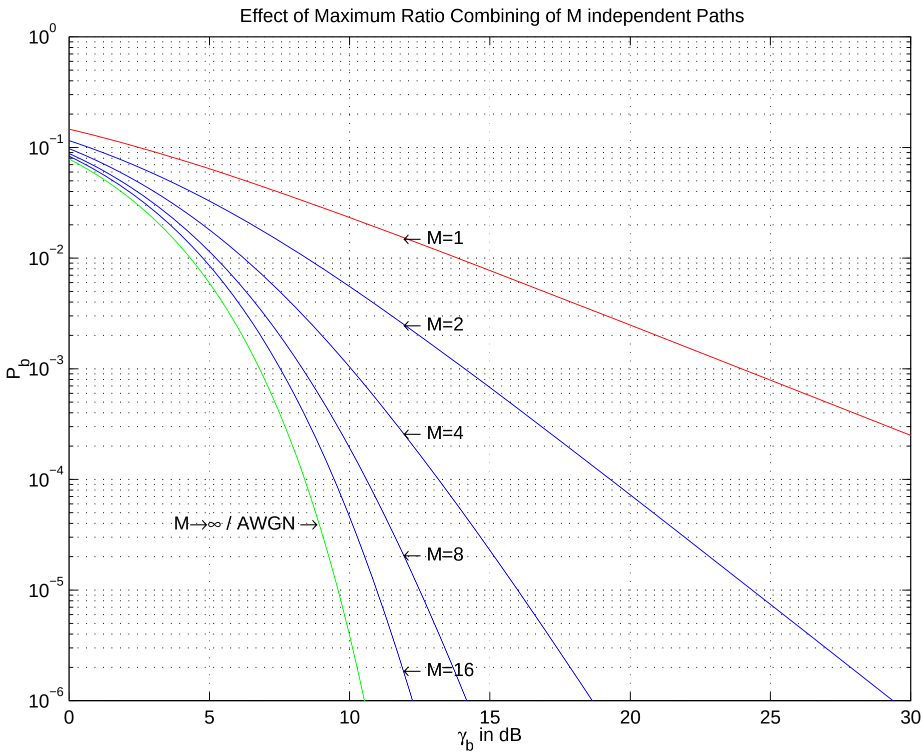

Figure 2: Influence of diversity using maximum ratio combining

4 Repercussions on Network Infrastructure

Changes in network infrastructure are necessary for implementing SFDMA. This includes an M-times increased number of receivers and transmitters per base station as well as increased load on the linking network between the base stations. The concept of a cell served by one base station is no longer applicable.
For the downlink (DL) the information is not transmitted by only one but M base station. Consequently each information bit has to be delivered to all M stations. This produces M times more load L on the fixed network.

$$L_{SFDMA,DL} = M \cdot L_{conventional,DL} \tag{6}$$

For the uplink (UL) this situation is even more difficult as we have to transmit the Q_I soft information bits and the Q_C channel state bits per received bit towards the maximum ratio combining unit. As one station can function as the MRC unit the load is increased as follows

$$L_{SFDMA,UL} = (M-1) \cdot (Q_I + Q_C) \cdot L_{conventional,UL} \tag{7}$$

The consideration of this fact and the asymmetry of demand betwenn uplink and downlink, suggests a better cost-benefit ratio for implementing SFDMA primarily for the downlink.

5 Location Determination

Matching the weights of an adaptive antenna array exactly towards the channel impulse response is a computationally complex task. In addition to being less demanding to achieve, an estimation of the mobile's position is valuable information for higher level services. By using the signals of the base stations and/or the signals of the mobile, the angle of arrival (AOA), the time of arrival (TOA) or the time difference of arrival (TDOA) can be estimated. The estimations can be carried out either at the mobile station (mobile station estimation, MSE) or at the base station (base station estimation, BSE). Performing standard navigation processing yields the position of the mobile. Alternatively the position can be determined using ranging signals from global navigation satellite systems (GNSS). For regulatory reasons most networks will have to provide mobile location determination by some means [Ang99].

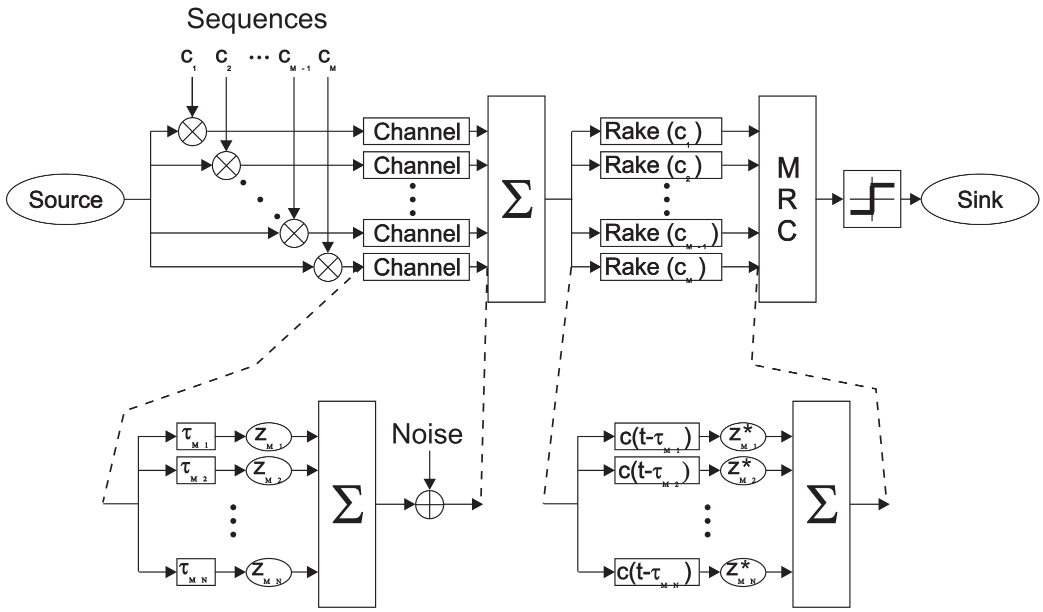

Figure 3: Channel and receiver structure

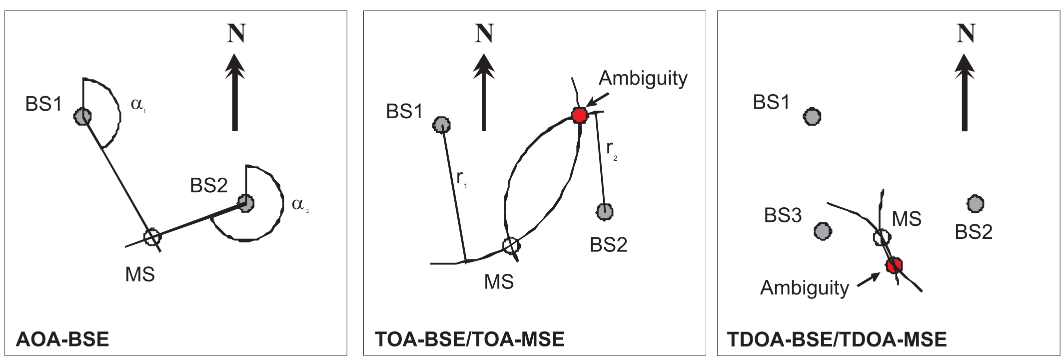

Figure 4: Methods for location determination within a personal communication system

6 Conclusions and Future Work

SFDMA intends to increase capacity by reducing the necessary energy per bit at the receiver and by injecting less interference into the system. A method to increase capacity as well as generating location information is presented. The fixed network part of the system has to bear a considerably increased load in order to sustain this increased capacity.

Bandwidth is the real-estate for mobile network operators. When demand for service exceeds what can be satisfied with current ressources and technology we might be willing to accept more complexity in infrastructure. What has been presented is so far an unverified idea. The capacity increasement has to be quantified analytically and simulations have to be performed. In the first step this will be done by combining spatio-temporal channel models [ECS+98], [FMB98] with the conditions given by the geometrical setup of the base stations, a multitude of active mobile units, assumed antenna characteristics and the assumption of perfect or imperfect user location information. The optimum number of active base stations per mobile is to be determined. In a second step the process of location determination is going to be included in the simulation and its accuracy determined. Algorithms for power control have to be studied. Finally matching coding schemes have to be implemented.

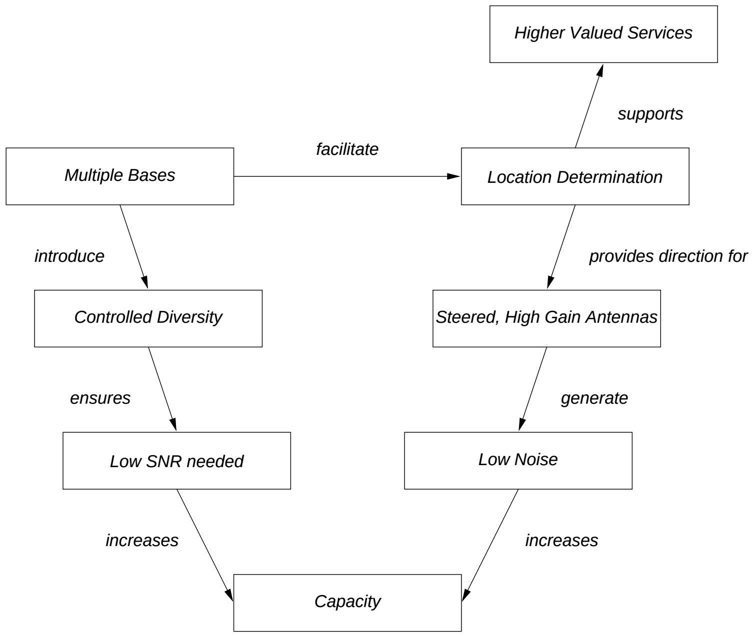

Figure 5: Argumentation scheme for SFDMA

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