APPLICATION OF SPACE DIVISION MULTIPLE ACCESS TO MOBILE RADIO

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Abstract: In this paper an approach is proposed to introduce a Space Division Multiple Access (SDMA) component into a frequency/time division multiple access (FTDMA) mobile radio system like the European GSM system [1] providing higher frequency reuse and spectral efficiency [2]. Except from signalling aspects the mobiles remain uneffected by the presented SDMA method without any need for antenna diversity or more sophisticated equalizers. Additional hard- and software demands due to the new SDMA features are only restricted to base stations as they have to be equipped with an adaptive antenna array. This array is used to separate wavefronts in coherent multipath environments by means of a new algorithm. The number of antenna elements needed is significantly lower than the number of wavefronts impinging on the array.

1 Introduction

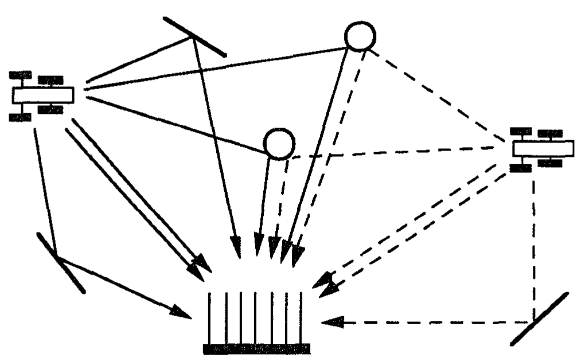

Figure 1: Multipath propagation in a multiuser system

Fig.1 shows a multipath situation allowing the separation of two users in the same radio channel by a base station equipped with a linear antenna array. There are three basic prerequisites for separating different radio sources that are active in the same FTDMA channel (i.e. in the same frequency band, time slot and cell):

1. The base station must be positioned in the far field of all users, reflectors and scatterers.
2. A sufficiently high amount of signal energy transmitted by the different users must reach the base station via discrete paths of propagation.
3. The signals transmitted by each user must have at least one dominant direction of arrival at the base station (DOA), which is not identical with that of another user.

The time delays and the DOA's of the W dominant propagation paths are the least time-varying parameters in an adaptive SDMA system of K users. Compared to typical data rates and even burst rates used in a GSM-like mobile radio system (270 kbits/s rsp. 1800 bursts/s) the mentioned characteristics of the channel are only slowly changed by the motion of the mobiles as long as they are in the far field of the base station antenna array. This fact can be exploited to spatially separate the K different radio sources on the uplink and downlink by means of base station antenna diversity. On the uplink the radio energy transmitted by the mobiles via all W paths can be used by a Maximum Likelihood Sequence Estimation (MLSE) detector. In the downlink case, which will not be further addressed in this paper, the base station antenna array is used as a phased array antenna adaptively forming beams of transmission [3] [4] into the directions of only $W' < W$ dominant propagation paths of the channel. In most cases the restriction $W' < W$ is neccessary in order to avoid the need of antenna diversity at the mobile. Therefore only those W' DOA's can be made use of, which are corresponding to propagation paths transmitting signal power exclusively to a single user.

This paper is organized as follows: Section 2 deals with a two-dimensional model of the mobile radio channel and the corresponding data model. In section 3 a method of estimating of the multi-user channel DOA delay profile and the corresponding flat fading complex amplitudes is presented. The proposed technique exploits a-priori knowledge of the user signals which is common practice in mobile communication systems e.g. for estimating single-user channel impulse responses by means of a training midamble [1]. The aim is a significant reduction of the number M of antennas needed at the base station. It will be shown that the presented algorihm can separate $W >> M$ wavefronts in contrast to single- [5] [6] or multi-snapshot techniques [7] [8] operating on unknown user data. Section 4 adresses the realtime joint detection of multi-user data and a summary in section 5 will conclude the paper.

2 Data model

Throughout this paper vectors, that are always considered to be column vectors, are denoted by lower, matrices by upper case bold faced letters. All vector and matrix elements are complex valued. The signals transmitted by one radio source are supposed to reach the base station via many propagation paths. All paths created by reflections and scattering of the radio waves in an environment of small spatial extension are considered to be subpaths of one discrete propagation path. This discrete path is characterized by a mean delay τ, a complex amplitude b and a direction θ of arrival at a linear array consisting of an odd number M of antennas equally spaced by distance d (fig.2). If the mobile is moving at velocity $v \neq 0$,

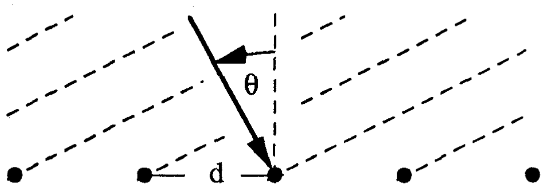

Figure 2: Planar wave impinging on an equally spaced antenna array consisting of $M = 5$ antennas

the parameters τ, b and θ are time-varying. Especially $b(t)$ is subject to flat fading, as the corresponding path is assumed to consist of a high number of subpaths of individual amplitude, phase and Doppler frequency [9]. Nevertheless, all three mentioned parameter types are considered to be only slowly time-varying compared to a GSM-like burst rate and will therefore be assumed constant for the period of one data burst. Furthermore the complex baseband signal $s(t)$ created by a single user is considered narrow-band compared to the reciprocal of the maximum time $\Delta t = (M-1) \cdot d/c_0$ that a planar radio wave with velocity c_0 of propagation needs to cover the length of the antenna array. Then, with f_0 denoting the radio carrier frequency, the signals received by the array via a single path of propagation can be expressed in complex baseband notation as follows:

$$\mathbf{a}(t) = b \cdot s(t-\tau) \cdot \mathbf{p} \qquad (1)$$

with $\mathbf{p}$ denoting the phase shift vector corresponding to the DOA θ:

$$\mathbf{p} = \begin{pmatrix} \Phi^0 & \ldots & \Phi^{M-1} \end{pmatrix}^T, \; \Phi = e^{j2\pi f_0 d \sin\theta / c_0}. \qquad (2)$$

Sampling the received signals of K users at the symbol rate $1/T$ and replacing the path delays τ by discrete delays $\tau_0 + c \cdot T$ $(c = 1 \ldots C)$ yields the array data vectors $\mathbf{a}_l$ $(l = 1 \ldots L + C)$

$$\mathbf{a}_l = \sum_{k=1}^{K} \sum_{w=1}^{W_k} b_{kw} \cdot s_{k,l-c_{kw}} \cdot \mathbf{p}_{kw}, \quad s_{k,i} = 0 \;\forall\; i \neq 1 \ldots L. \qquad (3)$$

They are caused by $W = W_1 + \ldots + W_K$ planar wavefronts, each representing one path of propagation. Here $C \cdot T$ denotes the maximum channel memory, whereas L is the number of data symbols created by every user. In order to get the channel model in matrix notation we define a $K(C+1) \times (L+C)$ user data matrix $\mathbf{U}$

$$\mathbf{U} = \begin{pmatrix} \mathbf{S}_1^T & \ldots & \mathbf{S}_K^T \end{pmatrix}^T, \qquad (4)$$

that is composed of K Toeplitz matrices $\mathbf{S}_k$ $(k = 1 \ldots K)$

$$\mathbf{S}_k = \begin{pmatrix} s_{k,1} & \cdots & s_{k,1+C} & \cdots & s_{k,L+C} \\ \vdots & \ddots & \vdots & & \vdots \\ s_{k,1-C} & \cdots & s_{k,1} & \cdots & s_{k,L} \end{pmatrix}. \qquad (5)$$

The $M \times (L+C)$ array data matrix $\mathbf{A}$ contains the sampled signals received by the array and is corrupted by an additive white Gaussian noise matrix $\mathbf{N}$ taken from a random stationary process of variance σ^2:

$$\mathbf{A} = \begin{pmatrix} \mathbf{a}_1 & \ldots & \mathbf{a}_{L+C} \end{pmatrix} + \mathbf{N}. \qquad (6)$$

Assuming that each user creates $Q \leq (M-1)/2$ planar wavefronts at each delay $\tau_0 + c \cdot T$, a tap weight vector $\mathbf{v}_{k,c}$ specific to user k and delay index c can be defined as follows:

$$\mathbf{v}_{k,c} = \begin{pmatrix} \mathbf{p}_{k,c,1} & \ldots & \mathbf{p}_{k,c,Q} \end{pmatrix} \begin{pmatrix} b_{k,c,1} & \ldots & b_{k,c,Q} \end{pmatrix}^T. \qquad (7)$$

Finally the array data matrix $\mathbf{A}$ is given by

$$\mathbf{A} = \mathbf{V}\mathbf{U} + \mathbf{N}, \qquad (8)$$

with

$$\mathbf{V} = \begin{pmatrix} \mathbf{v}_{1,0} & \ldots & \mathbf{v}_{1,C} & \ldots & \mathbf{v}_{K,0} & \ldots & \mathbf{v}_{K,C} \end{pmatrix}. \qquad (9)$$

Note that the system matrix $\mathbf{V}$ can be partitioned into $K \cdot M$ row vectors ${\mathbf{h}_{k,m}}^T$ as well, each denoting the sampled finite impulse response of the channel describing the transmission from user k to antenna m:

$$\mathbf{V} = \begin{pmatrix} {\mathbf{h}_{1,1}}^T & \ldots & {\mathbf{h}_{K,1}}^T \\ \vdots & \vdots & \vdots \\ {\mathbf{h}_{1,M}}^T & \ldots & {\mathbf{h}_{K,M}}^T \end{pmatrix}. \qquad (10)$$

3 Parameter Estimation

The correct estimation of the delays τ, the DOA's θ and the complex amplitudes b of all dominant propagation paths has great impact on the overall SDMA system performance. First of all the mentioned parameters are the bases for optimum user data detection (section 4) on the uplink. Moreover the correct estimation of the DOA profile of the channel is neccessary not only to form the downlink transmission beams (section 1), but also to yield criteria for the assignment and reassignment of users to the FTDMA channels to guarantee optimum spatial separability of all users. Decreasing spatial separability of two or more users approaching each other in a DOA sense must be foreseen by tracking the profile. It can then be easily encountered by reassigning the critical users to different FTDMA channels.

The easiest way of estimating channel parameters is sampling array data created by the transmission of a-priori known data. For this reason mobile radio systems sending in burst mode usually transmit a training sequence of L_T known data symbols in the middle of each burst. Assuming all L_T samples of the K training signals $s_k(t)$ to be known, a $K(C+1)\times(L_T-C)$ submatrix $\mathbf{U}_T$ with a-priori known entries can be extracted from $\mathbf{U}$. Denoting the corresponding $M\times(L_T-C)$ array data matrix $\mathbf{A}_T$ yields

$$\mathbf{A}_T = \mathbf{V}\mathbf{U}_T + \mathbf{N}_T. \tag{11}$$

If $L_T - C \geq K(C+1)$ holds and $\mathbf{U}_T$ is not rank-deficient, determining the least squares solution of (11) by means of the Moore-Penrose inverse $\mathbf{U}_T^+$ yields an estimate $\hat{\mathbf{V}}$ of the system matrix $\mathbf{V}$:

$$\hat{\mathbf{V}} = \mathbf{A}_T\mathbf{U}_T^+, \quad \mathbf{U}_T^+ = \mathbf{U}_T^*(\mathbf{U}_T\mathbf{U}_T^*)^{-1}. \tag{12}$$

Note that calculation of the Moore-Penrose inverse is not critical concerning realtime or accuracy aspects as the training signals are a-priori known. The choice of the training sequences is done a-priori, too, aiming at good insensitivity of the parameter estimation to additive white Gaussian noise (AWGN). A training matrix $\mathbf{U}_T$ is considered to be optimally conditioned concerning AWGN, if its rows are vectors of equal length forming an orthogonal base of a $K(C+1)$-dimensional subspace:

$$\mathbf{U}_T\mathbf{U}_T^* = \lambda\mathbf{I}, \quad \lambda \in]0\,,\infty[, \tag{13}$$

with $\mathbf{I}$ denoting the identity matrix.

According to (7), each tap vector $\hat{\mathbf{v}}_{k,c}$ can be seen as a single spatial sample of a wave field composed of Q planar waves with specific complex amplitudes and DOA's, but identical delays. So each estimate $\hat{\mathbf{v}}_{k,c}$ can be used to estimate the complex amplitudes and DOA's of the dominant radio wavefronts created by user k arriving at delay $\tau_0 + cT$ by means of a single snapshot DOA estimation method like the $4\times S$ -algorithm [6]. If there is an odd number M of antennas, this algorithm yields an estimation of the DOA's and complex amplitudes of the $Q=(M-1)/2$ dominant wavefronts by means of a singular value decomposition (SVD) of a $(Q+1)\times(Q+1)$-matrix containing data of one snapshot only. Note that by applying the $4\times S$ -algorithm to every tap vector $\hat{\mathbf{v}}_{k,c}$ a maximum of $W_{max} = Q\cdot K\cdot(C+1)$ wavefronts can be separated.

As the DOA profile is slowly time-varying in contrast to the complex amplitudes, the presented burst-by-burst parameter estimation is not only suboptimal, but can even lead to a severe degradation of the SDMA system due to fading. Suppose one dominant wavefront fades during the parameter estimation, it may well have a significant amplitude at the time of downlink transmission and cause inter-user interferences via its unrecognized DOA. Therefore methods of burst-by-burst updating instead of reestimating the DOA profile promise improvements of the SDMA system performance.

4 Multi-user Joint Data Detection

The joint data detection problem on the uplink can be mathematically seen as the estimation of the unknown user data matrix $\mathbf{U}$ in (8) by means of the known matrices $\mathbf{A}$ and $\mathbf{V}$. In the late past there have been many proposals to exploit coherent receiver diversity in order to jointly detect data sent by K users in the same frequency selective fading channel. Linear algorithms making use of diversity are the zero forcing block linear equalizer (ZF-BLE) and the minimum mean square error block linear equalizer (MMSE-BLE) presented in [10] [11]. Further improvement can be reached by introducing a nonlinear element like decision feedback leading to the zero forcing block decision feedback equalizer (ZF-BDFE) and the minimum mean square error block decision feedback equalizer (MMSE-BDFE) [10] [11]. Suboptimum variations of nonlinear maximum likelihood sequence estimation (MLSE) algorithms like the M-algorithm have also been successfully applied to the joint multi-user data detection problem [12].

Another interesting equalizer structure presented in [13] is based on a soft decision M-algorithm combining breadth-first trellis search with maximum a-posteriori equalization. With cardinality q of the symbol alphabet an optimum MLSE algorithm has to track q^C trellis states per sampled symbol by updating an accumulated minimum metric vector $\mathbf{m}$ of length q^C. The metric vector represents the a-posteriori probabilities, that the corresponding sequences had been originally transmitted. The mentioned suboptimum soft decision M-algorithm only keeps track of q states with minimum metrics such that each of the possible symbols represents one state. If we assume binary modulation and interpret the signal vector

$$\hat{\mathbf{s}}_l = \left(\ \hat{s}_{1,l}\ \ \ldots\ \ \hat{s}_{K,l}\ \right)^T \tag{14}$$

containing a trial of K complex user data symbols sampled at time $l\cdot T$ as a representative of $q=2^K$ possible symbols of a q-ary modulation, this algorithm can be applied to our data detection problem. Only 2^K states are tracked outputting a soft decision vector $\mathbf{m}$ of same dimension. The metric increment Δm for the transition to the state corresponding to symbol $\hat{\mathbf{s}}_l$ is calculated by

$$\Delta m = \|\mathbf{a}_l - \mathbf{V}(\ \mathbf{u}_{1,l}^T \ \ \dots \ \ \mathbf{u}_{K,l}^T\ )^T\|^2, \qquad (15)$$

with

$$\mathbf{u}_{k,l} = (\ \hat{s}_{k,l} \ \ \tilde{s}_{k,l-1} \ \ \dots \ \ \tilde{s}_{k,l-C}\ )^T, \quad k = 1\dots K, \qquad (16)$$

where $\hat{(\cdot)}$ denotes trial symbols and $\tilde{(\cdot)}$ decisions from the path history.

Note that all the mentioned algorithms implicitly operate on a linear system like (8), no matter whether the neccessary degrees of freedom were introduced by code diversity, space diversity or a combination of both. The only prerequisite for the existence of a unique optimum for $\mathbf{U}$ in a least squares or maximum likelihood sense is spatial separability of the users. This can be mathematically expressed by the condition

$$\mathrm{rank}(\mathbf{V}) > \mathrm{rank}(\bar{\mathbf{V}}_k) \quad \forall\ k = 1\dots K \qquad (17)$$

with $\bar{\mathbf{V}}_k$ denoting the submatrix that contains all columns of $\mathbf{V}$ except those vectors $\mathbf{v}_{k,0}\dots\mathbf{v}_{k,C}$ corresponding to user k.

5 Summary

An SDMA mobile radio concept has been presented which allows multi-user communication in the same frequency band, time slot and cell on both uplink and downlink. Basic prerequisite for spatial separation of the different users is the use of an antenna array at the base station, but not necessarily at the mobiles. A spatial channel model has been presented and a method of estimating its characteristic parameters. By means of these parameters the base station serves each user on the downlink by beamforming. Signal power is only sent into those directions corresponding to propagation paths exclusively reaching the specified user, but not the co-users in the same FTDMA channel. In this paper the beamforming problem itself has not been dealt with. Algorithms have been mentioned solving the uplink multi-user data detection problem by exploiting the degrees of freedom based on antenna diversity. Furthermore a modified multi-user soft decision M-algorithm has been presented combining realtime processing with low hardware expenses.

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