PROCEEDINGS OF ISAP2000, FUKUOKA, JAPAN

TRANSFORMATION BASED DOWNLINK BEAMFORMING TECHNIQUES FOR FREQUENCY DIVISON DUPLEX SYSTEMS

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1. Introduction

Adaptive antennas at the base station are one of the key-technologies to satisfy the increasing capacity demand of already existing and future cellular mobile communication networks. Several sophisticated uplink algorithms have been proposed for signal separation and detection. But downlink beamforming seems to be the pivotal point for the applicability of adaptive antennas in cellular mobile communication systems. Obviously, a similar performance gain is required in up- and downlink to achieve the possible capacity increase. The downlink beamforming process is very challenging, especially in frequency division duplex (FDD) systems, because of the uncorrelated fading in up- and downlink and the frequency dependent antenna array response [1]. Thus the direct reuse of the uplink antenna weights for downlink transmission is not advisable [2].

One well known beamforming approach for FDD systems uses the estimated discrete DOAs (direction-of-arrival) to calculate the complex antenna weights for downlink transmission [3]. But in case of a large angular spread (AS) as in urban environments, the robustness of high-resolution DOA estimation methods is substantially degraded [4]. Moreover, the nulls of the antenna pattern directed towards the interferers have to be broadened to keep the produced interference as low as possible. This requires adequate null broadening dependent on the angular spread of the interfering signals [5]. Beamforming algorithms based on spatial covariance matrices adjust the nulls of the antenna pattern perfectly to the actual propagation conditions and therefore outperform high-resolution DOA-based methods by far [6,7]. But the covariance matrices have to be transformed from uplink (receive) to downlink (transmit) frequency because of the different antenna array responses.

In this paper compare our Azimuth Power Spectrum based Spatial Covariance Matrix Frequency Transformation (ASCOFT) [7] with other proposed methods [8, 9] that also transform the spatial information included in the spatial covariance matrix from receive to transmit frequencies.

2. Downlink Beamforming Algorithms

Due to the frequency duplex distance in current and future mobile radio standards using FDD, fading is uncorrelated between uplink and downlink. Thus only the *mean* values of the mobile radio channel characteristics are the same in both communication links and this mean values have to be used for downlink beamforming. Therefore we average the spatial covariance matrices at the uplink frequency over small-scale (fast) fading. The mean spatial covariance matrix contains the mean power values and the corresponding DOAs of the signal paths, which are invariant to carrier frequency shifts.

Now the problem of the frequency dependent array response remains. Reusing the same antenna weights would lead to pointing errors in the downlink. The main beam as well as the nulls of the resulting antenna pattern are shifted in angle due to the duplex frequency. Thus the produced interference is increased dramatically. To overcome this problem we transform the spatial covariance matrix from the receive to the transmit frequency. After the transformation we calculate the weights by applying the beamforming algorithm [3] maximizing the SNIR (Signal-to-Noise-and Interference Ratio),

$$\mathbf{w} = \arg\max_{\mathbf{w}} \left\{ SNIR \right\} = \arg\max_{\mathbf{w}} \left\{ \frac{\mathbf{w}^H \cdot \mathbf{R} \cdot \mathbf{w}}{\mathbf{w}^H \cdot \mathbf{Q} \cdot \mathbf{w}} \right\}, \tag{1}$$

where **R** and **Q** denote the spatial covariance matrices of the desired user and of interference plus noise, respectively. The antenna weight calculation process for reception and transmission is illustrated in Fig.1. We apply the same beamforming algorithm (1) for both links and use either the uplink covariance matrices $\mathbf{R}_{up}$ and $\mathbf{Q}_{up}$ or their frequency transformed counterparts $\mathbf{R}_{down}$ and $\mathbf{Q}_{down}$ as input. In the following subsections we will shortly introduce our and other proposed methods for the *Frequency Transformation* of the spatial covariance matrix of Fig.1, namely the ASCOFT, RMFT as well as the FSFT algorithm.

2.1 APS based Spatial Covariance Matrix Frequency Transformation (ASCOFT)

Our *Azimuth Power Spectrum based Spatial Covariance Matrix Frequency Transformation (ASCOFT)* has been described in detail in [7], and thus we summarize here only its basic principle. The ASCOFT utilizes all information, including the angular spread, for the downlink beamforming process. The consecutive steps of the ASCOFT are shown in Fig. 2.

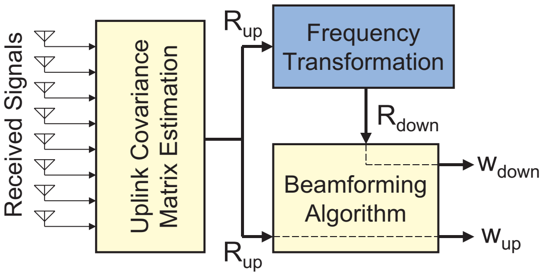

Fig. 1. Proposed structure for the antenna weight calculation of both communication links.

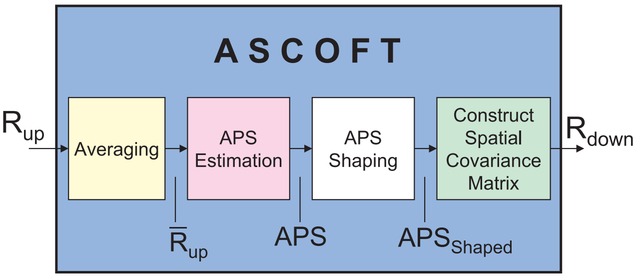

Fig. 2. APS based Spatial Covariance Matrix Frequency Transformation (ASCOFT).

The transformation is of course made for the user covariance matrix **R** as well as for that of interference plus noise **Q**. After the averaging coping with the uncorrelated fading (common to all three algorithms), we estimate the azimuth power spectra (APS) of user and interference using the Capons beamformer [10]. Then we shape the user APS to mitigate estimation inaccuracies and the interference APS to cope with minor angular separated users. This prevents beampointing errors for the desired user and provides adequate nulls in the direction of the interferers [7]. The *mean* amplitudes and the directions of arrival of the signal paths are invariant to carrier frequency shifts. Therefore we assume the *mean APS* to be the same in up- and downlink, and we are in a position to reconstruct the spatial covariance matrices at the downlink frequency.

2.2 Fourier Series based Frequency Transformation (FSFT)

We can express the spatial covariance matrix by a *Fourier series expansion* as proposed in [8]. It is possible to calculate the “Fourier” coefficients from the spatial covariance matrix at the uplink frequency and then use this information to reconstruct the downlink spatial covariance matrix. However, the assumption that the phase relation between independent signal paths is invariant to carrier frequency shifts seems to be unrealistic. Therefore we expect rather poor results, especially when strong multi-path propagation is present. Furthermore the transformation quality will depend on the distance of the element of the covariance matrix from its main diagonal. The elements near the main diagonal are transformed very well, but the transformation of elements farther away performs rather bad (in magnitude as well as in phase). But this drawback is inherently present in this approach. This distorts the shape of the resulting antenna pattern significantly, which will lead to a degradation of the downlink performance of the FSFT.

2.3 Rotation Matrix based Frequency Transformation (RMFT)

Here we rotate the phases of the elements in the spatial covariance matrix corresponding to a dominant DOA, following the method proposed in [9]. This approach is optimal in the line-of-sight (LOS) case, but performance degrades with increasing angular spread and duplex distance. The RMFT is based on the assumption of one dominant direction-of arrival. Therefore, the performance is substantially deteriorated if a single user has more than one dominant DOA or, especially, when more interferers with various positions and thus various DOAs are present.

3. Simulation Environment and Results

We model a GSM 1800 system applying adaptive (smart) antennas for Space Division Multiple Access (SDMA). The GSM 1800 system has a duplex distance of 95MHz and therefore a relative duplex distance of about 5%. We serve 2 or 3 spatial separable users simultaneously on a single traffic channel in a 120° sector cell. The used antenna array is a Uniform Linear Array (ULA) with M=8 antenna elements and an inter-element distance of half the wavelength (d=λ/2). For simulation purpose we use the Geometry-based Stochastic Channel Model (GSCM) [11], which automatically gives the correct uplink – downlink correlation. The principle of this semi-stochastic channel model in its general form with one scattering cluster is illustrated in Fig. 3. We simulated 10000 independent channel realizations with random mobile and scatterer positions and a uniformly distributed mobile speed within [0,50km/h].

We evaluated the Signal to Noise and Interference Ratio (SNIR) obtained by the *Azimuth Power Spectrum based Spatial Covariance Matrix Frequency Transformation (ASCOFT)* and compared it with the *Fourier Series based Frequency Transformation (FSFT)* [8] and the *Rotation Matrix based Frequency Transformation (RMFT)* [9]. In all simulations, we assumed perfectly known averaged uplink covariance matrices of the co-channel users and their corresponding interference covariance matrices. As a reference we also illustrate the case of direct weight reuse (uses the averaged uplink covariance matrices as input for the beamforming algorithm (1)).

Fig. 4 illustrates the performance of the algorithms in an LOS scenario with 2 co-channel users. There is only a single signal path (no local scatterers) present between base station (BS) and mobile station (MS). The ASCOFT shows an improvement of more than 20dB compared to the direct weight reuse. In this simple propagation scenario the RMFT gives the best results because it performs the transformation perfectly if the DOA is known (which was assumed in the simulations). The FSFT shows an improvement in 98% of the cases compared to the direct weight reuse.

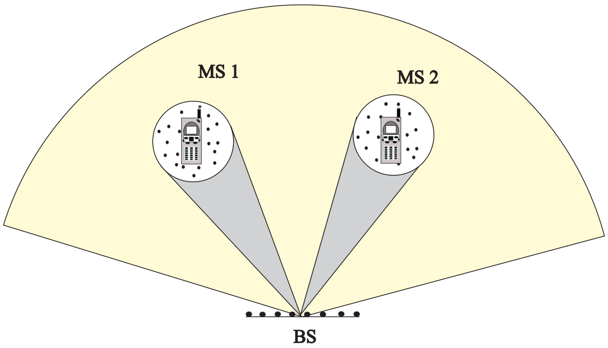

Fig. 3. Principle of the Geometry-based Stochastic Channel Model (GSCM).

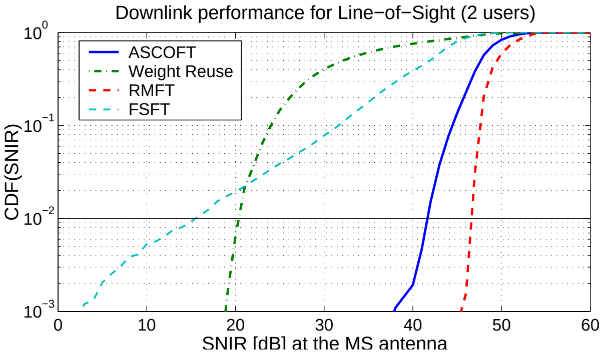

Fig. 4. Received downlink SNIR in the Line-of-Sight (LOS) case (2 co-channel users).

The downlink performance in urban environments with local scattering near the MS (rms. AS=10°) and 2 co-channel users is shown in Fig. 5. The ASCOFT and the RMFT lead to a similar gain of 3dB compared to weight reuse at the 1% level of the cumulative distribution function. The FSFT results in a link quality degradation and therefore its application does not seem to be useful.

In the case of 3 SDMA co-channel users and an angular spread of 7° (Fig. 6), the ASCOFT clearly leads to the best results. The performance of the RMFT of [9] is substantially degraded in such a propagation environment because the assumption of a single dominating DOA is violated (2 interferers with different nominal DOAs). The same problems will arise if there is more than one scattering cluster per user present. The RMFT can only compensate the changing array response for one interferer and the dominant DOA of the second interferer is wrongly corrected in the covariance matrix of interference plus noise. That restricts the applicability of this algorithm to systems with a single interferer and simple propagation conditions (one dominant DOA). The FSFT of [8] again give the worst results. This confirms that the distortion of the antenna pattern because of the inaccurate transformation of the off-diagonal elements of the covariance matrices influences the performance strongly.

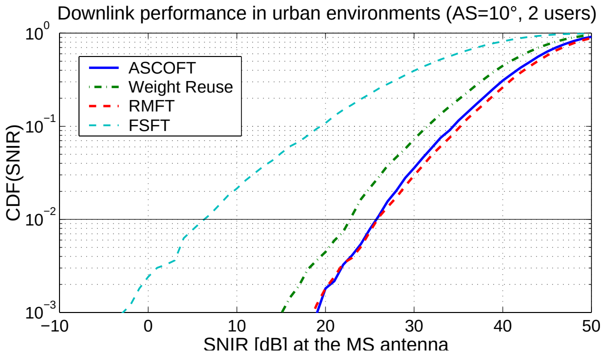

Fig. 5. Received downlink SNIR in urban environments (AS=10°, 2 co-channel users).

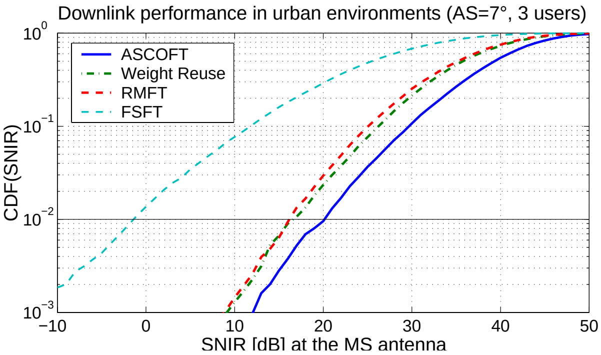

Fig. 6. Received downlink SNIR in urban environments (AS=7°, 3 co-channel users).

4. Conclusions

We compared the performance of our downlink beamforming approach for uncorrelated up- and downlinks with other proposed spatial covariance matrix frequency transformation methods. Our method leads to a performance improvement over the direct weight reuse from reception to transmission in mobile communication systems with FDD. Other known methods are restricted to propagation scenarios with small angular spread or a limited number of dominant directions of arrival or users and small relative duplex distances. Thus the other approaches are in contrast to our ASCOFT algorithm not in general applicable.

We would like to mention that our transformation performs independently of the frequency duplex distance. It is not restricted to TDMA systems, which we made our simulations for. We dare say that this method is the only straightforward approach in CDMA systems, where the spatial covariance matrix is usually required for uplink detection anyway.

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