SMART ANTENNA DOWNLINK BEAMFORMING FOR UNCORRELATED COMMUNICATION LINKS

Klaus Hugl [(1)], Juha Laurila [(1)], Ernst Bonek [(1),(2)]

[(1)]Institut für Nachrichtentechnik und Hochfrequenztechnik, Technische Universität Wien
Gußhausstraße 25/389, A-1040 Wien, AUSTRIA
Email: Klaus.Hugl@nt.tuwien.ac.at, Juha.Laurila@nt.tuwien.ac.at, Ernst.Bonek@nt.tuwien.ac.at

[(2)]Forschungszentrum Telekommunikation Wien (FTW)
Maderstraße 1/9, A-1040 Wien, AUSTRIA

INTRODUCTION

Smart antennas can be used to increase the capacity, the link quality and the coverage of existing and future cellular mobile communication networks. Several sophisticated uplink algorithms have been proposed for beamforming and signal detection. But downlink beamforming seems to be the bottleneck of 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.

Especially in frequency division duplex (FDD) systems, the downlink beamforming process is very challenging, because of the uncorrelated fading in up- and downlink and the frequency dependent array response [1]. As a consequence, direct reuse of the uplink antenna weights for downlink transmission is not practical [2].

One well known method for FDD systems is to estimate discrete DOAs (direction-of-arrival) from the received uplink data and use this information to calculate the complex antenna weights for transmission [3]. However, in suburban and urban environments the measured rms angular spread (AS) can be up to 15° [4], and under such conditions the robustness of high-resolution DOA estimation methods is substantially degraded [5]. Moreover, the nulls of the antenna pattern, which are pointed in the directions of the co-channel users or intercell 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 interference signals [6]. Algorithms based on the spatial covariance matrices transformed from uplink (receive) to downlink (transmit) frequencies adjust the nulls of the antenna pattern perfectly to the actual propagation conditions and therefore outperform high-resolution DOA-based methods by far [7,8].

In this paper we compare our Spatial Covariance Matrix Transformation (SCMT) [8] with other proposed methods [9, 10] that also transform the spatial information included in the spatial covariance matrix from receive to transmit frequencies.

DOWNLINK BEAMFORMING ALGORITHMS

Due to the frequency duplex distance in current and future mobile radio standards, the fading is uncorrelated between uplink and downlink. Thus we have to use *mean* values of the mobile radio channel characteristics for downlink beamforming. We average the spatial covariance matrices at the uplink (receive) 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 remaining problem is the frequency dependent array response. Reusing the same antenna weights and the same physical array 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 and therefore the interference produced during transmission is increased dramatically. To overcome this problem we transform the spatial covariance matrix from the uplink (receive) to the downlink (transmit) frequency. After the transformation we apply the beamforming algorithm (weight calculation) [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 the interference plus noise, respectively. Fig.1 illustrates the antenna weight calculation process for reception and transmission. We propose to apply the same beamforming algorithm (1) for both links and to 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* (Fig.1) of the spatial covariance matrix. Simulation results for the described methods will be presented in the next section.

Spatial Covariance Matrix Transformation (SCMT)

Our *Spatial Covariance Matrix Transformation (SCMT)* has been described in detail in [8], and thus we summarize here only its basic principle. This SCMT utilizes all information, including the angular spread, for the downlink beamforming process. The consecutive steps of the SCMT are shown in Fig. 2.

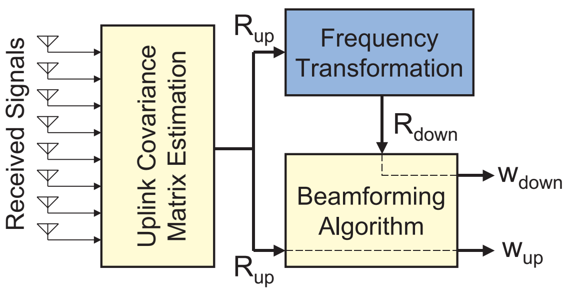

Fig. 1. Proposed structure for the antenna weight calculation of both communication links

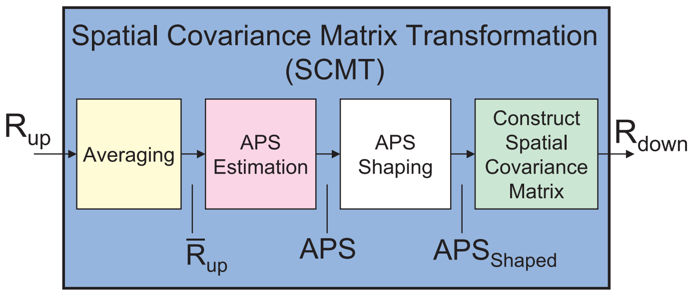

Fig. 2. Spatial Covariance Matrix Transformation

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 azimuthal power spectra (APS) of user and interference using the Capons beamformer [11]. Then we shape the user APS to cope with estimation inaccuracies and the interference APS to cope with minor angular separation of users. This prevents beampointing errors for the desired user and provides adequate nulls in the direction of the interferers [8]. 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.

Fourier Series based Transformation (FSBT)

Following the method proposed in [9] we can express the spatial covariance matrix by a *Fourier series expansion*. 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 multipath 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). This will distort the shape of the resulting antenna pattern significantly, which degrades downlink performance.

Rotation Matrix based Transformation (RMBT)

Here we rotate the phases of the elements in the spatial covariance matrix corresponding to a dominant DOA, following the method proposed in [10]. This method is optimal in the line-of-sight (LOS) case, but performance could degrade with increasing angular spread. The RMBT is based on the assumption of one dominant direction-of arrival. Therefore, the performance is substantially degraded if a single user has more than one dominant DOA or, especially, when more interferers with various positions and thus various DOAs are present.

SIMULATION ENVIRONMENT AND RESULTS

The simulation environment models a GSM 1800 system applying an adaptive antenna for Space Division Multiple Access (SDMA). We serve K=2 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 spacing of the half wavelength ($d=\lambda/2$). For the simulations we used the Geometry-based Stochastic Channel Model (GSCM) [12]. The principle of this semi-stochastic channel model in its general form with more than 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 *Spatial Covariance Matrix Transformation (SCMT)* and compared it with the *Fourier Series based Transformation (FSBT)* [9] and the *Rotation Matrix based Transformation (RMBT)* [10]. In all simulations, we assumed perfectly known averaged uplink covariance matrices of both co-channel users. As a reference we also illustrate the case of direct weight reuse (use the averaged uplink covariance matrices as input for the beamforming algorithm (1)).

Fig. 4 illustrates the performance of the algorithms in an LOS scenario. There is only a single signal path (**no** local and **no** far scatterers) between base station (BS) and mobile station (MS). The SCMT shows an improvement of more than 20dB compared to the direct weight reuse. In this simple propagation scenario the RMBT shows the best performance because it performs the transformation perfectly if the DOA is known (which was assumed in this simulation). The FSBT shows an improvement in 98% of the cases but the curve quickly flattens out.

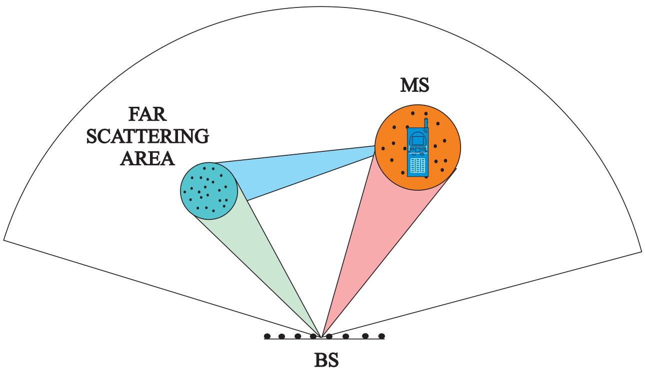

Fig. 3. Principle of the Geometry-based Stochastic Channel Model (GSCM)

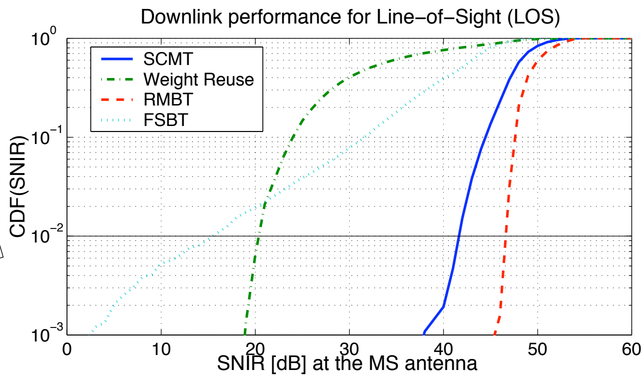

Fig. 4. Cumulative distribution function of the received downlink SNIR in the LOS case.

Downlink performance in urban environments with local scattering near the MS (rms AS=10°), but **no** far scatterers is shown in Fig. 5. The SCMT and the RMBT lead to a similar gain of 3dB compared to weight reuse at the 1% level of the cumulative distribution function. The FSBT results in a performance degradation.

In a situation with local scattering near the MS and a cluster of far-off scatterers, representing e.g. high-rise buildings in suburban environments, the SCMT shows clearly the best performance (Fig. 6 - 2 times 2° rms AS). The performance of the RMBT of [10] is substantially degraded in such propagation environment because the assumption of a single dominating DOA is not violated. The same problems will arise if there are more interferers present. That restricts the applicability of this algorithm to systems with a single interferer and simple propagation conditions (one dominant DOA). The FSBT of [9] again shows the worst performance. This confirms that the assumption of a constant phase relation, independent of the carrier frequency, is not valid in the wireless communication channel. Thus, the applicability of FSBT is in question.

CONCLUSIONS

We compared the performance of our downlink beamforming approach for uncorrelated up- and downlinks with other proposed spatial covariance matrix transformation methods.

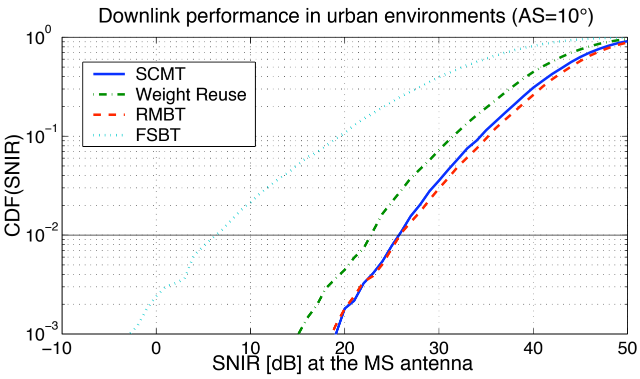

Fig. 5. Received downlink SNIR in urban environments (one scatterer cluster, rms AS=10°)

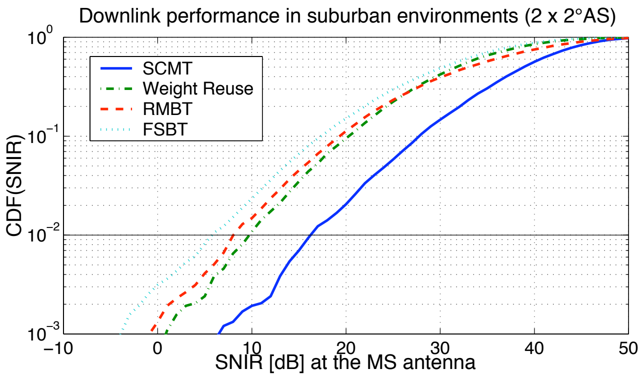

Fig. 6. Received downlink SNIR in urban environments (two scatterer cluster, AS=2x2°)

Our method is applicable in mobile communication systems with FDD leads to a performance improvement over the direct weight reuse from reception to transmission. Other known methods are restricted to propagation scenarios with small angular spread or a limited number of dominant directions of arrival, and are thus 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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