ON DOWNLINK BEAMFORMING TECHNIQUES FOR TDMA/FDD SYSTEMS*

Danilo Zanatta Filho[1], Cristiano Magalhães Panazio[1], Francisco Rodrigo Porto Cavalcanti[2], João Marcos Travassos Romano[1]

[1] DSPCom, DECOM, School of Electrical and Computer Engineering, State University of Campinas, CP 6101, CEP 13083-970, Campinas, SP, Brazil, {daniloz, panazio, romano}@decom.fee.unicamp.br

[2] Electrical Engineering Department, Federal University of Ceará, CP 6001, Campus do Pici, CEP 60455-760, Fortaleza, CE, Brazil, rod@dee.ufc.br

ABSTRACT

The performance of three downlink beamforming techniques in a TDMA/FDD context is investigated in the present work. Two techniques based on the uplink processing are studied together with a decoupled space-time structure that provides the antenna weights. The third one is a downlink beamforming technique, based on the spatial covariance matrix, which is independent of both uplink structure and algorithm. The performance of these techniques is analyzed by simulations for some parameters like angular separation between users and angular spread. The simulation results show that the three techniques are suitable for downlink beamforming but the technique based on the spatial covariance outperforms the other two.

1. INTRODUCTION

Evolutionary 3G mobile communication systems promise to deliver high data rate services such as video and Internet access. During the last years, space-time processing and adaptive beamformers have been widely studied as a feasible and interesting solution to enhance the performance of the wireless communications systems so that such new services could be provided.

As far as capacity is concerned, the reverse link has been considered to be the limiting one for typical 2G systems. However, in 3G systems, the major impairments to provide higher data rates are in the downlink, due to the internet traffic and its asymmetric nature (download/downlink rate >> upload/uplink rate). The achievement of spatial processing algorithms in the base station is also more challenging in the downlink, since the transmission must be carried out without a previous knowledge of the wireless channel conditions.

In fact FDD (frequency duplex frequency) system is characterized by the difference between uplink and downlink carrier frequencies. Then when an antenna array is employed for spatial processing, the steering vectors in the uplink and in the downlink are not the same, even if the physical distance between the elements of the array is fixed. This leads to different distances between the elements in terms of wavelengths for both links so that different antenna weights must be used in order to synthesize the same radiation pattern. Furthermore, in most practical systems the duplex frequency distance is larger than the channel coherence bandwidth, i.e. the uplink and downlink channels are decorrelated [1].

If the present parameters of the downlink channel are not available to provide the derivation of the array weights and since such weights are normally different than the uplink ones, they must be obtained by an approximate way. The methods can be based on a given mapping of the uplink weights or even by using an estimation of some parameters related to the downlink channel.

The objective of the present work is to provide a comparative analysis of possible methods to be employed in the calculation of the radiation pattern for the downlink antenna array. The evaluation is carried out by taking into account some systemic parameters like the angular separation between the users and the angular spread.

Three different approaches will be compared in this paper:

- The *direct algorithm*, which is just a direct employ of the uplink antenna weights, provided by some already existing uplink processing in the base station.
- The *uplink algorithm*, where the uplink weights vector is now mapped in order to provide the downlink one. In fact the direct algorithm is a trivial particular case of this one.
- The *downlink algorithm* based on the calculation of the downlink antenna weights using an estimation of the downlink spatial covariance matrix. The estimation can be obtained by a linear transform of the uplink matrix.

The first and second methods allow to use the set of antenna weights generated by a given uplink algorithm.

Another contribution of this paper is the proposition and the performance evaluation of the joint employ of the uplink algorithm together with a decoupled space-time structure [2], from which the uplink weights are obtained. In fact the use of such a decoupled space-time processing establish a duality between both link, since in downlink the spatial filter (in the base station) is obviously separated from the equalizer (in the mobile phone). Clearly, such approach cannot be used for the downlink algorithm since in this case the uplink weights are not used to obtain the downlink ones.

This paper is organized as follows, first we present the signal and propagation modeling where the antenna array, the space-time channel model and the mobile received signal are described. Section 3 presents the three different approaches

* This work was supported by a grant from Ericsson of Brazil Research Branch under ERBB-UFC.01 Technical Cooperation Contract.

together with the uplink to downlink frequency transposition and the decoupled space-time structure used in the uplink. Therefore, some simulation results in an IS-136 TDMA context are presented in section 4. Finally, in section 5, we draw some conclusions and present some future perspectives.

2. SIGNAL AND PROPAGATION MODELING

Let us consider a base station that employs the same linear antenna array for up- and downlink. The gain and phase of the antenna elements (taking the first antenna as a reference), as a function of the azimuth direction θ, are given by the complex-valued *steering vectors* $\mathbf{d}^{UL}(\theta)$ and $\mathbf{d}^{DL}(\theta)$, in the up- and downlink, respectively. In the case of a linear array of uniformly distributed omnidirectional antenna elements, as depicted in figure 1, $\mathbf{d}^{DL}(\theta)$ is given by

$$\mathbf{d}^{DL}(\theta)=[1 \quad \exp\left(-j2\pi f^{DL} d sin(\theta)/c\right) \quad \cdots \quad \exp\left(-j(M-1)2\pi f^{DL} d sin(\theta)/c\right)]^T \tag{1}$$

where f^{DL} and d, are the carrier frequency of the downlink and antenna elements spacing, respectively. The parameter M is the number of antenna elements in the array. Correspondingly, the uplink steering vector is calculated with the same antenna elements spacing but with the carrier frequency of the uplink f^{UL}.

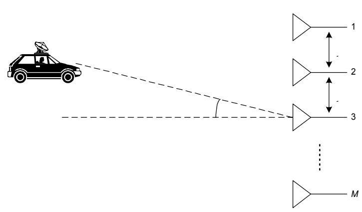

Figure 1. The Uniform Linear Array.

As far as the base-band model of the downlink is concerned, the multidimensional impulse response between the antenna array at the base and the single antenna at the mobile is denoted by $\mathbf{h}^{DL}(t,\tau)$, where t is time and τ is delay. Such function is complex-valued and time-dependent. The vector of signals to be transmitted from the multiple antennas in the base station, $\mathbf{x}^{DL}(t)$, is given by[1]

$$\mathbf{x}^{DL}(t)=\mathbf{w}^{DL}s(t) \tag{2}$$

where $\mathbf{w}^{DL}$ is a vector of complex weights (used for downlink beamforming) and $s(t)$ is the waveform modulated by the transmitted bits. The signal received at the mobile is, therefore, given by

$$u(t)=\mathbf{w}^{DL^H}\int_{\tau=-\infty}^{+\infty}\mathbf{h}^{DL}(t,\tau)s(t-\tau)d\tau \tag{3}$$

where ^{H} denotes complex conjugate transposition. Considering the transmitted signal $s(t)$ generated by a linear modulation, it can be written as

$$s(t)=\sum_{q=-\infty}^{+\infty}I_q^{DL}p(t-qT) \tag{4}$$

where I_q^{DL} are the downlink symbols, $p(t)$ is the modulation pulse shape and T is the symbol period. Combining (3) and (4), the following relation between the symbols transmitted from the base, I_q^{DL}, and the signal sampled at times $t=nT$ at the mobile, is obtained

$$u_n=\mathbf{w}^{DL^H}\sum_{k=-\infty}^{+\infty}I_{n-k}\mathbf{h}_k(t) \tag{5}$$

where the discrete-time impulse response of the channel $\mathbf{h}_k(t)$ is given by the time-dependent expression:

$$\mathbf{h}_k(t)=\int_{\tau=-\infty}^{+\infty}\mathbf{h}^{DL}(t,\tau)p(kT-\tau)d\tau \tag{6}$$

Assuming that the propagation can be described as the sum of P rays, the impulse response $\mathbf{h}^{DL}(t,\tau)$ can be written as

$$\mathbf{h}^{DL}(t,\tau)=\sum_{l=1}^{P}\alpha_l\exp\left(j2\pi d_l^{DL}t+\varphi_l^{DL}\right)\mathbf{d}^{DL}(\theta_l)\delta(\tau-\tau_l) \tag{7}$$

where α_l, d_l^{DL}, φ_l^{DL}, θ_l and τ_l, are respectively the path attenuation, Doppler frequency, phase-offset, azimuth direction (observed from the base) and the delay of the lth ray, while $\delta(\tau)$ denotes the Dirac function. It should be emphasized that the path attenuation, azimuth direction and delay are frequency independent, therefore they are the same for up- and downlink.

Assuming that the azimuth angle of the lth is ϕ_l, when the speed vector of the mobile is used as the reference, the Doppler frequency d_l^{DL} is given by

$$d_l^{DL}=\frac{f^{DL}\cos(\phi_l)v}{c} \tag{8}$$

where f^{DL}, v and c are the downlink carrier frequency, the mobile speed and the speed of the light, respectively. The ray parameters P, α_l, d_l^{DL}, φ_l^{DL}, θ_l and τ_l vary with time. However, the Doppler frequency d_l^{DL} and the phase-offset φ_l^{DL} are assumed to be practically fixe during a time slot. The number of rays P, the path attenuation α_l, the azimuth direction θ_l and the delay τ_l are also presumed to be fixe during a couple of time slots. Combining (6) and (7) yields

$$\mathbf{h}_k(t)=\sum_{l=1}^{P}g_l(t)\mathbf{d}^{DL}(\theta_l)p(kT-\tau_l) \tag{9}$$

[1] In the case of transmission to multiple mobiles on the same carrier at the same time, the signals to the different mobiles are superposed, i.e. $\mathbf{x}^{DL}(t)=\sum_i \mathbf{w}_i^{DL}s_i(t)$

where $g_l(t)$ is the gain function including the attenuation and the complex exponential. This gain function is the fading associated with each path. Despite the time-invariance of all the considered parameters, there is an inherent variability due to the fading. Figure 2 shows the Jakes' model [3] that considers a circular group of scatterers around the mobile for each path.

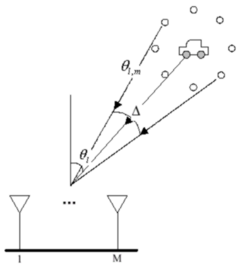

Figure 2. Jakes' model with Angular Spread.

Each scatterer generates different Doppler shifts $d_{l,m}^{DL}$, phase-offsets $\varphi_{l,m}^{DL}$ and azimuth directions $\theta_{l,m}$. The sum of all the rays arriving from this group of local scatterers generates the lth path in equation (7) with azimuth direction θ_l. It is important to notice the angular spread included by this model, i.e. the concept of a single and defined DOA (direction of arrival) is replaced by the notion of a cone that contains all the incoming rays from this group of scatterers. The width of this cone is the angular spread Δ.

Defining the local-mean symbol energy, at time t_0 as

$$\overline{E} = \frac{1}{T} \int_{t=t_0-T_e/2}^{t_0+T_e/2} E\{u_n u_n^*\} \tag{10}$$

where $E\{\cdot\}$ denotes the statistical expectation operator and T_e is a time-interval short enough for the ray parameters to remain fixed and long enough for the integration to converge. Combining (5), (9) and (10) yields

$$\overline{E} = \mathbf{w}^{DL^H} \left(\sum_{l=1}^{P} |g_l|^2 \mathbf{d}^{DL}(\theta_l) \mathbf{d}^{DL^H}(\theta_l) \right) \mathbf{w}^{DL} \tag{11}$$

where $|g_l|^2$ is the mean-power of the fading $g_l(t)$ and, without loss of generality, the follow normalizations were made

$$E\{I_q^{DL}\} = 1 \tag{12}$$

and

$$\int_{\tau=-\infty}^{+\infty} p(\tau) d\tau = 1 \tag{13}$$

Recognizing the *downlink spatial covariance matrix* $\mathbf{R}^{DL}$ as

$$\mathbf{R}^{DL} = \sum_{l=1}^{P} |g_l|^2 \mathbf{d}^{DL}(\theta_l) \mathbf{d}^{DL^H}(\theta_l) \tag{14}$$

(11) can be written as

$$\overline{E} = \mathbf{w}^{DL^H} \mathbf{R}^{DL} \mathbf{w}^{DL} \tag{15}$$

Similarly, the *uplink spatial covariance matrix* $\mathbf{R}^{UL}$ can be written as

$$\mathbf{R}^{UL} = \sum_{l=1}^{P} |g_l|^2 \mathbf{d}^{UL}(\theta_l) \mathbf{d}^{UL^H}(\theta_l) \tag{16}$$

where the mean-power of the fading $|g_l|^2$ is the same as in the downlink.

3. DOWNLINK BEAMFORMING

Let us consider the situation where one base station is transmitting simultaneously and on the same frequency to U mobile users. The purpose of the downlink beamforming is to generate a set of antenna weights $\{\mathbf{w}_1^{DL}, \mathbf{w}_2^{DL}, \ldots, \mathbf{w}_U^{DL}\}$, one for each user, so that a satisfactory SIR (signal to interference ratio) is provided for all users.

The principle is to transmit in the directions of all user multipaths and mitigate the other users. We preserve all the user multipaths so that the energy is transmitted in different directions, hence some degree of spatial diversity is provided for the mobile receiver. However, equalization needs to be done in the mobile in order to mitigate the eventual ISI (inter-symbolic interference) introduced by the multipaths. A pre-equalization at the base station is not feasible as long as the downlink channel is unknown.

In order to transmit into the correct directions for each user, the set of weights must be obtained in according with an efficient algorithm. As it was previously mentioned, these techniques need some sort of uplink to downlink transposition of the antenna weights or the covariance matrix. The three approaches under study are analyzed in the sequel.

3.1 Uplink to Downlink Transposition

Due to the frequency duplex distance between up- and downlink, the steering vectors are not the same. However, a linear transformation that provides the best estimation of the downlink steering vectors from the uplink one is proposed in [4]:

$$\hat{\mathbf{d}}^{DL}(\theta) = \mathbf{T}\mathbf{d}^{UL}(\theta) \tag{17}$$

Introducing the downlink *calibration table* of the antenna array as the matrix that contains the downlink steering vectors for a set of azimuth directions $\{\theta_1, \theta_2, \ldots, \theta_K\}$

$$\mathbf{D}^{DL} = \begin{bmatrix} \mathbf{d}^{DL}(\theta_1) & \mathbf{d}^{DL}(\theta_2) & \cdots & \mathbf{d}^{DL}(\theta_K) \end{bmatrix} \tag{18}$$

and likewise for the *uplink calibration table*

$$\mathbf{D}^{UL} = \begin{bmatrix} \mathbf{d}^{UL}(\theta_1) & \mathbf{d}^{UL}(\theta_2) & \cdots & \mathbf{d}^{UL}(\theta_K) \end{bmatrix} \tag{19}$$

the transformation that minimizes the mean square error between the true downlink steering vector and the estimated one is given by

$$\mathbf{T} = \mathbf{D}^{DL}\mathbf{D}^{UL^H}\left(\mathbf{D}^{UL}\mathbf{D}^{UL^H}\right)^{-1} \quad (20)$$

Hence, this transformation can be used to transpose the antenna weights from uplink to downlink

$$\hat{\mathbf{w}}^{DL} = \mathbf{T}^{-H}\mathbf{w}^{UL} \quad (21)$$

The only parameters that are not link-dependent are the path attenuation α_l or mean-power, azimuth direction θ_l and path delay τ_l. These parameters are all *mean* values of the mobile channel response. Besides, the up- and downlink spatial covariance matrices are composed by a sum where the same mean-power of the fading and the up- and downlink steering vectors for the same azimuth directions are involved.

Hence, in order to transpose the spatial covariance we only have to transpose the steering vectors, resulting in

$$\hat{\mathbf{R}}^{DL} = \mathbf{T}\mathbf{R}^{UL}\mathbf{T}^{H} \quad (22)$$

Physically, in a multipath model, the up- and downlink share the same paths, with the same average path attenuations, the same azimuth directions and the same path delays.

3.2 Uplink Space-Time Structure

The space-time structure to be used in the uplink is proposed in [2]. The adaptation process of the antenna weights makes use of a modified training sequence, obtained by filtering the original one by a channel estimator. In such structure, the mitigation of CCI (co-channel interference) and ISI (inter-symbolic interference) are done in different stages [5], as shown in figure 3. The mitigation of ISI is performed by a temporal equalizer, which is decoupled from the antenna array. Such procedure constrains the task of the antenna array just on the CCI cancellation. Then a greater degree of freedom is attained for the array, since it does not take care of the desired user multipaths.

As far as downlink transmission is concerned, the multipaths preservation results in a more suitable antenna pattern, after the weights transform. Moreover, there is a great similarity between this structure and the whole downlink processing, where the spatial processing is done at the base station and the equalization at the mobile.

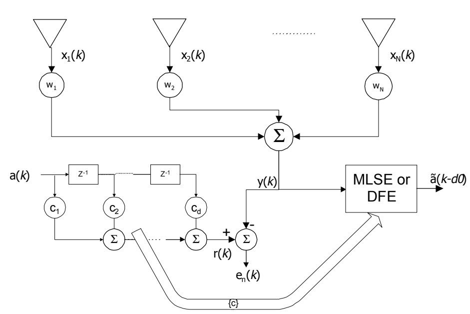

Figure 3. Decoupled Space-Time structure (D-ST).

3.3 *Direct Algorithm* and *Uplink Algorithm*

In these two algorithms, we make use of the uplink processing to obtain the downlink antenna weights. In both, we use the proposed decoupled structure and the RLS (recursive least squares) algorithm for adaptation. After the training period, we obtain the antenna weights to be used for SIR calculation.

The direct algorithm simply employs the uplink antenna weights for the transmission, without any kind of post-processing. On the other hand, the uplink algorithm makes use of the frequency transposition to generate the equivalent downlink antenna weights.

Consequently, the direct and the uplink algorithms are tied to the uplink structure and greatly dependent on the uplink processing performance.

3.4 Downlink Algorithm

The downlink algorithm is based on the maximization of the SPR (signal to pollution ratio). Where by *signal* we mean the power that the desired user receives and *pollution* is the total power received by all other users. For the desired user i, the received signal power is given by

$$S_i = p_i \mathbf{w}_i^{DL^H}\mathbf{R}_i^{DL}\mathbf{w}_i^{DL} \quad (23)$$

where p_i, $\mathbf{w}_i^{DL}$ and $\mathbf{R}_i^{DL}$ are respectively the transmission power, the downlink antenna weights and downlink spatial covariance matrix of user i. Furthermore, the pollution power with respect to the user i is given by

$$P_i = p_i \mathbf{w}_i^{DL^H}\mathbf{R}_{p,i}^{DL}\mathbf{w}_i^{DL} \quad (24)$$

where $\mathbf{R}_{p,i}^{DL}$ is the so-called pollution matrix of user i, given by

$$\mathbf{R}_{p,i}^{DL} = \sum_{\substack{j=1 \\ j\neq i}}^{U}\mathbf{R}_j^{DL} \quad (25)$$

Hence, the downlink antenna weights for user i is obtained by the maximization of the following criterion:

$$\mathbf{w}_i^{DL} = \arg\max_{\mathbf{w}}\left\{\frac{\mathbf{w}^H\mathbf{R}_i^{DL}\mathbf{w}}{\mathbf{w}^H\mathbf{R}_{p,i}^{DL}\mathbf{w}}\right\} \quad (26)$$

It can be shown that $\mathbf{w}_i^{DL}$ is the generalized eigenvector of the matrix pair $\left(\mathbf{R}_i^{DL}, \mathbf{R}_{p,i}^{DL}\right)$, associated to the largest eigenvalue [6]. After the calculation of the set of weights, it is necessary to calculate the set of transmission powers $\{p_1, p_2, \ldots, p_U\}$ in order to equalize the SIR for all users. The SIR for user i is given by

$$SIR_i = \frac{p_i \mathbf{w}_i^H \mathbf{R}_i^{DL}\mathbf{w}_i}{\sum_{\substack{j=1 \\ j\neq i}}^{U} p_j \mathbf{w}_j^H \mathbf{R}_i^{DL}\mathbf{w}_j} \quad (27)$$

The set of transmission powers is then calculated to force all the SIR_i to have the same value.

It should be emphasized that this algorithm is transparent to the uplink structure or processing since it is based only on the spatial covariance matrices. However, it requires the knowledge of the downlink spatial covariance matrices of each user, which cannot be estimated on the base station. Hence, we employ the frequency transposition on the estimated uplink spatial covariance matrices to obtain the transposed downlink ones.

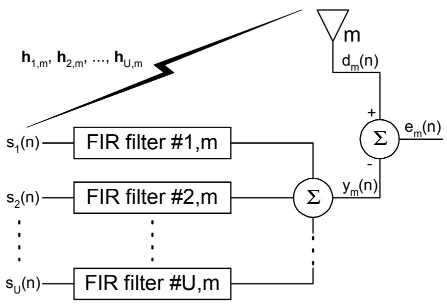

Figure 4. Uplink Channels Estimation Structure

Such matrices are estimated by means of a filter bank as shown in figure 4. $\mathbf{h}_{i,m}$ stands for the uplink channel between user i and the antenna element m; d_m, y_m and e_m are the desired signal, the filter bank output and the error signal to be employed in the adaptive channel estimation for the element m. So, the estimation is jointly carried out in the same antenna for all users. It is performed by means of a RLS algorithm. Then, the uplink estimated space-time channel of user i is composed by

$$\hat{\mathbf{H}}_i^{UL} = \begin{bmatrix} \hat{\mathbf{h}}_{i,1} & \hat{\mathbf{h}}_{i,2} & \cdots & \hat{\mathbf{h}}_{i,M} \end{bmatrix}^T \quad (28)$$

and the uplink estimated spatial covariance matrix is given by

$$\hat{\mathbf{R}}_i^{UL} = \hat{\mathbf{H}}_i^{UL} \hat{\mathbf{H}}_i^{UL^H} \quad (29)$$

4. RESULTS

The simulations were carried in an IS-136 TDMA context [7]. It uses a π/4-DQPSK modulation and a raised cosine with roll-off factor $\alpha = 0.35$. The channel follows the two-path model in [8] with the same average power for each path. This is considered as a worst case for the IS-136. Additionally, the delay between paths was chosen to be a half symbol period. We consider a slot with 162 symbols including 14 training symbols.

The simulation context was a single cell with $U = 2$ mobile users in a SDMA (spatial division multiple access) mode where both mobiles share the same frequency, the same time slots but are spatially separated. The base station uses an uniform linear antenna array with $M = 3$ antenna elements and an inter-element spacing of half the downlink wavelength ($d = \lambda_d/2$) to serve a 120° sector cell. We carried out the simulations using the Jakes' space-time channel model [3] and users speed of 100km/h. The uplink carrier frequency was set to 900MHz while the downlink one was 995MHz.

Firstly, we present the results for a typical case (see [9] and references) where 35° of angular separation and 10° of angular spread is used. Figure 5 shows the CDF (cumulative distribution function) of the SIR for 10000 trials. In each trial we draw different user positions and calculate the SIR for one slot. It can be noted that the difference between the uplink and the direct algorithm is almost negligible. Moreover, the downlink algorithm performs better with an improvement of approximately 2dB in the region of interest (around 10dB) when compared to the others

Figure 6 shows the antenna pattern behavior of the downlink algorithm for 0° of angular spread in a stationary situation, i.e. without fading. User 1 has DOAs (direction of arrival) of –50° and –30° while user 2 has DOAs of +40° and +60°. The result makes clear the capability of the algorithm in preserving all multipaths from one user and rejects the other user multipaths.

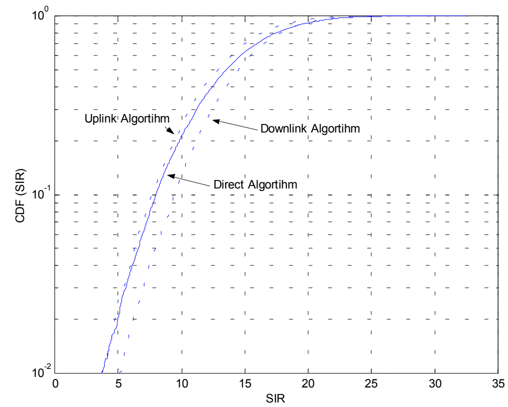

Figure 5. Performance for 2 users, 35° of angular separation and 10° of angular spread

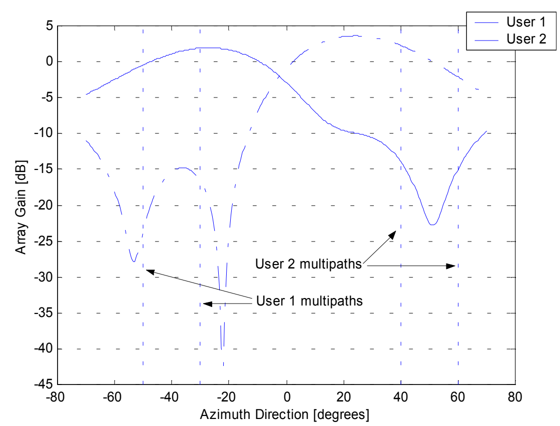

Figure 6. Downlink Algorithm Antenna Pattern

In figure 7 we plot the antenna patterns for all the algorithms together with the so-called *True Downlink*. This one is obtained by the downlink algorithm with a perfect knowledge of the downlink channel and serves as a performance reference. We consider the same situation of figure 6. The figure shows that the algorithms have very similar antenna patterns in the directions of users multipaths, even if they are slightly different elsewhere.

In figure 8, we show the effect of the angular separation between users. The result is presented in terms of outage probability, i.e. the probability of the SIR be less than a given threshold, so that the user will not be accepted in the cell. We have simulated 10000 trials for each value of angular separation with 0° of angular spread. The outage threshold was chosen as 10dB, a typical value for TDMA systems. It can be observed that the downlink algorithm performs fair for angular separations below 30^o, which is evidenced by [9], and outperforms the direct and uplink algorithms, in particular for higher angular separations.

Figure 9 presents the outage probability versus angular spread, with an angular separation given by 35^o. Again 10000 trials for each value of angular spread was carried out. This figure shows the dependence of the three algorithms on the angular spread. Besides, it can be shown that the downlink algorithm has a better performance of about 5% to 10% in terms of outage probability, while the direct and uplink algorithm are almost equivalents.

5. DISCUSSION AND CONCLUSION

In this paper, we have investigated the performance of three downlink beamforming approaches for TDMA/FDD systems. All approaches have the capability to preserve the user multipaths and then are suitable for downlink beamforming. Further, the direct algorithm and the uplink algorithm performs almost equally in typical cases. It was shown that all the approaches have a greatly dependence on the angular separation of users and on the angular spread of the space-time channel. However, in a SDMA context where the angular separation of users is typically high, the downlink algorithm has a good performance. Hence, the use of the downlink algorithm is a convenient approach for downlink beamforming in TDMA systems even if the user speed is as high as 100km/h, which is a worst case for this scenario.

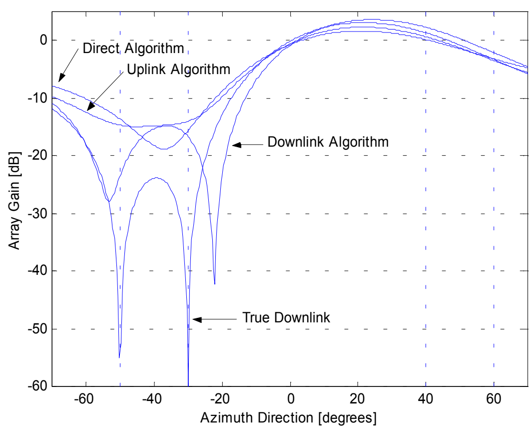

Figure 7. Antenna Pattern comparation

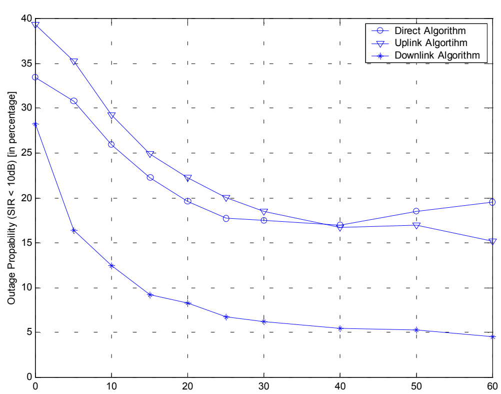

Figure 8. Performance *versus* Angular Separation

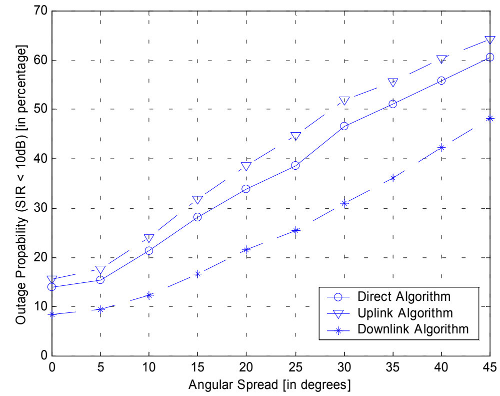

Figure 9. Performance *versus* Angular Spread

ACKNOWLEDGMENTS

The authors are grateful to Dr. Féty and Prof. Bellanger, from CNAM-Paris, for precious discussions about this work.

REFERENCES

[1] A. J. Paulraj and C. B. Papadias. “Space-time Processing for Wireless Communications”. *IEEE Signal Processing Magazine*, pp 49-83, November 1997

[2] C. M. Panazio and F. R. P. Cavalcanti. “Decoupled Space-Time Processing Performance Evaluation for TDMA Systems”. *XIX SBrT*, Fortaleza, Brazil, 2001, submitted.

[3] W. C. Jakes. *Microwave Mobile Communications*. Wiley-Interscience, 1974.

[4] Thierry Asté. “Méthodes de traitement d’antenne adaptatives pour un système de communications numériques radiomobiles de type GSM”. *Ph.D. thesis, Conservatoire National des Arts et Métiers – Paris*, France, December 1998.

[5] Maw-Lin Leou, Chien-Chung Yeh and Hsueh-Jyh Li. “A Novel Hybrid of Adaptive Array and Equalizer for Mobile Communications”. *IEEE Transactions on Vehicular Technology*, vol. 49, no. 1, January 2000.

[6] Thierry Asté, Philippe Forster, Luc Féty and Sylvie Mayrargue. “Downlink Beamforming for Cellular Mobile Communications (GSM system)”. *Annales des Télécommunications*, 53, n^o 11-12, 1998, pp 435-448.

[7] TIA/EIA-136-131-B, TIA/EIA Standard, TDMA Third Generation Wireless Digital Traffic Channel Layer 1, March, 2000.

[8] TIA/EIA-136-280-B, TIA/EIA Standard, TDMA Third Generation Wireless Base Stations Minimum Performance, March, 2000, pp –31.

[9] Klaus Hugl, Juha Laurila and Ernst Bonek. “Downlink Beamforming for Frequency Division Duplex Systems”. *Global Telecommunications Conference – Globecom’99*, Rio de Janeiro, Brazil, 1999.