A NOVEL COMBINING TECHNIQUE FOR ADAPTIVE ANTENNA ARRAYS

Nicolae CRIŞAN, Ligia Chira CREMENE
Technical University of Cluj-Napoca, 15 Daicoviciu street
Nicolae.Crisan@com.utcluj.ro

Abstract: In the context of new high-data-rate wireless communications, multiple antenna systems are now taken into account early in the design phase. MIMO (Multiple Input Multiple Output) transmission schemes are still based on high redundancy algorithms. This paper proposes a new combining technique, OSC-SSBC (Orthogonal Space Combining – Space-Space Block Coding), and demonstrates that multiple antenna systems can significantly increase channel capacity (close to double), in LOS conditions, by implementing the OSC method at the receiver, on an adaptive antenna array. The block diagram and mathematics are presented and discussed, for a 2Tx-2Rx configuration.

Key words: *space diversity, spatial multiplexing, beamforming and beam-steering, OSC – Orthogonal Space Combining, MRC – Maximum Ratio Combining, MIMO – Multiple-Input-Multiple-Output.*

I. INTRODUCTION

3GPP LTE is nowadays more than a concept, work has been done since 2004 and release 8 standards are now to be complete. Because of the many deployment options it is a real challenge to design and test the first equipments. Baseband, RF, as well as layer 2/3 issues should be clarified and finally summed in a conformance test specifications. Regarding the RF part, there is no specific spectrum allocated to LTE, nor is it known whether it will coexist with CDMA or GSM systems. However, we know that the underlying air interface specifies an OFDM downlink (very similar to the WiMAX one) and a SC-FDMA uplink (single carrier frequency division multiple access) to reduce peak-to-average power ratio [1].

Multiple Input Multiple Output (MIMO) is required in order to achieve the peak data rates; LTE aims to provide 50 Mbps uplink and 100 Mbps downlink, for single antenna, rising to over 170 Mbps for 2x2 downlink MIMO [2]. Peak data rates are often quoted without mentioning the assumed channel conditions: for MIMO, the quoted figures represent the theoretical potential, and usually rise linearly with the number of propagation paths, but in reality they are determined by the correlation degree between the paths. MIMO seems to work best indoors [2], [3] where there are slow changing conditions and NLOS (Non Line-of-Sight), and multipath is used to a benefit. MIMO needs highly uncorrelated paths, so it cannot operate with significant LOS. In outdoor environments LOS is common and performance is achieved using receive diversity rather than MIMO, especially for cell edge coverage. Another reason to study and attempt to enhance receive diversity performance is the fact that, as stated in [2], for UE cost reasons, it was decided to only mandate 2x2 SU-MIMO for the downlink. Although 4x4 MIMO is defined in the standards, this is probably only going to be practical for PC-based devices.

This paper demonstrates the fact that a wireless communication system can almost double its capacity, in LOS conditions, by implementing an OSC (Orthogonal Space Combining) method at the receiver, on an adaptive smart antenna array. This proposal, along with the ones presented by the authors in [7] and [9] are the steps toward a multi-reconfigurable antenna, which can be prototyped nowadays due to novel RF MEMS (Micro-Electro-Mechanical Systems) and SDCs (Software-Defined Components). Section II discusses the similarities of receiver diversity and beamforming / beam-steering. Section III describes the OSC block diagram and mathematics. Section IV explains the Alamouti MIMO-STBC. Section V demonstrates how the integration of OSC in a multiple antenna system can increase channel capacity. Sections VI and VII determine and discuss the impact and the conditions on the spatial channel matrix for different scenarios. Section VIII shows the theoretical improvements in terms of channel capacity and our conclusions are presented in section IX.

II. RECEIVE DIVERSITY AND BEAMFORMING/BEAMSTEERING COMMON GROUND

There are several types of receiver diversity combiners, with different implementation complexity and overall performance: Threshold Combining (ThC), Selection Diversity Combining (SDC), Maximum Ratio Combining (MRC), and Equal Gain Combining (EGC). A

Manuscript received June 20, 2008; revised July 7, 2008

performance comparison of the four is presented in [4], and MRC is at the head of this performance hierarchy. The main benefit of receive space diversity is the array gain. This gain is achieved only when the energy received by each antenna is coherently combined [5]. The useful signal will be, in this case:

$$y = \sum_{i=1}^{N_r} y_i = N_r hx + \sum_{i=1}^{N_r} n_i \qquad (1)$$

where N_r is total number of receive antennas and $h = h_i$ are the channel matrix coefficients, since all paths are perfectly correlated. The very last term is the noise of the channel, usually associated with a Rayleigh distribution [5]. Assuming that only the noise of each branch is uncorrelated, the maximum gain, in terms of SNR, will be: $\gamma_s = N_r \frac{|h|^2}{\sigma^2} = N_r \bar{\gamma}$, where $\bar{\gamma}$ is the SNR of the system in a SISO configuration (Single Input Single Output - no diversity). In reality, $h_i \neq h_j$ and the MRC algorithm estimates the channel parameters, h_i, in order to maximize the array gain to γ_s, and the capacity of the channel to $C = BW \log_2\left(1 + N_r \bar{\gamma}\right)$. The channel variation is compensated by the complex weights c_i (fig. 1) which must be estimated.

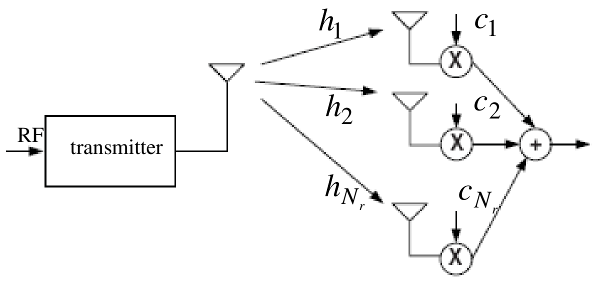


Figure 1. Classical MRC receiver - block diagram

III. ADAPTIVE BEAMFORMING USING OSC

The proposed method smartly combines steering and beam-forming, by using smart antenna arrays. For the sake of simplicity we assume only two antennas, in a LOS 2Tx - 2Rx MIMO configuration. In this case only two signals (two fronts of equal-phase) arrive at the receiver array, having the same frequency: y_A, arriving perpendicularly onto the receiver antenna array from TxA, and y_B, arriving at an angle α (fig. 2) from TxB. The block diagram resembles that of a classical MRC receiver with some differences.

The smart antenna array has the ability to dynamically change the antenna spacing *d*, with a given step Δ (where $n \in N^*$, fig.2). Signals y_A and y_B arrive at the receiver at the same time.

At the decision symbol time both signals are crossing through the antennas, and the resulted signal will be a sum [6]:

$$\begin{aligned} y_S = y_1 + y_2 &= |y_A| c_1 e^{j\omega_c t} + |y_A| c_2 e^{j\omega_c t} + \\ &+ |y_B| c_1 e^{j(\omega_c t+\theta+\varphi)} + |y_B| c_2 e^{j(\omega_c t+\theta)} \end{aligned} \qquad (2)$$

where ω_c is the angular carrier frequency, θ is the phase due to the path delay, and φ is the phase the AC distance adds to signal y_B (A and B are RxA and RxB in fig. 2), CB is the equal-phase wave front of y_B, that reaches the array.

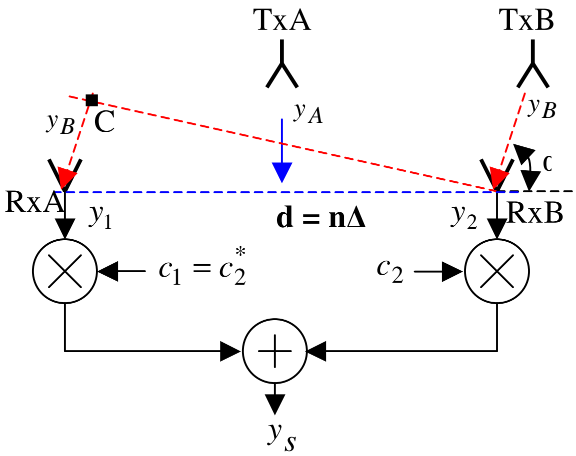


Figure 2. Proposed Orthogonal Space Combiner – OSC is based on the ability to control antenna spacing (d) and angle (Ω-Figure 6)

An equal-phase wave front is a plane where the waves have the same phase, in the far-field of the transmitter, and the direction of the propagating wave is always perpendicular to the equal-phase front ($\angle BCA = 90^o$). The input signals, y_1, y_2, and the weights, c_1 and c_2, are all complex. We consider that the useful signal, y_s, can be expressed in a simplified form as: $y_S = |y_A| e^{j\omega_c t}$, by keeping the weights unchanged, but dynamically spacing the antennas (the OSC concept). The main function of the MRC combiner is to find a smart combination of the c_i weights, in order to mitigate the effect of multipath propagation.

The initial idea, in the case of the OSC combiner, is to find the right antenna spacing, *d*, for which: $\varphi = \beta |AC| = \frac{\pi}{2}$ which is valid when:

$$d = \frac{\lambda_c}{4\cos\alpha} \qquad (3)$$

in order to separate one wave from the other (λ_c is the carrier wavelength). In this case we try to select the y_A wave and equation (2) becomes:

$$y_S = y_1 + y_2 = |y_A| c_1 e^{j\omega_c t} + |y_A| c_2 e^{j\omega_c t} + \\ + |y_B| c_1 e^{j(\omega_c t + \theta + \frac{\pi}{2})} + |y_B| c_2 e^{j(\omega_c t + \theta)} = \\ = |y_A| e^{j\omega_c t}(c_1 + c_2) + |y_B| e^{j(\omega_c t + \theta)} \left(c_1 e^{j\frac{\pi}{2}} + c_2 \right) \quad (4)$$

The interferer (undesired) signal is:

$$|y_B| e^{j(\omega_c t + \theta)} \left(c_1 e^{j\frac{\pi}{2}} + c_2 \right),$$

and it will be equal to zero when: $\mathrm{Real}\{c_1\} = \mathrm{Real}\{c_2\} = a$, $c_1 = c_2^* = a + jb$ where $a, b \in R$. Then, one possible solution is:

$$c_1 = \frac{1}{2} + j\frac{1}{2} = \frac{\sqrt{2}}{2} e^{j\frac{\pi}{4}}, \quad (5)$$

$$c_2 = \frac{1}{2} - j\frac{1}{2} = \frac{\sqrt{2}}{2} e^{-j\frac{\pi}{4}}, \quad (6)$$

$$y_S = |y_A| e^{j\omega_c t}\left(c_2^* + c_2\right) + |y_B| c_2 e^{j(\omega_c t + \theta)}\left(jc_2^* + c_2\right),$$

$$y_S = |y_A| e^{j\omega_c t} \quad (7).$$

As one can notice, the signal y_B becomes orthogonal to the desired signal y_A, and the resulted signal, y_S, is not influenced by y_B when $d = \frac{\lambda_c}{4\cos\alpha}$. This result leads to the idea that the antenna array can discriminate two signals arriving at the same time, but under different angles. When the coefficients c_1 and c_2 are under control, we deal with a beam-steering procedure and we can change the directions of the antenna lobes. When distance *d* is changed the antenna spacing is affected and we deal with a beamforming effect, this time the shape of the lobes is affected [6].

A classical MRC combiner uses MMSE (Minimum Mean – Square Error) or LMS (Least Mean Squares) algorithms, for channel estimation based on pilot signals. These methods look for channel responses to estimate the c_i coefficients. When we try to find the c_i coefficients we actually have a space-time combiner (e.g. the MRC case), and when we change only the antenna array geometry - element spacing *d*, and antenna orientation - we have a space-space combiner (the OSC case).

Thus, discrimination of the signals is possible, even if they come from a transmitter with the same frequency. A MRC scheme works with the coefficients and keeps the antenna parameters constant. Equation (5) must be evaluated for the MRC case, from the weights point of view:

$$y_S = |y_A| e^{j\omega_c t}(c_1 + c_2) + \\ + |y_A| e^{j(\omega_c t + \theta)}\left(c_1 e^{j\varphi} + c_2\right) = 2a|y_A| e^{j\omega_c t} \quad (8)$$

The equation is valid for the following conditions:

$$\begin{cases} c_1 = c_2^*, \\ c_1 e^{j\varphi} + c_2 = 0 \end{cases}$$

and these conditions lead to:

$c_2^* e^{j\varphi} + c_2 = 0$, and after multiplication by c_2 we have: $e^{j(2\theta_2 - \varphi)} = -1$, where θ_2 is the phase of the complex weight c_2. The solution of the last equation leads to:

$$c_1 = |c| e^{j\theta_1} = |c| e^{j\frac{(2k+1)\pi + \varphi}{2}} = \\ = |c| \left(\cos\left(\frac{(2k+1)\pi + \varphi}{2} \right) + j\sin\left(\frac{(2k+1)\pi + \varphi}{2} \right) \right) \quad (9) \\ c_2 = |c| e^{j\theta_2} = |c| e^{-j\frac{(2k+1)\pi + \varphi}{2}}$$

Equation (9) reveals the possibility of achieving orthogonality of y_A and y_B, based on weights only, but the weighting coefficients are not constant in this case. At this point, we can conclude that there are some correlations between adaptive beam-steering/beamforming and diversity that we can exploit in a smart way.

IV. THE ALAMOUTI STBC CONFIGURATION

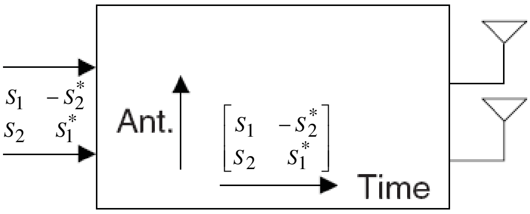
In 1998, Alamouti proposed a MIMO-STBC scheme (Fig. 3) that achieves both Tx and Rx diversity gains. The OSC-SSBC 2x2 configuration resembles the Alamouti 2x2 scheme, which is discussed here for a better understanding of the OSC-SSBC proposed concept. The MIMO-Alamouti 2x2 STBC scheme (Fig. 3.a) is successfully used in current wireless communication systems (e.g. WiMAX). As long as the channel is a flat-fading one, and can be considered constant over two symbols, the STBC scheme can be applied, and the channel is described by the 2x2 matrix, H_1:

$$H_1 = \begin{bmatrix} h_{11} & h_{12} \\ h_{21} & h_{22} \end{bmatrix} \quad (10).$$

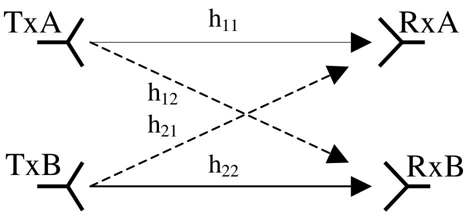
A symbol is transmitted twice ($T(t=0)=[S_1\ S_2]$, and $T(t=T_{symb})=[-S_2^*\ S_1^*]$). For the moment, we accept that signals $[S_1\ S_2]$ will interfere at the receiver and we have:

$$\begin{aligned}[r_1\ \ r_2] &= \begin{bmatrix} S_1 & S_2 \\ -S_2^* & S_1^* \end{bmatrix} \begin{bmatrix} h_{11} & h_{12} \\ h_{21} & h_{22} \end{bmatrix} + \\ &+ \begin{bmatrix} n_1(0) & n_2(0) \\ n_1(T_{symb}) & n_2(T_{Symb}) \end{bmatrix}\end{aligned} \tag{11}$$

The matrix H_1 of the radio channel is estimated based on pilot signals [5], for instance in WiMAX (CSI is estimated for the receiver).



a)



b)

Figure 3. a) MIMO-STBC Alamouti 2Tx b) 2T – 2Rx Configuration

The resulting signals at the receiver at 0 and T_{symb} for antennas A and B are:

$$r_1(0) = h_{11}S_1 + h_{21}S_2 + n_1(0)$$
$$r_1(T_{symb}) = -h_{11}S_2^* + h_{21}S_1^* + n_1(T_{symb})$$
$$r_2(0) = h_{12}S_1 + h_{22}S_2 + n_2(0)$$
$$r_2(T_{symb}) = -h_{12}S_2^* + h_{22}S_1^* + n_2(T_{symb})$$

The decoded Alamouti STBC signals at the receiver are:

$$y_1 = h_{11}^* r_1(0) + h_{21} r_1^*(T) + h_{12}^* r_2(0) + h_{22} r_2^*(T),$$
$$y_2 = h_{21}^* r_1(0) + h_{11} r_1^*(T) + h_{22}^* r_2(0) + h_{21} r_2^*(T),$$

which leads to the following results:

$$y_1 = \left(|h_{11}|^2 + |h_{12}|^2 + |h_{21}|^2 + |h_{22}|^2\right) S_1 + 4 noiseterms,$$
$$y_2 = \left(|h_{11}|^2 + |h_{12}|^2 + |h_{21}|^2 + |h_{22}|^2\right) S_2 + 4 noiseterms.$$

As one can see complex symbols S_1 and S_2 are orthogonal and the SNR increases at:

$$\rho = \frac{\left(\sum_j \sum_i |h_{ij}|^2\right)^2}{\sigma^2 \sum_j \sum_i |h_{ij}|^2} \frac{\varepsilon_x}{2} = \frac{\sum_j \sum_i |h_{ij}|^2}{\sigma^2} \frac{\varepsilon_x}{2} \tag{12}$$

With a 3dB penalty compared to the MRC's SNR, due to transmitting each symbol twice (ε_x is the transmitted energy along one symbol for the equally weighted power for each antenna at the transmitter). The MIMO channel capacity [10] is:

$$C_{MIMO} = \log_2\left(\det\left[I_{M_r} + \frac{\rho}{M_t} H_1 H_1^H\right]\right) [bps/Hz] \tag{13}$$

where M_r and M_t are the number of the receiver and transmit antennas respectively. I_{Mr} is the unity matrix of order M_r and H_1^H is the Hermitian of matrix H_1.

V. OSC-SSBC 2Tx – 2Rx CONFIGURATION

OSC-SSBC 2Tx – 2Rx (fig. 4) is a space to space orthogonal combiner that works similarly with the Alamouti STBC (the differences are underlined in fig. 4) but behaves differently. Redundancy is reduced here by transmitting a symbol only once. Due to this fact the data rate will be double at least at a glance in the case of the proposed OSC-SSBC (fig. 4), compared to the well known MIMO-STBC (fig. 3). We also assumed that the channel is flat fading and constant over two symbols, represented by the 2x2 matrix H_1 but, in a LOS environment for the OSC-SSBC scheme. In the case of OSC-SSBC 2x2 configuration, the signals are as follows:

$$\begin{aligned} r_1(0) &= h_{11}S_1 + h_{21}S_2 + n_1(0), \\ r_2(0) &= h_{12}S_1 + h_{22}S_2 + n_2(0) \end{aligned} \tag{14}$$

$$\begin{aligned} y_1 &= h_{11}^* r_1(0) + h_{12}^* r_2(0) \\ y_2 &= h_{21}^* r_1(0) + h_{22}^* r_2(0) \end{aligned} \tag{15}$$

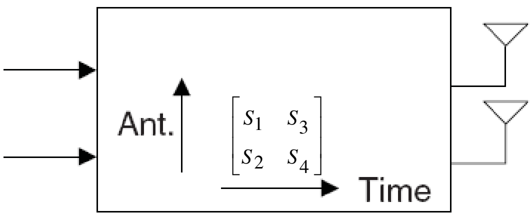


Figure 4. OSC-SSBC 2Tx – 2Rx Configuration

Replacing r_1 and r_2 in (14) and (15) we get:

$$y_1 = S_1\left(|h_{11}|^2 + |h_{12}|^2\right) + \\ + S_2\left(h_{21}h_{11}^* + h_{12}^* h_{22}\right) + 2noiseterms \quad (16)$$

$$y_2 = S_2\left(|h_{21}|^2 + |h_{22}|^2\right) + \\ + S_1\left(h_{11}h_{21}^* + h_{22}^* h_{12}\right) + 2noiseterms \quad (17)$$

As foreseen, symbols S_1 and S_2 interfere, because terms $S_2\left(h_{21}h_{11}^* + h_{12}^* h_{22}\right)$ and $S_1\left(h_{11}h_{21}^* + h_{22}^* h_{12}\right)$ are not zero in general. This is why Alamouti STBC inserts a redundancy by transmitting the same symbol twice ($T(t=0) = [S_1\ S_2]$ and $T(t = T_{symb}) = [-S_2^*\ S_1^*]$). A simple space diversity at the receiver is not enough and an additional time diversity is introduced by Alamouti. The cost is the decreasing in data rate and an energy penalty of 3 dB. The transmitter power remains the same but the data packet time increases. In the OSC-SSBC scheme the interfering terms appear, but in order to avoid their affecting the received signal, they are equalled to zero. This condition is fulfilled for a matrix of the following form:

$$H_2 = \begin{bmatrix} h_{11} & h_{11}e^{j\frac{\pi}{2}} \\ h_{22}e^{j\frac{\pi}{2}} & h_{22} \end{bmatrix} \quad (18)$$

The interfering terms are equalled to zero:

$$S_2\left(h_{21}h_{11}^* + h_{12}^* h_{22}\right) = j|h_{11}h_{22}|e^{j(\varphi_{22}-\varphi_{11})} - \\ - j|h_{11}h_{22}|e^{j(\varphi_{22}-\varphi_{11})} = 0 \quad (19),$$

$$S_1\left(h_{11}h_{21}^* + h_{22}^* h_{12}\right) = -j|h_{11}h_{22}|e^{j(\varphi_{11}-\varphi_{22})} + \\ + j|h_{11}h_{22}|e^{j(\varphi_{11}-\varphi_{22})} = 0 \quad (20).$$

We call the H_2 matrix the matrix of the orthogonal channel due to the fact that H_2 matrix is an ortho-goal [10] matrix ($H_2 H_2^H = nI_n$ considering all modules $|h_{ij}| = 1$, where n is the number of transmit or receiver antennas, n = 2 in our case, and I_n is the identity matrix). It is proven in [10] that the capacity of the MIMO channel is maximized for an ortho-goal matrix that is as we assumed,

$$C_{mimo} = 2\log_2\left(1 + \rho_{osc-ssbc}\right) \quad (21)$$

(double if $\rho_{osc-ssbc} = \rho$ where ρ is the SNR, for a SISO system). The antenna plays an important role in H_2 selection considering that even if the antenna can't change the parameters of the channel, it can select the suited matrix from an infinite number of matrices by changing its geometrical parameters like: antenna spacing and its placing in the electromagnetic field.

VI. THE ANTENNA ARRAY AND THE ORTHO-GOAL MATRIX

The distance between transmitter and receiver, their speed, their transmit powers, the obstacles, all have an impact on the channel matrix. These are factors difficult to control. Yet, there is another system that has a great influence on the H_2 matrix, a system that is under the control of the receiver: it is the receiver antenna array. The position of the antenna array in the field and the spacing between array elements are the main parameters that can influence the H_2 matrix. There is an antenna condition that brings the H_2 matrix to the form presented in equation (18). Multiple waves always travel following the equal-phase front. For the 2x2 MIMO configuration there is an equal-phase front corresponding to each transmitter. In the far field of the Tx antenna, the equal-phase front is plane and propagates at the speed of light in free space. According to the LOS assumption and H_1 matrix, there is only one equal wave front for each transmit antenna. Based on the 2Tx-2Rx OSC-SSBC proposed configuration, let us consider the two equal-phase fronts, one coming from Tx antenna 1 and the other one from Tx antenna 2, both arriving at the Rx antennas under the same angle (α) (Fig. 5-Case 1) in a LOS environment.

NA and MB indicate the direction of each front, AM and BN, respectively. The AM front carries symbol S_2 and the BN front, symbol S_1.

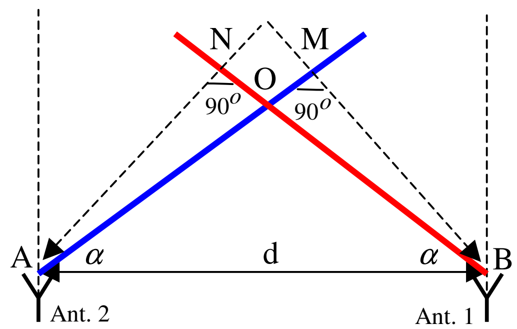


Figure 5. Case 1 - Equal- phase fronts AM and BN arrive at the same angle α

The angle $\alpha \in (0, \pi)$ and there is a diversity factor because a symbol is not received at the same time by the antennas. In this case, Rx antennas are decorrelated. When $\alpha = k\pi$, $k \in N$, the Rx antennas are correlated and there is no diversity because there is no path differences

(AN=BM=0). As we demonstrated in III the antenna beamforming can mitigate the effect of one front against the other by means of OSC concept but applying a different diversity scheme as was shown in V (eq. (14) and (15)). In case 1 (Fig. 5) the matrix channel is in the desired form (ortho-goal form) assuming that the wave magnitude is constant across a wavelength (d, BN, AN, BM, AM are smaller than λ_c) which is true when $d < \lambda_c$. It is proved in III that the antenna spacing must be: $d = \frac{\lambda_c}{4\sin\alpha}$ (eq. (3)), OSC concept, and matrix H_2 is found in the ortho-goal form:

$$H_2 = \begin{bmatrix} h_{11} & h_{11}e^{j\varphi} \\ h_{22}e^{j\varphi} & h_{22} \end{bmatrix} = \begin{bmatrix} h_{11} & h_{11}e^{j\frac{\pi}{2}} \\ h_{22}e^{j\frac{\pi}{2}} & h_{22} \end{bmatrix}$$

where $\varphi = \frac{2\pi}{\lambda_c} d \sin(\alpha)$. When $d = \frac{\lambda_c}{4\sin\alpha}$, then $\varphi = \frac{\pi}{2}$, and the receiving system can discriminate symbols S_1 and S_2, if the receiver applies a combining scheme as described by equations (14) and (15). One can notice that symbols S_1 and S_2 are orthogonal, and only the antenna spacing is the key for equations (18). The optimal antenna spacing $d = \frac{\lambda_c}{4\sin\alpha}$, geometrically obtained here, matches Amir's results [11-pg. 4 eq. (31)] that were obtained using a different method.

In a real-life environment, fronts AM and BN arrive at the receiver at different angles. A real case is considered in Fig. 6 (case 2) and this time the two fronts arrive at angles γ and α. For case 2 we have six sub-cases (Eq. (16)).

In Fig. 6 case 2, sub-case *a)* is illustrated. The antenna array changes its position in the field with $\left|\frac{\alpha-\gamma}{2}\right|$, taking into account the reference axes. The reference axes can be arbitrary chosen, one of the sub-cases will be met.

$$a)\ \begin{cases}\alpha+\gamma<\pi \\ \alpha\text{-}\gamma>0\end{cases} \qquad b)\ \begin{cases}\alpha+\gamma<\pi \\ \alpha\text{-}\gamma<0\end{cases}$$
$$c)\ \begin{cases}\alpha+\gamma>\pi \\ \alpha\text{-}\gamma>0\end{cases} \qquad d)\ \begin{cases}\alpha+\gamma>\pi \\ \alpha\text{-}\gamma>0\end{cases} \qquad (22)$$
$$e)\ \{\alpha+\gamma=0 \qquad f)\ \{\alpha+\gamma=\pi$$

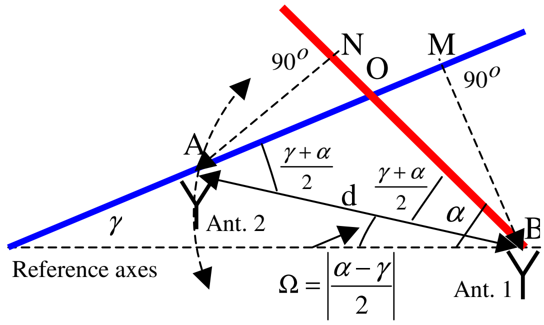


Figure 6. Case 2 - Equal- phase fronts AM and BN arrive at different angles, γ and α

In case *a)*, the fixed point of the array is B, while A is moving along the circle of center B and radius *d*. Element spacing must be $d = \frac{\lambda_c}{4\sin\frac{\gamma+\alpha}{2}}$ and $\Omega = \left|\frac{\alpha-\gamma}{2}\right|$ in order to meet (18) (AN=BM, $\varphi = \frac{2\pi}{\lambda_c} d \sin\left(\frac{\gamma+\alpha}{2}\right) = \frac{\pi}{2}$).

More detailed results regarding the array antenna parameters, *d* and Ω, are presented in table 1. We have identified 6 cases (*a* to *f*), which show how an array antenna can bring its contribution to data rate increasing.

Another important question is related to angle of arrival (γ and α) estimation methods. The pilot signal can be useful in this approach. The process of estimating γ and α is similar that of channel matrix estimation. This is done in two steps. First, antenna 1 transmits a pilot signal and antenna 2 transmits nothing. The receiver finds out the phase difference Ψ between the received signals (between the antennas). If the receiver antenna array is in a reference position (Ω = 0), then $\alpha = \arcsin\left(\frac{\lambda_c \Psi_1}{2d\pi}\right)$. The second step, antenna 2 transmits the pilot signal while antenna 1 transmits nothing. Then, when Ω = 0 $\gamma = \arcsin\left(\frac{\lambda_c \Psi_2}{2d\pi}\right)$.

This algorithm can be implemented in the context of the SDAA (Software Defined Autonomous Antenna) which was discussed by the authors in [7] and [9].

Case	*a*	*b*	*c*	*d*	*e*	*f*
Rotation direction	A – CW	B – CCW	A – CCW	B – CW	-	-
Ω	$\frac{\alpha-\gamma}{2}$	$\frac{\gamma-\alpha}{2}$	$\frac{\alpha-\gamma}{2}$	$\frac{\gamma-\alpha}{2}$	0	0
d	$\frac{\lambda_c}{4\sin\frac{\gamma+\alpha}{2}}$	$\frac{\lambda_c}{4\sin\frac{\gamma+\alpha}{2}}$	$\frac{\lambda_c}{4\sin\left(\pi-\frac{\gamma+\alpha}{2}\right)}$	$\frac{\lambda_c}{4\sin\left(\pi-\frac{\gamma+\alpha}{2}\right)}$	d = 0 no diversity	$\frac{\lambda_c}{4}$ Minimum distance

Table 1. OSC-SSBC 2x2 configuration – antenna array parameters

VII. THE PSEUDO ORTHO-GOAL MATRIX ISSUE

We envisage some problems regarding the OSC-SSBC use, due to the fact that in the case of an OFDM signal the ortho-goal form of the matrix H_2 (from 18) is not valid for all OFDM sub-channels, but only for the central carrier. For an i^{th} subcarrier, matrix H_2 can be found in the form:

$$H_{2i} = \begin{bmatrix} h_{11} & h_{11} e^{j\frac{\lambda_c}{\lambda_i}\frac{\pi}{2}} \\ h_{22} e^{j\frac{\lambda_c}{\lambda_i}\frac{\pi}{2}} & h_{22} \end{bmatrix} \qquad (23).$$

We call H_{2i} the pseudo ortho-goal matrix of the OFDM signal, where λ_i is the wavelength of the i^{th} subcarrier. According to the OFDM coherence bandwidth BW, we have:

$$\frac{\lambda_c}{\lambda_i} = \frac{f_c - \frac{BW}{2}}{f_c} \qquad (24).$$

The interfering terms (eq. (19) and (20)) are almost zero for an OFDM signal. In the worst case scenario, for a 20 MHz bandwidth and f_c = 2 GHz, the C_i/I ratio is 36.08 dB and increases toward the centre of the bandwidth.

Another problem regards the spacing step Δ from Fig. 2. Antenna spacing mismatching determines a pseudo – ortho-goal matrix in the form:

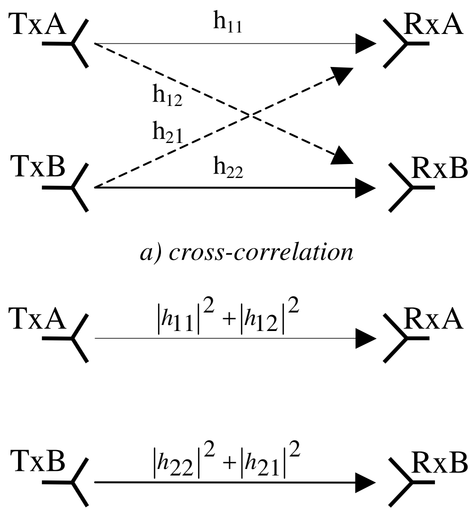
$$H_{2n} = \begin{bmatrix} h_{11} & h_{11} e^{j\frac{\lambda_c \sin\alpha}{4n\Delta}\frac{\pi}{2}} \\ h_{22} e^{j\frac{\lambda_c \sin\alpha}{4n\Delta}\frac{\pi}{2}} & h_{22} \end{bmatrix} \qquad (25)$$

where $\alpha \neq 0, (2k+1)\pi ...$ Fortunately, the coefficients of this matrix can be controlled by reducing the step Δ.

VIII. THE OSC-SSBC GAIN

It is remarkable that, when the ortho-goal matrix is found, there are two space sub-channels that are orthogonal. The simplest way to understand this is to consider the channel divided into two paths (h_{11} and h_{22}) which normally are cross-correlated (h_{12} and h_{21} – Fig. 7.a). When the receiver finds the H_2 matrix in an ortho-goal form, the channel is divided into two orthogonal sub-channels (Fig. 7.b) and the resulted channel matrix is the convolution of the two sub-channels' matrices (eq. (23)). The mathematical formalism that, by a linear transformation, leads n SISO sub-channels is known, and yields a capacity equal to the sum of the individual capacities of the SISO channels [10]. Unfortunately, the noise remains cross-correlated and, in the worst case, the SNR of the OSC-SSBC is reduced by half compared to the SISO SNR.

$$\begin{aligned}[y_1 \quad y_2] &= \\ &= [S_1 \quad S_2]\begin{bmatrix} |h_{11}|^2 + |h_{12}|^2 & 0 \\ 0 & |h_{22}|^2 + |h_{21}|^2 \end{bmatrix} + \\ &+ \begin{bmatrix} n_1(0)+n_2(0) & 0 \\ 0 & n_1(0)+n_2(0) \end{bmatrix} \qquad (26)\end{aligned}$$



a) cross-correlation

b) orthogonal sub-channels

Figure 7. Spatial sub-channels

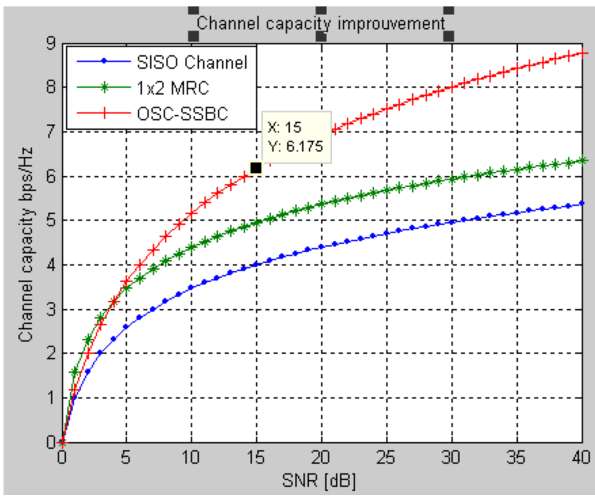


Figure 8. Capacity comparison

A comparison in terms of capacity vs. SNR is depicted in Fig. 8, for three configurations: 2x2 OSC-

SSBC (worst case $\rho_{OSC-SSBC} = \rho / 2$ eq. (21)), 1x2 MRC and a simple SISO channel. As we anticipated, the capacity increases significantly (close to double) especially for higher SNR values, reaching a 50% improvement for a 10 dB SNR. In a real case scenario, with a pseudo ortho-goal matrix, the capacity can be reduced. Even so, a 15 to 20% increase of the channel capacity can be remarkable.

IX. CONCLUSIONS

This paper demonstrates the fact that a multiple antenna system can theoretically increase channel capacity somewhere between 50 to 90% (for a SNR range of 10 to 40 dB), in LOS conditions, by implementing an OSC (Orthogonal Space Combining) method at the receiver, on an adaptive antenna array. This proposal, along with the ones presented by the authors in [7] and [9] are the steps toward a multi-reconfigurable antenna, which can be prototyped nowadays due to novel RF MEMS (Micro-Electro-Mechanical Systems) and SDCs (Software-Defined Components). The idea is to transmit two symbols at the same time, on two antennas, in a OSC-SSBC 2Tx – 2Rx configuration which resemblances the Alamouti 2x2 MIMO-STBC. At the receiver, the two symbols will be orthogonal if we use a smart array antenna that finds the right spacing (d) and angle (Ω) in the electromagnetic field with respect to the channel matrix. It is known that adaptive beamforming and beam-steering can enhance the performance of a space diversity scheme by significantly increasing the channel capacity. Reference [8] discusses the benefits of adaptive antenna spacing and angle diversity, based on accurate simulations, but without an explanatory mathematical model. Passive antenna diversity alone is not enough to ensure significant capacity improvements in MIMO systems, and this paper shows that spacing and angle reconfiguration of the antenna array is enough to significantly increase the system data rate; the impact of adaptive antenna reconfiguration on LOS wireless communications is mathematically evaluated and demonstrated here. More investigations and simulations need to be performed in order to accurately establish when and where the OSC-SSBC uses orthogonality of space sub-channels to a benefit, and that is probably for slowly variable channels.

ACKNOWLEDGEMENT

The authors thank Professor Vasile Bota for his critical advice that helped increase the quality of this paper.

REFERENCES

[1] Long Term Evolution of the 3GPP radio technology, http://www.3gpp.org

[2] Sandy Fraser, "Examining the Design and Test Challenges of the 3GPP LTE", Agilent Technologies Inc., WiMAX Supplement, nov. 2007.

[3] Paul Farago, Ligia Cremene, Nicolae Crisan, "WLAN 802.11n Tests and Measurements for Optimum Network Planning", SSET 2008 Symposium for Students in Electronics and Telecommunications, Technical University of Cluj-Napoca, 2008.

[4] Ligia Chira Cremene, Tudor Palade, "The Adaptive Potential of Space Diversity Techniques", *The Mediterranean Journal of Electronics and Communications,* Vol. 3, No. 3, 2007, pp.100-109, Copyright © 2007 SoftMotor Ltd. ISSN: 1744-2400

[5] J.G. Andrews, "Fundamentals of WiMAX", Prentince Hall Communications Engineering and Emerging Technologies Series, ISBN 0-13-222552-2, 2007.

[6] J. Litva, T. K. Yeung Lo, "Beamforming in Wireless Communications", Artech House Publisher, ISBN 0-89006-712-0, 1996.

[7] Ligia Chira Cremene, Nicolae Crisan, "The Adaptive Potential of Reconfigurable MEMS in MIMO Antenna Technology", CISSE 2007 IEEE Conference, University of Bridgeport, USA Dec 3 -12, 2007.

[8] J. D. Boerman, J. T. Bernhard, "Performance Study of Pattern Reconfigurable Antennas in MIMO Communication Systems", *IEEE Transactions on Antennas and Propagation*, Vol. 56, No. 1, January 2008.

[9] Nicolae Crisan, Ligia Chira Cremene, "The Impact of Novel RF MEMS and SDCs on Smart Antenna Technologies", The Fourth International Conference on Wireless and Mobile Communications - ICWMC 2008, Athens, Greece.

[10] Ed. By G. Tsoulos, *MIMO System Technology for Wireless Communications,* CRC Press Boca Raton London New York, ISBN – 13: 978-0-8493-4190-6, 2006

[11] Amir Masoudi Nasri Nasrabadi, H. R. Bahrami, S. H. Jamali, A. Afzali Kusha, "Effect of Antenna Separation on Capacity and Performance of MIMO Systems", 2003