

ADAPTIVE TRANSCIVER/ANTENNA TECHNIQUES FOR MOBILE BROADBAND COMMUNICATIONS AT MILLIMETRE-WAVE FREQUENCIES

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ABSTRACT: This paper is concerned with the implementation of a Mobile Broadband System, currently under research in Europe. We present a low-complexity, adaptive transceiver/antenna approach where simple, linear, phased arrays are adjusted under a transmission quality measurement provided by a decision-feedback equalizer. Several simulation results are presented and discussed.

1. INTRODUCTION

The Mobile Broadband System (MBS) [1], currently under research in Europe, aims at offering to mobile users an ATM-based radio access to the future integrated broadband communication network. Service bit rates of several tens of Mbit/s are intended; therefore, it is necessary to resort to mm-wave frequencies for radio transmission, since the required high gross bit rates imply a very wide band, which is not available below 30 GHz.

The main problems to solve in order to design a cellular mobile broadband system, at reasonable costs, are related to radio propagation conditions in outdoor environments: these conditions can give rise to both "delay spread difficulties" (heavy distortion effects on the required wideband signals) and "coverage difficulties" (obstruction of the LOS path whenever relevant reflections are not available).

Within the European RACE Project R2067-MBS, a set of preliminary specifications has been proposed for the MBS air interface, namely the following:

- A 4QAM scheme (2 bits per symbol), allowing the use of strongly nonlinear power amplifiers, in a first system implementation stage; also a compatible 16QAM scheme (4 bits per symbol) in later implementation stages.
- Two gross symbol rates: 40 Msymbol/s, for indoor environments; 20 Msymbol/s, for outdoor environments.
- A flexible TDMA/FDMA scheme, allowing the use of multiple slots on a single carrier and several carriers (up to four) in parallel, when the highest user bit rates are intended.

The activities carried out within the MBS/RACE Project with regards to the characterization of the propagation channels have clearly shown that their characteristics strongly depend on cellular configurations and antenna choices. A certain directivity (in both the horizontal and vertical planes) of BS and MS antennas helps in avoiding too a high delay spread in certain scenarios; therefore, it ensures a good performance when employing equalization schemes of moderate complexity. Moreover, antenna directivity can

also allow reduced transmit power requirements and an increased frequency reuse.

Having in mind the MBS requirements, a class of adaptive, low-cost, "serial OQAM-type" receivers was reported in [2], with decision-feedback equalization (DFE) and three alternatives with regards to the use of space diversity: no diversity at all; conventional, RSSI-driven, switched diversity; two-branch combining diversity which can be regarded as a wideband version of the well-known "maximal-ratio combining" (MRC). As in GSM receivers, channel estimation/equalization and off-line processing, on a burst-by-burst basis, are employed in these receivers. During the *training mode* of the adaptive operation, prior to message detection, the estimates of one (no diversity and switched diversity) or two (approximate "maximal ratio" combining diversity) overall Channel Impulse Responses (CIR) are obtained through a standard correlation technique, thanks to a 30-bit long training sequence, located in the middle of the burst. The CIR estimates are then used, on the one hand, to obtain the tap coefficients of one (no diversity and switched diversity) or two (combining diversity), approximately matched, FIR filters; on the other hand, they are used to calculate the tap coefficients of the single DFE required, under an MMSE (Minimum Mean Square Error) criterium. An additional *tracking mode* (employing an LMS iterative algorithm) allows the receiver to follow and compensate for the channel changes from the midamble to both burst edges.

Several simulation results [3] show that a certain directivity (in both the horizontal and vertical planes) of BS and MS antennas helps in avoiding too a high delay spread in certain scenarios, therefore ensuring a good performance when equalization schemes of moderate complexity are employed (moreover, antenna directivity can also allow reduced transmit power requirements and an increased frequency reuse).

In this paper, we propose low complexity adaptive transceiver/antenna techniques for mobile broadband communications. In Sec. 2, we present guidelines for the design of low complexity, adaptive antennas, including an iterative, MSE-driven algorithm (Mean Square Error). A set of simulation results is shown and discussed in Sec. 3. Some final remarks, in Sec. 4, conclude the paper.

2. ADAPTIVE ANTENNAS

A. Linear Phased Arrays

Let us consider a linear array with N equally spaced elements. The "array factor" can be written as

$$F(\theta) = \sum_{n=0}^{N-1} e^{j\Psi_n} e^{-j2\pi n \frac{d}{\lambda} \sin \theta} \quad (1)$$

where the phase Ψ_n pertains to the n th array element, d denotes the spacing between the array elements, λ is the wavelength and θ is the arrival angle. If we consider a multipath channel with an impulse response, at the output of a specific array element, given by

$$h(t) = \sum_{l=0}^{L-1} \alpha_l e^{j\phi_l} \delta(t - \tau_l) \quad (2)$$

then the equivalent channel impulse response at the array output can be taken as

$$h_{eq}(t) = \sum_{l=0}^{L-1} \alpha_l e^{j\phi_l} F(\theta_l) \delta(t - \tau_l) \quad (3)$$

where θ_l is the angle of arrival of the l th ray in (2).

B. Antenna Structure and Adaptation algorithm

In the following, we consider a class of low complexity adaptive antennas, to be used for reception at the MS, where the signals received by several antenna elements are appropriately combined. The adaptive antennas presented here (within the serial OQAM receiver [2]) are made of four linear antenna arrays, each one being a "phased array" that provides a sectorial coverage, adaptively shaped and limited to about 90° in the azimuth plane; they are designed to work in close interaction with the above-mentioned equalization scheme and do not require any DOA (Direction Of Arrival) estimation prior to the beam-shaping procedures.

The adaptation process is done in two steps, which can be described as follows:

- In a first step, one linear phased array is selected from the set of four linear phased arrays, under a power measurement criterium, as for a conventional switchable-beam scheme; this means the selection of an "operating 90° -sector". At this step, the set of weighting phases for each linear array is defined in advance so that a "nearly uniform" coverage of the 90° -sector is provided.
- In a second step, the weighting phases of the selected linear array are subjected to an updating procedure, which adapts the radiation pattern to the environment, under a performance criterium no longer relying on a power measurement but rather on a quality measurement. The quality measure is a burst-by-burst estimate of the "mean square error" (MSE) resulting from the equalizer adaptation, and is derived from the signal samples at both the input and the output of the decision device of the DFE.

The iterative algorithms (one iteration per burst) proposed here for array adaptation can be regarded as modified versions of the algorithm presented in [4], which uses the sign of the "measured power" differences between iterations. The modification basically consists of replacing "measured power" by "measured MSE" and adopting a variable, MSE-dependent, "adaptation coefficient", instead of a fixed one; the simultaneous use of two adaptive antennas

("MRC" diversity) is also considered, as an option that improves performance.

The "estimated MSE" for the k th burst, $\hat{e}(k)$, is easily derived from the samples $y_n(k)$, at the input to the decision device of the DFE, and the corresponding decisions $\hat{v}_n(k)$:

$$\hat{e}(k) = \overline{[y_n(k) - \hat{v}_n(k)]^2} \quad (4)$$

Of course, the "true MSE" during burst detection, $e(k)$, can be obtained by replacing in (4) the estimated sequence $\{\hat{v}_n(k)\}$ by the transmitted sequence $\{v_n(k)\}$. It is assumed that both $v_n(k)$ and $\hat{v}_n(k)$ take on the values ± 1 (4OQAM) or $\pm 1, \pm 3$ (16OQAM).

The contributions of the several array elements are burst-by-burst adjusted (weighted in phase) in a sequential way. In this paper, we consider four antenna elements per linear array; the initial set of phases, denoted $\{\psi_0(0), \psi_1(0), \psi_2(0), \psi_3(0)\}$, is chosen so as to provide a "nearly uniform" coverage of the operating 90° -sector, as reported above (see the corresponding antenna pattern in fig. 1A). The adaptation procedure can be described as follows, for $k \geq 0$:

$$\psi_j(k+1) = \psi_j(k) + \gamma(k) U_j(k), \quad j = i \quad (5a)$$

$$\psi_j(k+1) = \psi_j(k), \quad j \neq i \quad (5b)$$

where $i = k \bmod 4$, $\gamma(k)$ denotes the "adaptation coefficient" and $U_j(k)$ ($j=0, 1, 2, 3$) denote binary variables ($U_j(k) = \pm 1$), assigned to each array element so as to control the sign of the term used for phase adjustment.

When $\psi_j(k+1)$ given by (5a) leads to a decreased MSE estimate, it is just employed in the next iteration, and, with regards to the binary control variable, $U_i(k+1) = U_i(k)$; when $\psi_j(k+1)$ given by (5a) leads to an increased MSE estimate, the next iteration employs $\psi_j(k+1) = \psi_j(k)$ and $U_i(k+1) = -U_i(k)$. For the remaining antenna elements, $U_j(k+1) = U_j(k), j \neq i$.

In this paper, the MSE-dependent adaptation coefficient was chosen as follows:

$$\gamma(k) = \begin{cases} 5'' & \hat{e}(k) < 0.075 \\ 10'' & 0.075 \leq \hat{e}(k) < 0.15 \\ 12.5'' & \text{otherwise} \end{cases} \quad (6)$$

Until now, we have considered a single adaptive antenna in the MS. If double-branch space diversity is employed (e.g., MRC diversity, which still requires a single equalizer), through the use of two identical phased arrays, the adaptation procedures can be very similar. Since the sets of four array elements in branches "A" and "B" can be alternately adjusted (in a sequential way, as before, for each branch), the

adaptation procedures are still described by eqn (5), but with $j=0, 1, \dots, 7$ replacing $j=0, 1, 2, 3$ and $i=k \bmod 8$; a set $\{U_j(k); j=0,1,\dots,7\}$ is also required.

3. SIMULATION RESULTS

The set of simulation results shown in this section illustrates the advantages of the adaptive antennas described in Sec. 2. In the several examples chosen for this section, we adopted the proposed air interface specifications for outdoor (E_1 environment), e.g. gross bit rates of 40Mbps and 80Mbit/s, for 4OQAM and 16OQAM, respectively, a slot duration of 19.2μs, etc. [1, 3], and a carrier frequency of 40GHz. Serial OQAM-type receivers [2] were assumed in all cases; DFE (3,5) and (5,7) were considered for 4OQAM and 16OQAM, respectively.

3.1. Examples on array adaptation

The following examples are concerned to array adaptation within the adaptive antennas (made of four linear phased arrays) described in Sec. 2. Although just the 16OQAM scheme is considered, these results apply to 4OQAM (and other schemes). For the sake of comparisons, we considered both the MSE-directed algorithm proposed here and an RSSI-directed algorithm, similar to that presented in [4], with an adaptation coefficient equal to 10^0 . In both cases, we adopted a $d=\lambda/2$ spacing between the elements of each linear array; the radiation pattern of each array element, in the azimuth plane, was chosen in accordance with fig. 1A. The equalizer was supposed to use no tracking, since a "static" situation during the reception of each burst was assumed.

Very simplified propagation scenarios were adopted in the four examples below, so as to give evidence to the impact of different channel conditions, easy to characterize, on the behaviour of the adaptive antennas. No movement was assumed for the MS and only two incident rays (denoted "ray 1" and "ray 2"), both in the azimuth plane, were considered, leading to a channel impulse response $h(t) = \alpha_1 \delta(t - \tau_1) + \alpha_2 \delta(t - \tau_2)$ (complex α_1 and α_2) with regards to the "useful" channel as seen by the "reference" array element.

First example

Figs. 2 and 3 are concerned to this example, where $\tau_2 = \tau_1$, $(\theta_1, \theta_2) = (10^\circ, -22^\circ)$ pertain to the two directions of arrival, corresponding to the dashed lines in fig. 2, and $|\alpha_2|^2 = |\alpha_1|^2$. The arguments of α_1 and α_2 were chosen so that, in the beginning of the adaptation process, there is a perfect cancellation of the two rays, as seen by the phased array.

The evolutions of the "true MSE" with the RSSI-directed algorithm and the MSE-directed algorithm, respectively, are depicted in fig. 3 (the same noise level was assumed in both cases, so as to get a fair comparison). The behaviour and performance of the two adaptive arrays is somewhat similar: the weighting phases are adjusted in order to co-phase the two rays and/or eliminate one of them.

Second example

Fig. 4 is concerned to this example, where $\tau_2 - \tau_1 = 50\text{ns}$, and $(\theta_1, \theta_2) = (30^\circ, -30^\circ)$ pertain to the two directions of arrival. In the beginning of the phase adaptation procedure

$|\alpha_1|^2 = 2|\alpha_2|^2 = P$. After 100 iterations (100 received bursts), there is a sudden change in the level of "ray 1", with $|\alpha_1|^2 = P/8$ (i.e., an attenuation of 9dB) ever since.

The evolutions of the "true MSE" with the RSSI-directed algorithm and the MSE-directed algorithm, respectively, are depicted in fig. 4. The behaviour and performance of the two adaptive arrays is somewhat similar, with a first choice of ray 1 and the choice of ray 2 when this ray becomes the strongest one.

Third example

In this example, $\tau_2 - \tau_1 = 100\text{ns}$ and $(\theta_1, \theta_2) = (20^\circ, -20^\circ)$, with $|\alpha_2| = |\alpha_1|$ and the same noise level in both array types. The evolutions of the "true MSE" are shown in fig. 5: clearly, the MSE-adjusted array performs much better than the RSSI-adjusted array, which exhibits a very unstable behaviour when searching for an increased received power, while "forgetting" signal distortion due to delay spread.

Fourth example

In this example, $\tau_2 = \tau_1$ and $(\theta_1, \theta_2) = (20^\circ, -20^\circ)$ with $|\alpha_1|^2 = 0.7|\alpha_2|^2$. A co-channel interference signal, having the same angle of arrival as "ray 2" and $|\alpha_I| = |\alpha_2|$, is added to the useful signal. For the same noise level in both array types, the evolutions of the "true MSE" are shown in figs. 6. The much better performance with the MSE-adjusted array can be easily explained by observing fig. 7: the RSSI-adjusted array tries to receive as much power as possible (even if most of this power is interference power); the MSE-adjusted array is able to cancel the co-channel interference.

3.2. Example on robustness against fading

An example is given in the following, so as to illustrate the behaviour of the adaptive array antennas described in Sec. 2 with regards to the fading effects of multipath propagation.

The simulation scenario is similar to that described in [4], but the BS antenna is now assumed to be located in the middle of the street (and not close to a building wall); when employing an appropriate ray-tracing tool [5] for obtaining the propagation data, we also consider different values for the reflection coefficients. The MS speed is supposed to be $v=15\text{m/s}$; both 4OQAM and 16OQAM schemes are adopted, and only the "even" slots of the frame are assumed to be used. We consider either the MSE-adjusted, phased array antennas, as before, or conventional, switchable-beam antennas with a 3dB beamwidth of 90° in the azimuth plane (the same pattern as for the array elements, depicted in fig. 1A). A 3dB beamwidth of 30° is chosen for the elevation plane, with both antenna types, and polarization is supposed to be vertical. The path of the moving MS is parallel to the

street axis and the "operating sector", with both antenna types, is oriented according to this path.

Figs. 8 to 11 allow a fair comparison between the adaptive array antennas and the switchable-beam antennas

(E_s / N_0 was supposed to be 6dB higher in the switchable-beam antenna than in the reference element of the phased array antenna). The evolution of the "true MSE" is shown in these figures for both antenna types, with or without two-branch "MRC" diversity (in the beginning of the adaption procedure, a distance of 90m was supposed between the BS and the MS); both 4QAM and 16QAM were considered. For diversity, one of the antennas is below the other and the antenna spacing is 15cm. The adaptive array antennas, clearly have a performance advantage: even the adaptive array approach *without* diversity has better performance than the switchable-beam approach *with* diversity.

4. CONCLUSIONS AND FINAL REMARKS

A low-complexity, jointly adaptive, transceiver/antenna approach was proposed which can be of interest for MBS, namely for advanced system implementation stages. Even when a single adaptive antenna is employed, multipath propagation and co-channel interference effects are mitigated, leading to high performance levels; this can be very advantageous, especially when using a distributed antenna system (so as to cope with the LOS obstruction problem) and when a high frequency reuse is required.

This paper presents results concerning adaptive antennas to be used in the mobile stations. It should be noted that the same approach can be adopted for the base stations, leading to similar conclusions.

ACKNOWLEDGEMENTS

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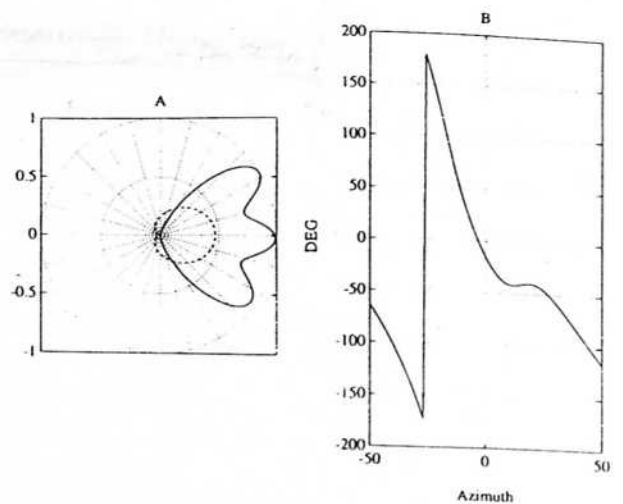


Fig. 1 - Amplitude (A) and phase (B) of the array radiation pattern before the adaptation process. (The radiation pattern of an array element is shown as a dashed line in (A).)

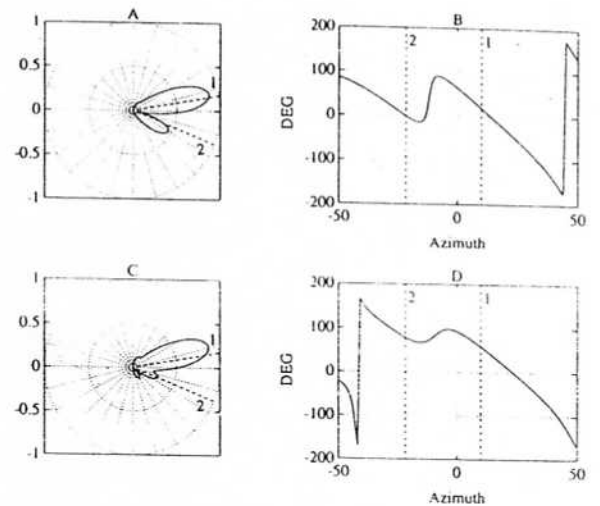


Fig. 2 - Adaptation behaviour for the first example: amplitude (A) and phase (B) of the array radiation pattern after adaptation with the RSSI-directed algorithm; amplitude (C) and phase (D) of the array radiation pattern after adaptation with the MSE-directed algorithm.

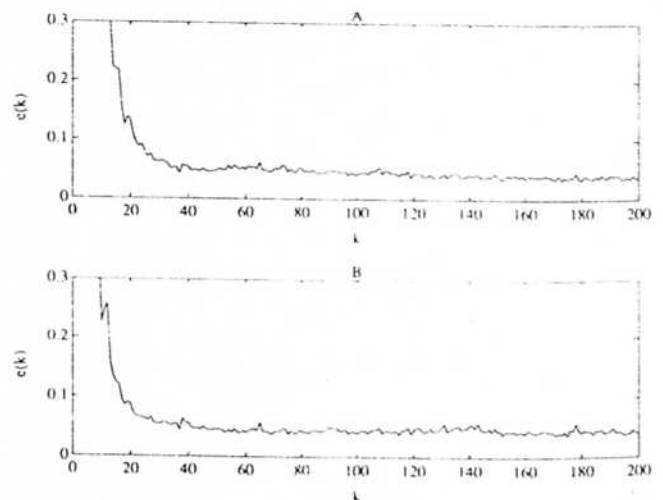


Fig. 3 - Evolution of MSE with the RSSI-directed algorithm (A) and the MSE-directed algorithm (B), for the first example.

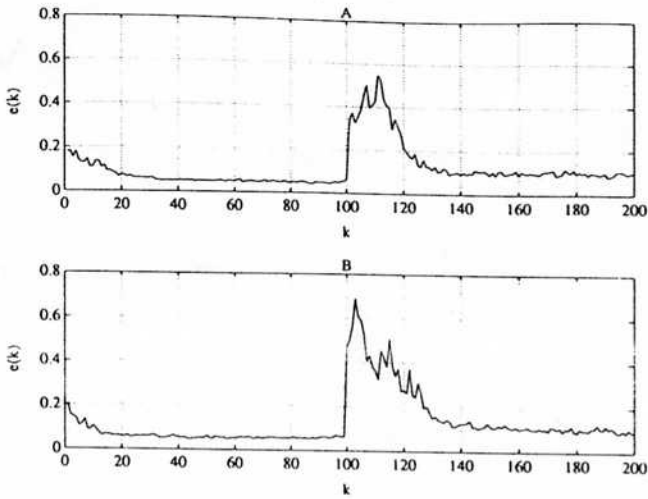


Fig. 4 - Performances with the RSSI-directed algorithm (A) and the MSE-directed algorithm (B) for the second example.

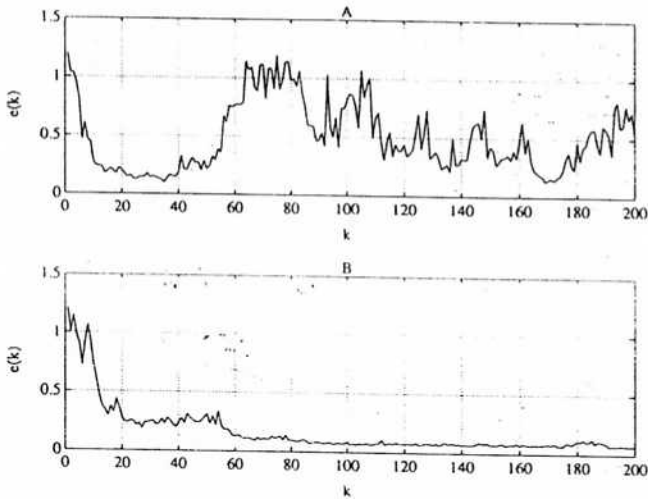


Fig. 5 - Performances with the RSSI-directed algorithm (A) and the MSE-directed algorithm (B) for the third example.

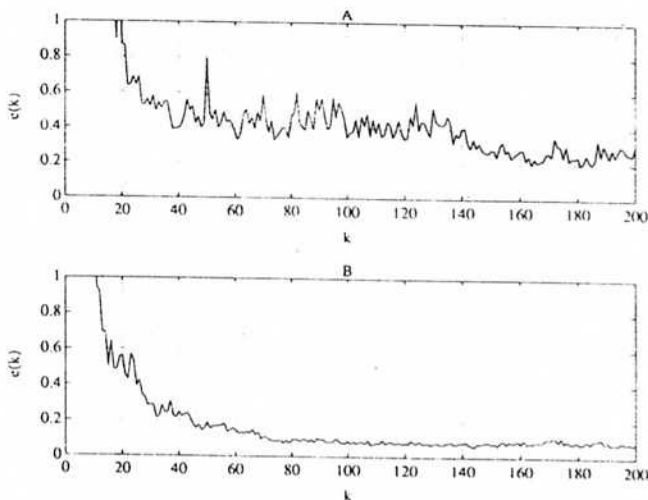


Fig. 6 - Performances with the RSSI-directed algorithm (A) and the MSE-directed algorithm (B) for the fourth example.

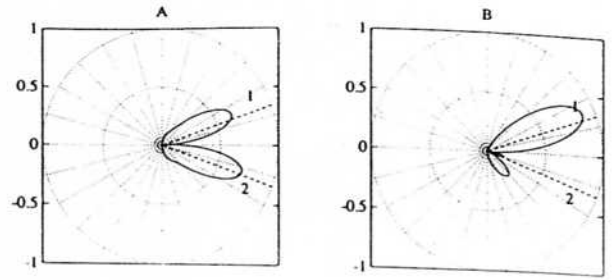


Fig. 7 - Radiation patterns at $k=200$ with the RSSI-directed algorithm (A) and the MSE-directed algorithm (B), for the fourth example.

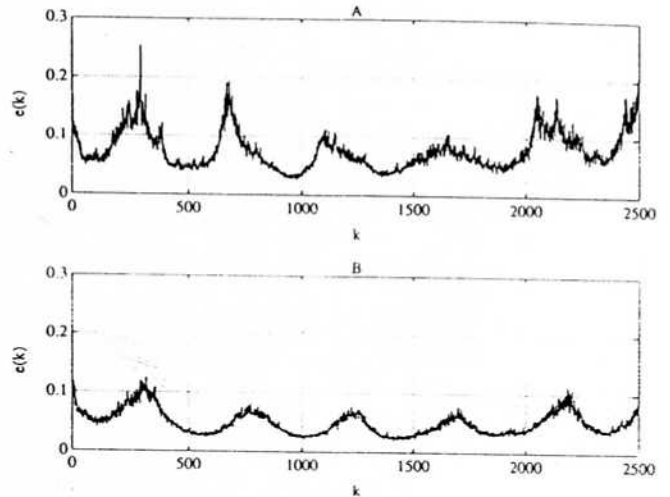


Fig. 8 - Performances for 4QAM with the phased array scheme: without diversity (A); with "MRC" diversity (B).

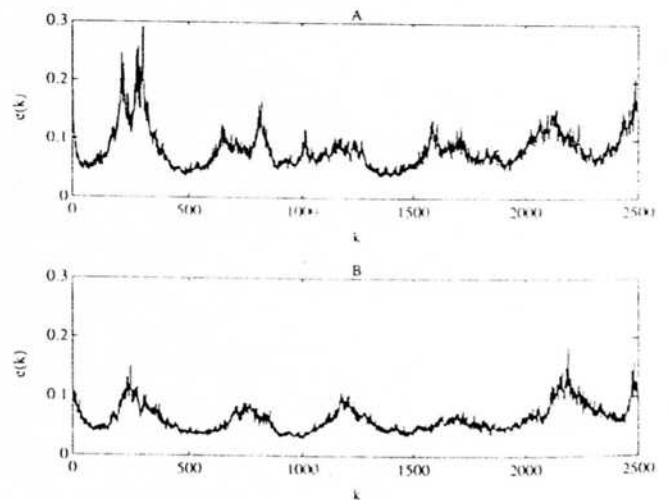


Fig. 9 - Performances for 16QAM with the phased array scheme: without diversity (A); with "MRC" diversity (B).

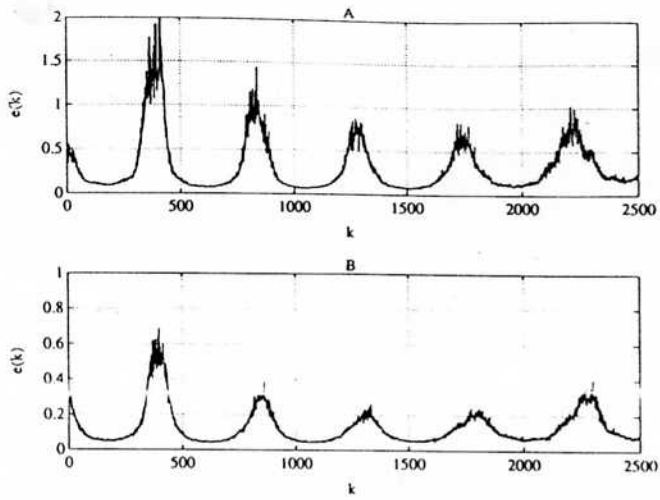


Fig. 10 - Performances for 4QAM with the switchable-beam scheme: without diversity (A); with "MRC" diversity (B).

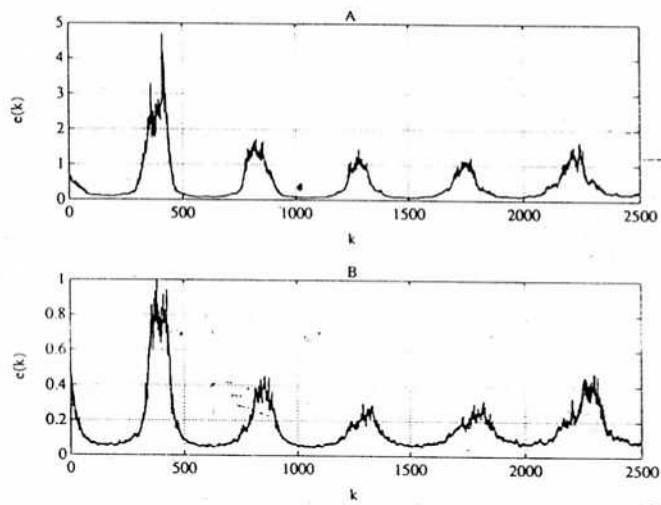


Fig. 11 - Performances for 16QAM with the switchable-beam scheme: without diversity (A); with "MRC" diversity (B).