Impact of Antenna Choices on the Reliability of Mobile Broadband Transmission at Millimetre-Wave Frequencies

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ABSTRACT: This paper deals with the impact of several antenna choices on the radio transmission performance within a cellular Mobile Broaband System (MBS) currently under research in Europe. Several antenna types are considered, namely switchable-beam antennas and adaptive antennas employing a phased array approach. Several simulation results are presented and discussed: they show that some directivity in the MS antenna is recommendable for an acceptable performance, and that the proposed adaptive MS antennas can be of interest for MBS, namely for advanced system implementation stages.

1. INTRODUCTION

The implementation of a cellular system, able to offer to mobile users an ATM-based radio access to the future IBCN, certainly represents a considerable challenge: the range of services is very wide (multimedia, HDTV contribution, etc.), with a variety of requirements and characteristics, including service bit rates of several tens of Mbit/s, much higher than in current mobile radio systems; 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.

Within the European RACE Project R2067-MBS, a set of preliminary specifications has been proposed for the air interface of a cellular Mobile Broadband System (MBS) [1], namely the following:

- A 4-OQAM scheme (2 bits per symbol), allowing the use of strongly nonlinear power amplifiers, in a first system implementation stage; also a compatible 16-OQAM scheme (4 bits per symbol) in later implementation stages.
- Two gross symbol rates: 40 Msymbol/s, for selected indoor environments (small areas); 20 Msymbol/s, for other indoor environments (large areas) and 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 main problems to solve in order to implement such a cellular system, at reasonable costs, are related to radio propagation conditions in outdoor environments. The activities carried out within the MBS/RACE Project with regards to the characterization of the radio channels have clearly shown that this characterization strongly depends on cellular configuration and antenna choices; appropriate antenna/cell design options certainly are one of the key issues for the RF feasibility of MBS.

Having in mind the MBS requirements, a class of adaptive, low-cost, "serial OQAM-type" receivers was proposed 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 that can be regarded as a wideband version of the well-known "maximal-ratio combining" (MRC).

In this paper, we study the impact of the antenna choices on the performance achieved through the use of the adaptive receivers reported above, within appropriate cell structures (designed to cope with the hostile propagation conditions, allowing a reliable transmission).

In Sec. 2, we report some of the MBS/RACE results on transmission performance, which illustrate the antenna/receiver tradeoff problem. Sec. 3 presents guidelines for the design of adaptive antennas suitable for MBS. A set of simulation results is shown and discussed in Sec. 4. Some final remarks, in Sec. 5, conclude the paper.

2. TRANSMISSION PERFORMANCE AND THE ANTENNA/RECEIVER TRADEOFF PROBLEM

An extensive simulation work carried out within the MBS/RACE project (see, for example, [3] and [4]), as well as some experimental work using the MBS/RACE demonstrator [1], have shown that the radio propagation 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). A certain directivity (in both the horizontal and vertical planes) of BS and MS antennas was shown to help 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). By adopting circular polarization, a delay spread reduction was also observed.

The adaptive receivers proposed in [2] have been assumed for the performance evaluation reported in [4]. 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.

Performances were evaluated in [4] under the following antenna assumptions, for a selected outdoor scenario (consisting of a 30m wide city street where a "typical" bus can give rise to strong back-reflected rays): either omnidirectional or switchable-beam antennas, with 9 sectors and sector selection on an average power basis, were considered in the mobile station (MS), both having a 3dB beamwidth of 20^o in the vertical plane; high-gain base station (BS) antennas were assumed, able to provide a one-sided coverage of the street, from 40m to 240m approximately (the area below each BS was supposed to be covered by adjacent base stations). Either vertical polarization or (only for the omnidirectional MS antenna case) circular polarization were assumed.

Some simulation results of [4] are also reported here, for the sake of comparisons between the above-mentioned antenna choices. For identical conditions - including a 4-OQAM modulation, a vehicle speed of 50km/h, "MRC" diversity and a "complex" tracking for the equalization within a serial OQAM receiver [2] - in all cases, the required average values of E_b / N_0 for a raw BER of approximately 4×10^{-3} were as depicted in TABLE I (O or S: omnidirectional or switchable-beam antennas, respectively, with vertical (V) or circular (C) polarization. The significant performance degradation with omnidirectional MS antennas and vertical polarization is obviously due to the strong (and greatly delayed) back-reflected rays, which lead to very high delay spread values: an rms delay spread of about 90ns is exceeded with probability 1/10 in this case. The nine-sectors, switchable-beam antenna obviously eliminates the back-reflected rays, leading to a very good performance even with an equalizer of very low complexity. The contribution of those rays for time dispersion is also less severe with circular polarization than with vertical polarization; this explains the better performance achieved, for the same DFE (9, 11).

TABLE I

MS Ant.	BS Ant.	DFE	E_b / N_0(dB)
O/V	V	(9, 11)	16.0
O/C	C	(9, 11)	8.2
S/V	V	(3, 5)	7.3

3. ADAPTIVE ANTENNAS

The above-mentioned switchable-beam antennas can be regarded as a particular class of "adaptive antennas"; the adaptation procedures involve a selection of the "operating element" (corresponding to the "operating sector"), from a set of antenna elements, according to a given criterium, e.g. the received power level. In the following, we consider a class of more sophisticated 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 [3], 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 (a detailed description is given in [4]).

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 $\hat{v}_n(k)$:

$$\hat{e}(k) = \overline{\left[y_n(k) - \hat{v}_n(k)\right]^2} \quad (1)$$

Of course, the "true MSE" during burst detection, *e*(*k*), can be obtained by replacing in (1) 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 (4-OQAM) or ± 1, ± 3 (16-OQAM).

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. 2A). The adaptation procedure can be described as follows, for $k \geq 0$:

$$\psi_j(k+1) = \psi_j(k) + \gamma(k) U_j(k),\ j = i \quad (2a)$$

$$\psi_j(k+1) = \psi_j(k),\ j \neq i \quad (2b)$$

where $i=k$ mod 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 $\psi_i(k+1)$ given by (2a) 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 $\psi_i(k+1)$ given by (2a) leads to an increased MSE estimate, the next iteration employs $\psi_i(k+1) = \psi_i(k)$ 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:

$$\gamma(k) = \begin{cases} 5^{o}, & \hat{e}(k) < 0.075 \\ 10^{o}, & 0.075 \leq \hat{e}(k) < 0.15 \\ 12.5^{o}, & \text{otherwise} \end{cases} \quad (3)$$

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 (2), but with j=0, 1, ..., 7 replacing j=0, 1, 2, 3 and $i=k$ mod 8; a set $\{U_j(k); j = 0,1,\ldots,7\}$ is also required.

4. SIMULATION RESULTS

The set of simulation results shown in this section illustrates the advantages of the adaptive antennas described in Sec. 3, having in mind later stages of MBS implementation, where the 16-QAM scheme and an increased frequency reuse are foreseen due to spectrum efficiency and capacity reasons. In the several examples chosen for this section, we adopted the proposed air interface specifications for outdoor environments (option ATM-2), e.g. a gross bit rate of 80Mbit/s, a slot duration of 19.2μs, etc. [1, 4], and a carrier frequency of 40GHz. Serial OQAM-type receivers [2] were assumed in all cases, with a DFE (5, 7) equalizer.

4.1. 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. 3. For the sake of comparisons, we considered both the MSE-directed algorithm reported here and an RSSI-directed algorithm, similar to that proposed in [3], with an adaptation coefficient equal to 10°. 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. 1. 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 three 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 τ_2-τ_1=50ns, and (θ_1, θ_2)=(30°, - 30°) pertain to the two directions of arrival, corresponding to the dashed lines in B, C and D. In the beginning of the phase adaptation procedure (after the selection of the "operating sector"), the radiation pattern of the "operating phased array" is as shown in B, and $|\alpha_1|^2 = 2|\alpha_2|^2 = P$. 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. 2-A and fig. 3-A (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, with a first choice of ray 1 (see C in both fig. 2 and fig. 3) and the choice of ray 2 (see D in the same figures) when this ray becomes the strongest one.

Second example

In this example, τ_2-τ_1=100ns and (θ_1,θ_2)=(20°,-20°), with $|\alpha_2| = |\alpha_1|$ and the same noise level in both array types. The evolutions of the "true MSE" are shown in fig. 4: 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.

Third example

In this example, τ_2=τ_1 and (θ_1,θ_2)=(20°,-20°) 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. 5. The much better performance with the MSE-adjusted array can be easily explained by observing fig. 6: 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.

4.2. Example on robustness against fading

An example is given in the following, so as to illustrate the advantages of the adaptive array antennas described in Sec. 3 over conventional switchable-beam antennas, with regards to the fading effects of multipath propagation.

The simulation scenario is somewhat 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=15m/s and, for a service bit rate of 20Mbit/s through "option ATM-2" (e.g. 16-OQAM scheme, etc.), 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. 1). 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. 7 and 8 allow a fair comparison between the adaptive array antennas and the switchable-beam antennas ($\overline{E}_b / N_0$ 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 adaptation procedure, a distance of 90m was supposed between the BS and the MS). 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 b switchable-beam approach *with* diversity.

5. FINAL REMARKS

The simulation results presented in Sec. 4-as well as other simulation results obtained so far, with the help of a reliable ray-tracing tool [5]- indicate that the adaptive antennas described in Sec. 3 (e.g. those employing the MSE-adjusted phased arrays) 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 adaptive antenna approach can be adopted for the base stations, leading to similar conclusions.

Acknowledgements

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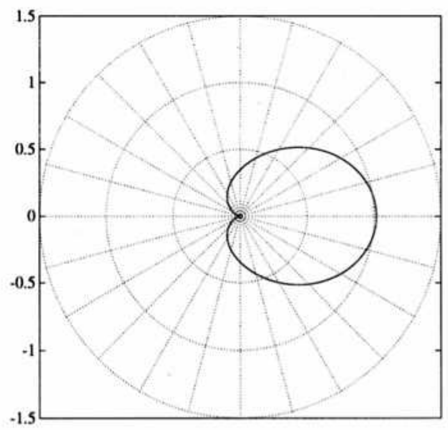

Fig. 1 - Radiation pattern (azimuth plane) of a phased array element.

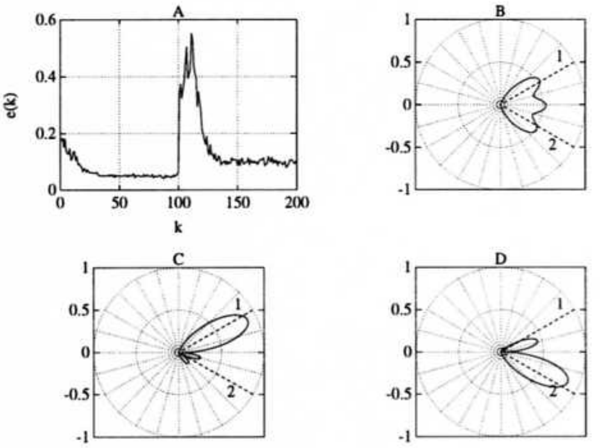

Fig. 2 - Adaptation behaviour with the RSSI-directed algorithm for the first example: evolution of MSE (A); initial radiation pattern (B); radiation patterns for k=100 and k=200 (C and D, respectively).

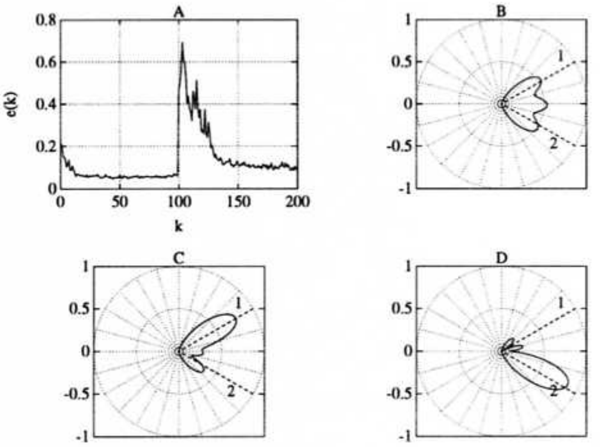

Fig. 3 - Adaptation behaviour with the MSE-directed algorithm for the first example: evolution of MSE (A); initial radiation pattern (B); radiation patterns for k=100 and k=200 (C and D, respectively).

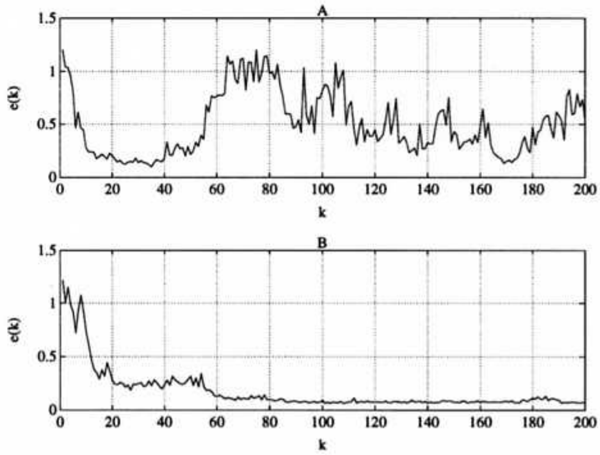

Fig. 4 - Performances with the RSSI-directed algorithm (A) and the MSE-directed algorithm (B) for the second example.

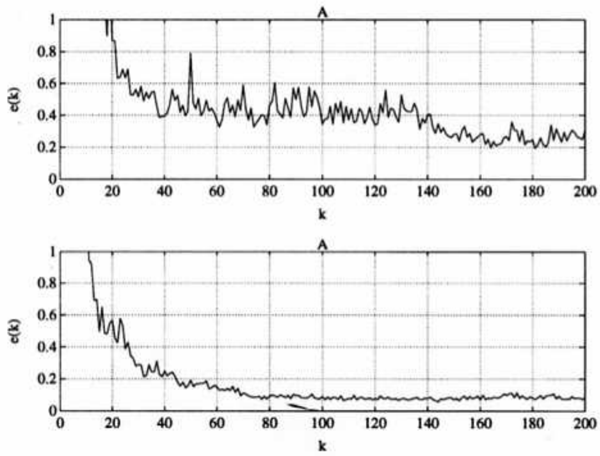

Fig. 5 - Performances with the RSSI-directed algorithm (A) and the MSE-directed algorithm (B) for the third example.

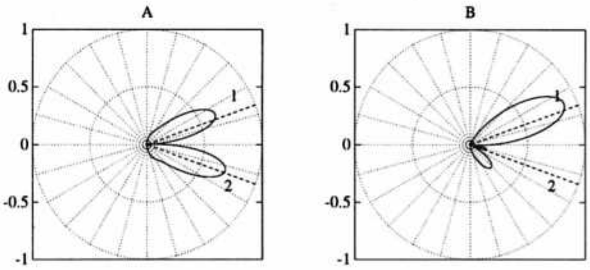

Fig. 6 - Radiation patterns with the RSSI-directed algorithm (A) and the MSE-directed algorithm (B), for k=200.

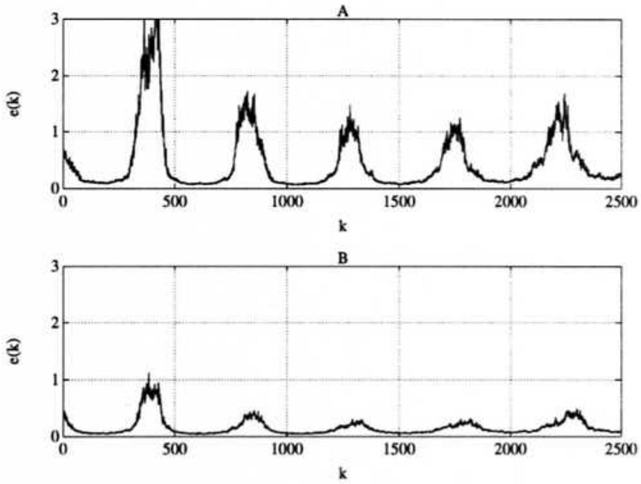

Fig. 7 - Performances for the switchable-beam scheme: without diversity (A); with "MRC" diversity (B).

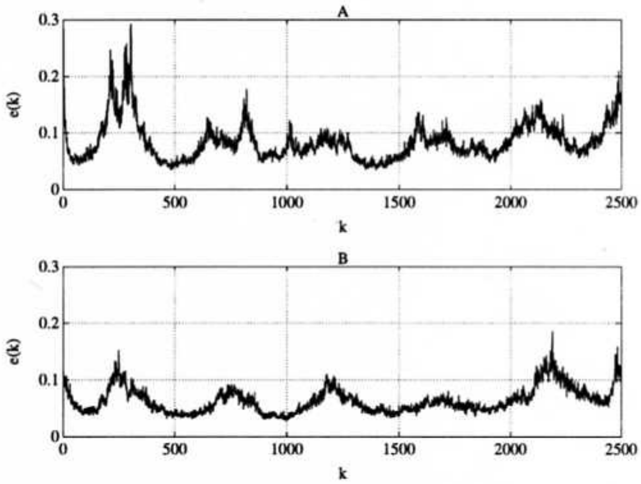

Fig. 8 - Performances for the phased array scheme: without diversity (A); with "MRC" diversity (B).