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## **UWB Spatial Multiplexing by Multiple Antennas and RAKE Decorrelation**

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# UWB Spatial Multiplexing by Multiple Antennas and RAKE Decorrelation

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## Abstract

An Ultra Wide Band (UWB) spatial multiplexing technique by Multi Elements Antennas (MEA) at the emitter side using ideal isotropic or biconical antennas is presented and analyzed in this paper. This work evaluates the performance of the demultiplexing process at the receiver side, as ensured by multiple parallel RAKE receivers in order to achieve channel decorrelation efficiently. The quality of signals restitution, the subchannels isolation caused by the selective RAKE combiners and the quality of the communication links are evaluated by a normalized similarity coefficient, an inter-channel interferences level ratio and a Bit Error Rate (BER) curve respectively. It appears that beyond a minimum value of the channel multipath density, the quality of the restitution does not depend very much on the latter if an adequate spatial diversity is satisfied. However the discrimination between signals becomes difficult for a large number of transmitting antennas. In addition the sensitivity of this scheme to the channel angular scenario is assessed. The BER has always a lower bound due to the neighbouring subchannels interferences which cannot be totally eliminated.

## I – Introduction

According to the Federal Communications Commission (FCC), one speaks of Ultra Wide Band (UWB) technology when the transmitted signals occupy a frequency band greater than 20 % of the central frequency or more than 500 MHz [1]. This large spectral band can combat the multipath effects of the radio channel. Because of the fast development of information systems and the explosion of radiocommunications, “complex” data (ex: audio or video data) and multi-users contexts have to be taken account for UWB services deployment. In consequence, UWB communication systems have to be able to hold a big quantity of information as quickly as possible. Generally speaking, it is necessary to operate with high data rate and all techniques for increasing data rate are welcomed. A multiplexing technique in spatial domain is one possible solution. Multi Element Antennas (MEA) have to be installed at both emission and reception side, leading to a Multiple Input Multiple Output (MIMO) system of several parallel subchannels [2]. We investigate here a partial (Multiple Input Single Output: MISO) solution, where only one antenna is installed at the receiver side. From the works of Weisenhorn and Hirt [3], it appears possible to successfully receive sequences of independent symbol transmitted simultaneously. In this paper, we try to see if the discrimination between the different transmitted signals is adequately ensured by several parallel RAKE receivers of reasonable complexity [4], for channels of realistic complexity including antenna effects or not. Insight is provided by the evaluation of the quality of the demultiplexing process through a normalized similarity coefficient between a demultiplexed signal and that which would be received for single isolated emission antennas. The subchannels isolation is also studied by defining an adequate quantity. Finally the multiplexing scheme performance is evaluated through simulations Bit Error Rate (BER) simulations. In what follows we will describe the multiplexing architecture principle involving RAKE combiners, then the radio channel model. In consideration of antennas effect, the employed antennas are suitably optimized bicones [5]. The quantities which measure the quality of signals restitution and the subchannels isolation are subsequently defined and the method to obtain the BER is explained, after which simulation results are

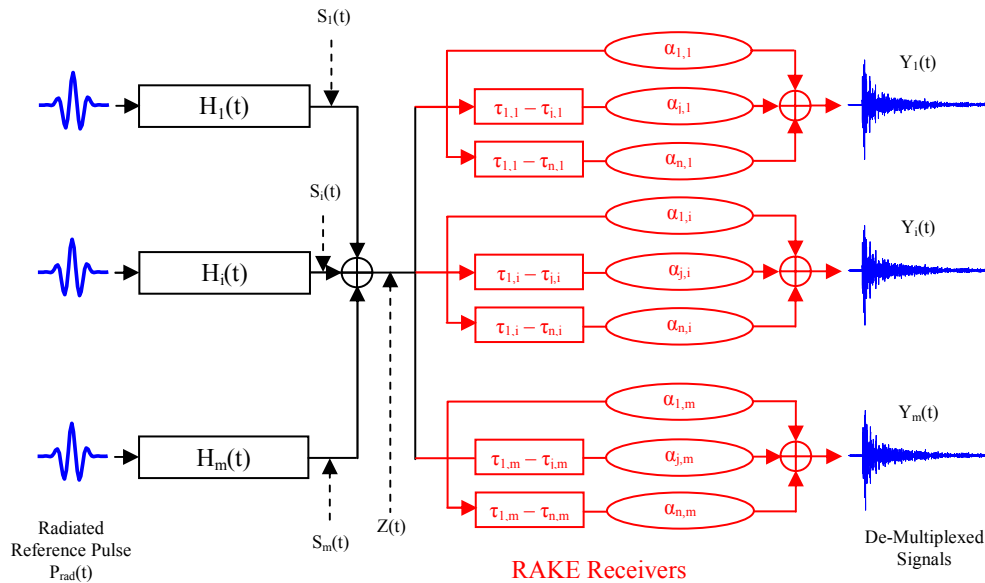
discussed. Finally, we conclude about the potentiality of this multiplexing method in UWB communications.

## II – System Description

In the scheme investigated here (Figure 1), there are  $m$  antennas at the transmitter side and one antenna at the receiver side. Each transmission antenna is related to the reception antenna by a Channel Impulse Response (CIR),  $H_i(t)$  characterizing the propagation environment,  $i$  being the antenna index. All antennas are assumed to radiate independent data flows in parallel using an identical FCC compliant pulse waveform  $P_{\text{rad}}(t)$  built from a cardinal sinus. The reception antenna captures a superposition  $Z(t)$  of the various transmitted signals  $S_i(t)$  affected by the radio channel:

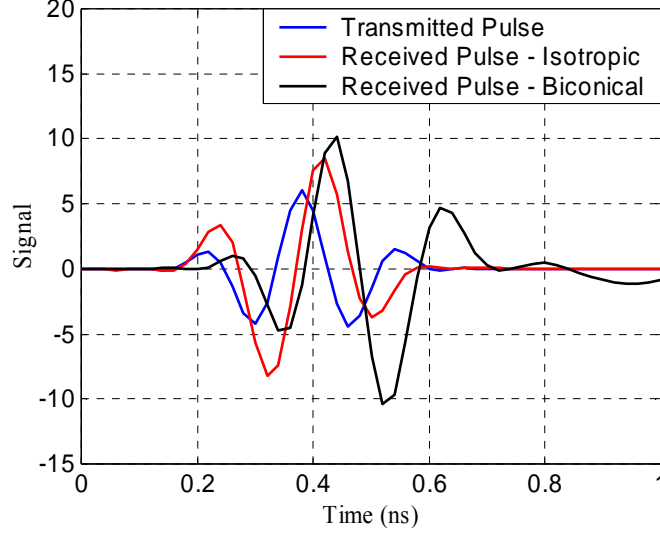
$$Z(t) = \sum_{i=1}^m S_i(t) \text{ where } S_i(t) = H_i(t) * P_{\text{rec}}(t) \quad (1)$$

$P_{\text{rec}}(t)$  is the received pulse waveform and is considered as the primitive of  $P_{\text{rad}}(t)$ :  $P_{\text{rec}}(t) = \int P_{\text{rad}}(t) dt$  if the antennas are ideally isotropic without frequency dependence. This property materializes the proportionality of the capture area to the squared wavelength, i.e. the inverse proportionality to the squared frequency (Integrating behaviour) [6]. These reference pulses are plotted in Figure 2. The received pulse is also plotted for a channel configuration with a biconical antenna [5] (with frequency dependence) at each end of the link.



**Figure 1: Multiplexing system with multiple RAKE receivers**

The discrimination between the different signals is ensured by  $m$  parallel RAKE receivers with  $n$  fingers, where the parameters of each RAKE stage are adjusted in order to combine received signals constructively according to the corresponding CIR  $H_i(t)$ .



**Figure 2: Reference Pulse Waveforms**

We can thus see the role of each RAKE receiver as a channel-specific equalizer, allowing to retrieve correctly only the nominal transmitted signal and to reject signal from the other parallel subchannels (Figure 1). The fingers delays  $\tau_{j,i}$  are calculated according to the  $n$  best peaks of  $|\gamma_{P_{rec}S_i}(\tau)|^2$  (selective RAKE).  $j$  is the fingers index and  $\gamma_{AB}(\tau)$  designates the crosscorrelation function between the functions  $A(t)$  and  $B(t)$ :

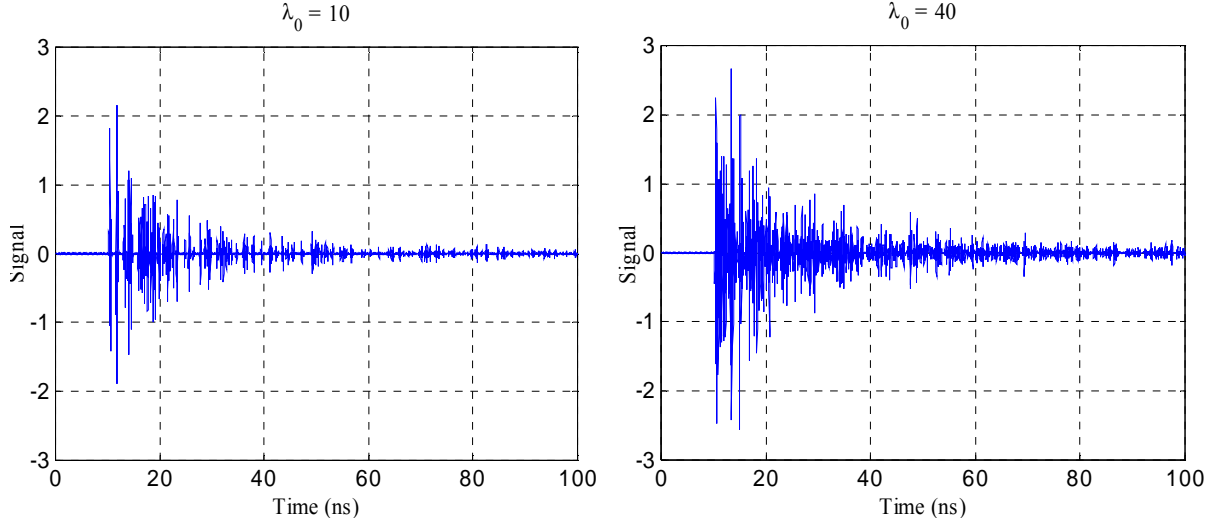
$$\gamma_{AB}(\tau) = \int_{-\infty}^{+\infty} A(t-\tau)B(t)dt \quad (2)$$

The weights  $\alpha_{j,i}$  have the same amplitude (Equal Gain Combining: EGC) and the signs are fixed according to a reference finger (finger 1). Destructive superposition is not possible. Although the received waveforms of the ideal and biconical antennas somewhat differ, we have constantly used the former as the reference template in the correlator. The emitted signals are expected to be retrieved on each RAKE output  $Y_i(t)$  expressed by:

$$Y_i(t) = \sum_{j=1}^n \alpha_{j,i} Z(t-\tau_{1,i}+\tau_{j,i}) \quad (3)$$

It is clear that this multiplexing technique is efficient only if the diversity at the emitter side is sufficient, the element antennas have to be sufficiently spaced i.e. the CIR have to be as different as possible. Indeed, all RAKE combiners must not have the same parameters, so that the differing data flows could be extracted. The propagation environment also has to be “rich” (many paths), in order to guarantee a strong channel decorrelation thanks to path diversity.

The channel model used in this work is based on a Poisson distribution of parameter  $\lambda_0$  for the multipath delays in 5 ns temporal sub-interval: the probability to obtain  $k$  echoes in each sub-interval is  $P(k) = \exp(-\lambda_0)\lambda_0^k/k!$ . The channel multipath density is thus controlled by this parameter  $\lambda_0$ . Some realizations of channel response to the UWB excitation presented in Figure 2 are plotted for  $\lambda_0 = 10$  and  $\lambda_0 = 40$  in Figure 3. The delays are uniformly distributed in each sub-interval. The amplitudes of the paths are distributed according to a Rice law. Firstly, the simulations will be performed with omnidirectional azimuth angular scenarios.



**Figure 3: Realizations of channel response to an UWB pulse waveform (omnidirectional scenarios and isotropic antennas)**

### III – Performance Evaluation

In order to evaluate the performance of the demultiplexing process, it is useful to define a quantity expressing the “similarity” between the true demultiplexed signal  $Y_i(t)$  from antenna  $i$  in presence of the interfering signals from the other transmitting antennas, and signal  $X_{i,i}(t)$  subject to its nominal RAKE processing but without the other antennas interfering signals. A normalized correlation (“similarity coefficient”) is thus defined as:

$$\Gamma_i = \frac{\max[\gamma_{X_{i,i}, Y_i}(\tau)]}{\sqrt{\max[\gamma_{X_{i,i}, X_{i,i}}(\tau)] \max[\gamma_{Y_i, Y_i}(\tau)]}} \quad (4)$$

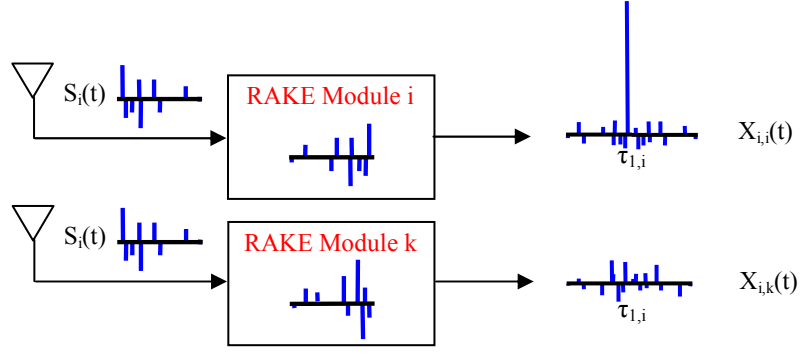
Ideally of course  $\Gamma_i$  should be equal to 1. Another issue is to ensure no crosstalk between the parallel multiplexed data flows. For this purpose, another quantity is now introduced in order to measure the isolation ratio (i.e. inter-channel interference ratio) between the various subchannels:

$$I_{i,k} = \frac{|\gamma_{P_{rec}, X_{i,k}}(\tau_{1,i})|^2}{|\gamma_{P_{rec}, X_{i,i}}(\tau_{1,i})|^2} \quad (5)$$

$I_{i,k}$  ( $i \neq k$ ) is the ratio between the power induced on the neighbouring subchannel  $k$  intended to the subchannel  $i$  and the power delivered by its nominal RAKE receiver.  $X_{i,k}(t)$  denotes the received signal  $S_i(t)$  from the antenna  $i$  in the case of a single emission antenna affected by the RAKE processing appropriate for channel  $k$  (Figure 4):

$$X_{i,k}(t) = \sum_{j=1}^n \alpha_{j,k} S_i(t - \tau_{1,k} + \tau_{j,k}) \quad (6)$$

$\tau_{1,i}$  is the delay introduced in the first branch of the nominal RAKE receiver and is also the instant where  $|\gamma_{P_{rec}, X_{i,i}}(\tau)|^2$  is maximal. We indeed consider that each receiver reconstitutes its nominal digital information sequence by a specifically synchronized detection.



**Figure 4: Sub-channels isolation ( $i \neq k$ )**

The BER performance of the multiplexing scheme is evaluated with a Binary Phase Shift Keying (BPSK) modulation, and is given by:

$$\text{BER} = \frac{1}{2} \operatorname{erfc} \left( \sqrt{\frac{|\gamma_{P_{\text{rec}}, X_{i,i}}(\tau_{1,i})|^2}{N_0 + \sum_{k \neq i} |\gamma_{P_{\text{rec}}, X_{i,k}}(\tau_{1,i})|^2}} \right) \quad (7)$$

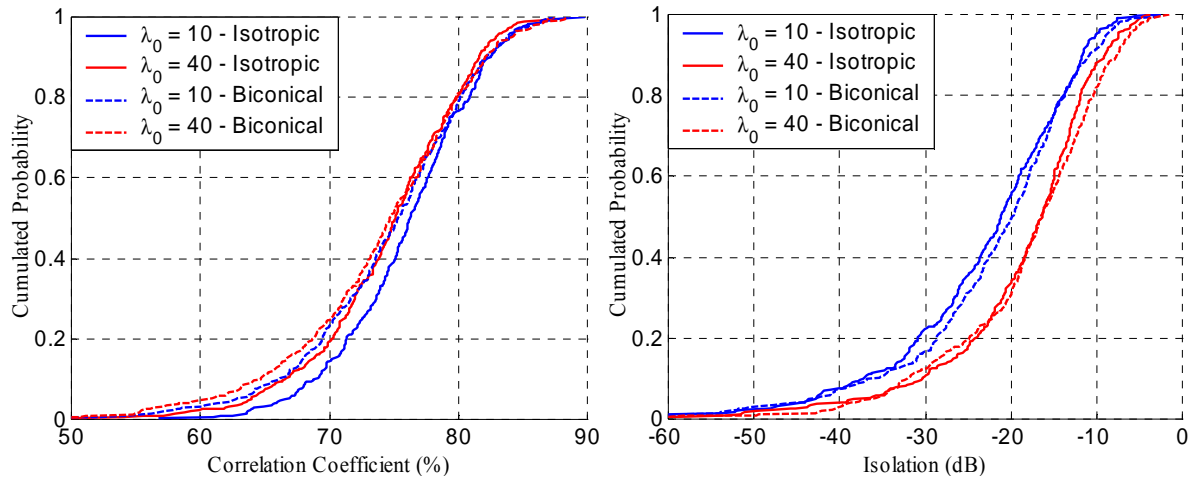
$N_0$  is the noise level and  $\operatorname{erfc}(\cdot)$  designates the complementary error function. The interferences coming from the other subchannels are considered to have the same statistical properties as the Gaussian noise. Several noise level  $N_0$  are considered leading to several signal to noise ratios (SNR):

$$\text{SNR} = \frac{\frac{1}{m} \sum_{i=1}^m \max \left[ |\gamma_{P_{\text{rec}}, X_{i,i}}(\tau)|^2 \right]}{N_0} \quad (8)$$

The numerator is indeed the received signal power level corresponding to the classical SISO configuration. It is taken as the mean received power for each subchannel. For several channel realizations, the mean of all BER curves will be analyzed.

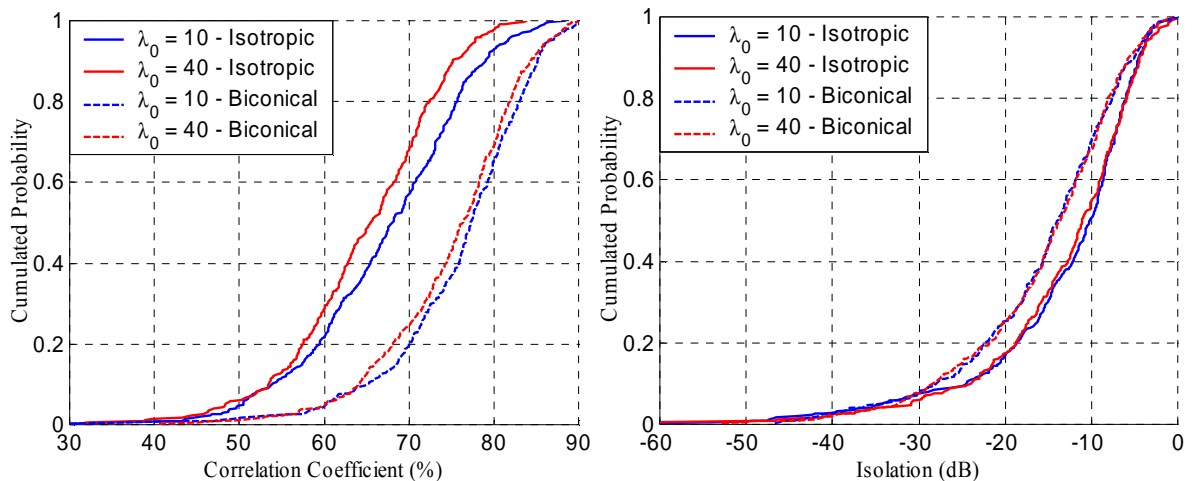
#### IV – Simulation Results

The Cumulative Density Functions (CDF) of the normalized correlation coefficients  $\Gamma_i$  and of the isolation  $I_{i,k}$  are plotted in Figure 5 for the case of 2 emission antennas spaced by a distance of 50 cm corresponding to a very good spatial diversity. They are computed for 200 channel realizations, the RAKE modules consisting of 10 RAKE fingers. No inter-antenna coupling is here presented. The electromagnetic interactions can be neglected at this distance whatever the antenna type.



**Figure 5: CDF of similarity coefficient and isolation (10 RAKE fingers – 50 cm spaced antennas)**

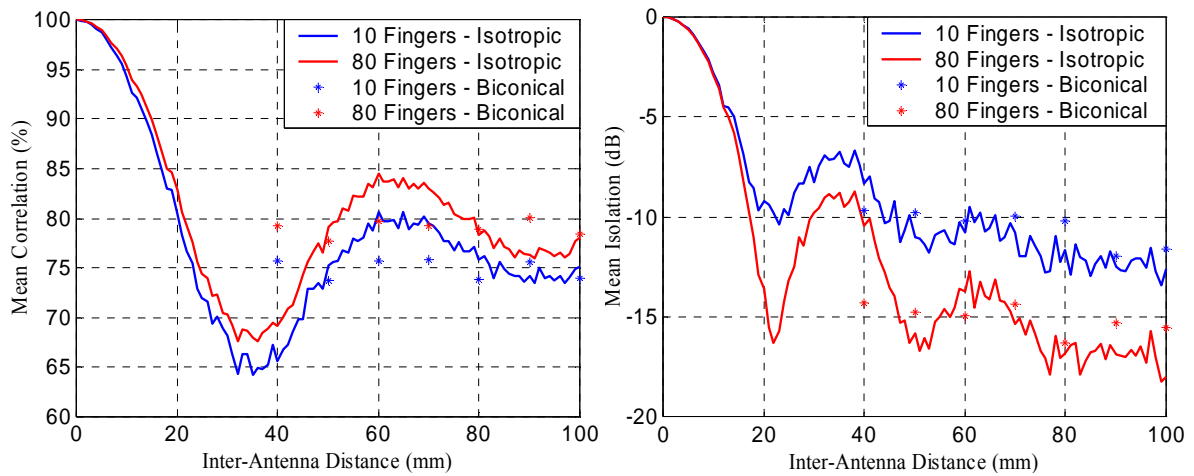
The performance of the demultiplexing is not dramatically influenced by the channel complexity, at least for the chosen parameters. It is stated that for a greater number of antennas, the correlation is clearly worse. Logically indeed, it is more difficult to extract a given data flow from the superposition of a larger number of data flows. There is more signal distortion in the case of a large number of paths due to more constructive or destructive (random) summations. In many cases, the isolation can be considered as good (Figure 5). Increasing the channel density leads to a worse isolation (more induced power in the neighbouring channels). This stems from the fact that a RAKE module grabs power from as many paths as fingers. Increasing the number of paths degrades the RAKE decorrelation, if the number of fingers is not correlatively increased. There is not much difference between both antennas at this large spacing.



**Figure 6: CDF of similarity coefficient and isolation (10 RAKE fingers – 4 cm spaced antennas)**

Figure 6 shows the computed CDF of the demultiplexing quality  $\Gamma_i$  and the isolation ratio  $I_{i,k}$  with closely spaced antenna arrays at the emission side (inter-antenna distance = 4 cm) where spatial diversity is low and mutual coupling is high inside the biconical antenna arrays. The channel density here plays a more important role with respect to the similarity coefficient and it appears to be worse than the results in Figure 5 for the case of isotropic antennas and

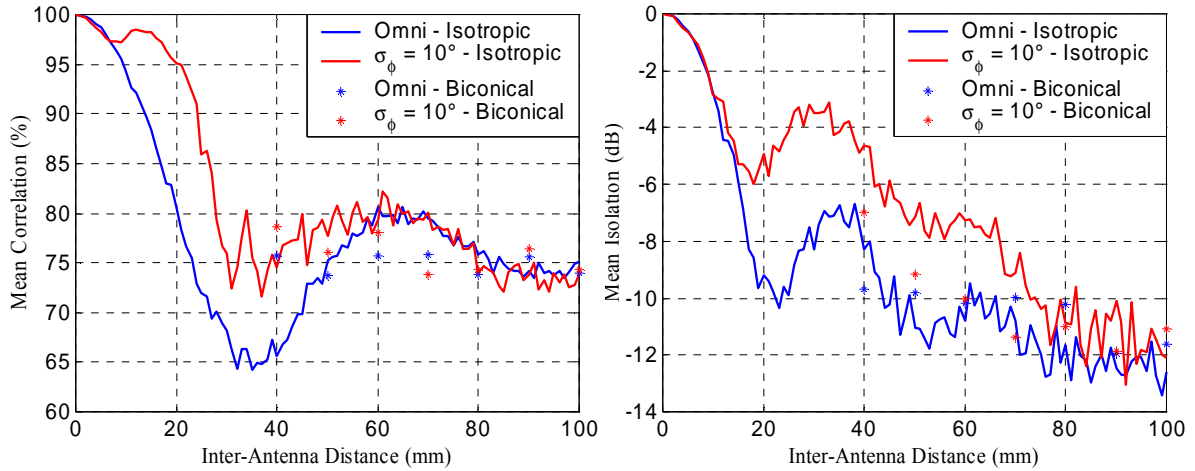
approximately equal for the case of biconical antennas. Additional pulse superpositions are due to the fact that the CIR are approximately the same because of low diversity, i.e. the paths in each CIR have approximately but not exactly the same positions in time. Creating diversity by increasing the number of paths leading to a supposed more complex environment does not improve the demultiplexing quality, because this results in distortion at reception. Concerning the isolation, it is also worse and obviously results from the resemblance between the CIR of the various subchannels. We can notice that the biconical arrays give better performances both in terms of restitution and isolation. Indeed mutual coupling can create CIR diversity resulting in different radiation pattern of each element. No strong influence of the channel density on the isolation can be observed. The RAKE modules have approximately the same configuration whatever the channel complexity leading to the same proportion of induced power.



**Figure 7: Influence of the inter-antenna distance on the similarity and the isolation ( $\lambda_0 = 10$  - 2 antennas)**

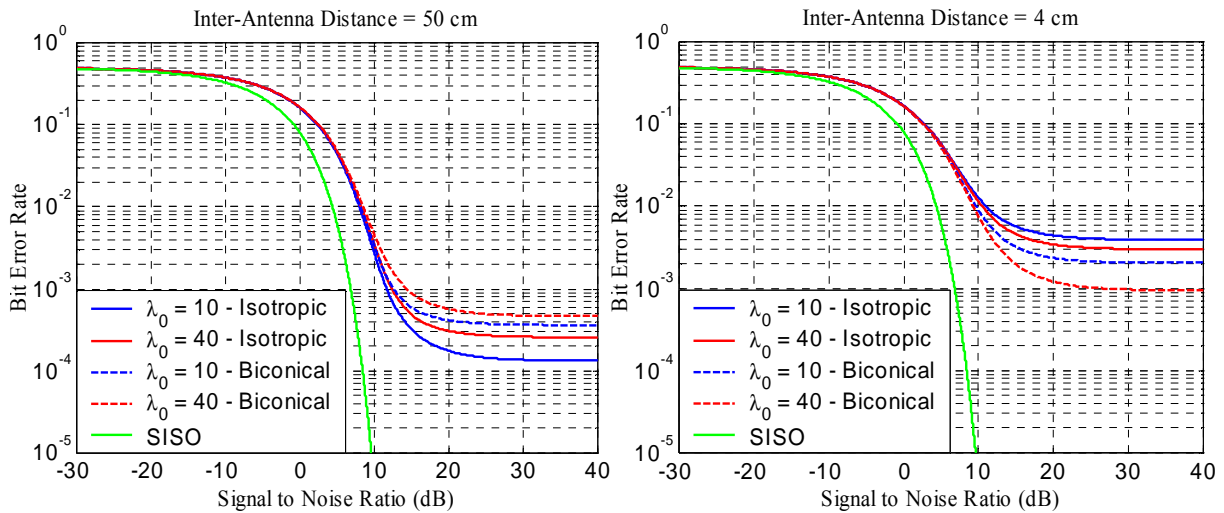
Figure 7 illustrates the mean similarity coefficient  $\Gamma_i$  and the mean isolation ratio  $I_{i,k}$  as a function of the inter-antenna distance in the case of the two types of antenna. Due to their size, the biconical antennas cannot be spaced by less than 40 mm. The value 100 % of the correlation coefficient is logically attained with isotropic antennas and a distance of 0 mm but has no interest since obviously no multiplexing is possible ( $I_{1,2} = I_{2,1} = 0$  dB). Increasing the number of RAKE fingers enhances the similarity coefficient and reduces the isolation ratio but there is probably a limit. The shape of the similarity curves appears to be linked to the pulse temporal waveform  $P_{rec}(t)$  as the distance is related to the time delay. Indeed, a distance where the correlation is minimal corresponds to a time interval between a positive peak and a negative peak of the pulse (destructive superpositions, implying distortions). A maximum of correlation can be attributed to a time interval between two peaks of the same sign (no deformation). These curves are calculated for an omnidirectional angular scenario. The statistics of the delay between received signals are not the same with directional scenario. We can observe dips in the isolation curves at certain distances. These dips can be associated to a temporal interval between a peak and a zero of the pulse  $P_{rec}(t)$ . Thus, to obtain a satisfying isolation between subchannels, it is not necessary to choose a large inter-element distance. Nevertheless it is shown below that these curves are also sensitive to the channel properties. If biconical antennas are employed, the inter-element distance has no importance both in terms of similarity and isolation. As we have seen, mutual coupling can enhance the CIR diversity (by decreasing the inter-element distance). Otherwise, improving the inter-element distance

can also enhance the CIR diversity by spatial decorrelation. From these facts, the diversity level may be the same.



**Figure 8: Influence of the angular spreading (2 antennas – 10 RAKE fingers –  $\lambda_0 = 10$ )**

Figure 8 shows results obtained for various angular scenarios,  $\sigma_\phi$  being the standard deviation. The mean azimuth angle  $\phi$  is randomly distributed on the range  $[0^\circ-360^\circ]$ . As we can expect, the decreasing of the isolation ratio with the distance is worse if the scenario is directional due to more resemblances between the CIR. The demultiplexing quality is better in the range  $[7\text{ mm}-60\text{ mm}]$  but has no interest because of worse isolation. For inter-antenna distances greater than 60 mm, the angular spread has no visible effect on the similarity. The inter-antenna distance has also no influence with biconical antennas. The directionality on the scenarios does not affect the diversity introduced by inside electromagnetic interactions.



**Figure 9: Bit Error Rate (10 RAKE fingers – 2 antennas spaced by 50 cm/4 cm: top, and 1 antenna: bottom)**

Some BER curves for a BPSK modulation are plotted in Figure 9 for omnidirectional scenarios of propagations. In the MISO configuration, the emitted power by each antenna is divided by 2 to obtain the same radiated power level as the SISO case. In consequence, a 3 dB shift between the SISO and MISO curves appears if the noise level is important. We can clearly see the lower bound of the BER in the 2 transmit antennas case due to co-channel

interferences. In MISO multiplexing systems, it is clearly preferable to investigate isotropic antennas and large spacing distances. Electromagnetic interactions in arrays of biconical antennas are weak at this distance but have visible effects in the BER curves. Under dense channels, the interference power is greater leading to worse BER in the absence of noise. If the emission antennas are closely spaced, better performances are obtained with a dense channel and biconical antennas. Diversity of the CIR results from different radiation patterns of the biconical antennas as we have seen.

## **V – Conclusion**

A multiplexing/demultiplexing technique in the spatial domain employing MEA and RAKE receivers was presented, and its performance in terms of demultiplexing quality, subchannels isolation and communication quality was analyzed. We have seen that the number of antennas needs to be moderate in order to obtain a good demultiplexing performance while avoiding excessive complexity of the multiple RAKE receivers, which will limit the multiplexing gain. A sufficient number of fingers in the RAKE stages is necessary for adequate demultiplexing. The CIR also have to be as different as possible, which implies a sufficient spacing of antennas particularly in the case of directional angular scenarios with isotropic antennas. The demultiplexing quality as a function of the distance is also linked to the pulse waveform. The distance has to be chosen at best in order to avoid destructive superpositions, while taking into account the scenario angular characteristics. The curves of isolation ratio versus the distance exhibit several dips (omnidirectional scenarios). In consequence, a very large distance between the antennas is not indispensable to obtain a good isolation. The transmission array design has to optimize at best the trade-off between demultiplexing quality and subchannels isolation. In the case of biconical antennas, the inter-element distance has no influence in closely spaced arrays. The BER is always limited by the other subchannels crosstalk (reducing the noise become useless). A low channel density is favourable for the BER if the antennas are largely spaced. In the contrary case, the BER can be reduced by introducing biconical antennas and denser channels.

## **Acknowledgements**

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