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MIMO diversity for ultra wide band communications

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Abstract

The development of Ultra Wide Band (UWB) communications is impeded by the drastic transmitted power limitations imposed by regulation authorities, due to the "polluting" character of these radio emissions with respect to existing services. Technical solutions must be researched in order either to limit the level of spectral pollution by UWB devices, or to increase their reception sensitivity. In the present work, MIMO diversity is investigated as one such possible solution. We propose a few MIMO operating principles, allowing to benefit from an $N_t \times N_r$ diversity order, either to enhance the link range, or to reduce the total UWB emitted power. These approaches are tested by simulations using a parametric empirical stochastic channel model. They confirm the potential interest of MIMO solutions, even for "difficult" UWB channels.

I Introduction

UWB technologies are among the "hot topics" in the present days, as their specificities are promising for future communications or positioning applications. Extremely cautious regulations are expected however, due to the wide emitted radiation spectra which ignores the numerous protected bands. The latter exist for a great variety of scientific, public or commercial services, and particularly sensitive to electromagnetic pollution are those requiring very low noise levels (spatial scientific services, fixed wireless access, GPS ..). The FCC for instance imposes to indoor communications a maximum EIRP of -41.3 dBm/MHz between 3.1 and 10.6 GHz, and much less outside this band. Although this is still a subject of debate, European authorities will probably adopt conditions at least as stringent as the FCC. In spite of the numerous advantages of UWB, the transmitted power, at most -2.6 dBm but likely several dB less, will thus tend to limit applications to relatively short ranges, or to moderate data rates. It is therefore crucial to develop solutions making the best possible use of the radiated and received power, for the feasibility and the future commercial success of UWB communications systems.

In the present work we address Multiple Input-Multiple Output (MIMO) diversity, as one possible solution to improve the UWB link robustness, or its range. MIMO techniques for UWB have recently been investigated in the context of space-time coding for pulse position modulations [1]. Here we consider 3 kinds of approaches employing multi-element antennas at one or at both sides of the radio link. They are:

- Switched beam (angular) diversity on the receive side. This brings diversity gain.
- Switched beam diversity on the transmit side. Usually this would be considered to bring diversity gain also. However on account of regulation issues, it is probably more appropriate to keep the Equivalent Isotropic Radiated Power (EIRP) constant, which

means a smaller total emitted power with respect to a single antenna and therefore less electromagnetic "pollution".

- Spatial diversity on the receive side, or on the transmit one, or on both, using several combining schemes. In this case the antenna elements are basically omnidirectional, and combining at transmitter or receiver reduces the emitted power or enhances the received signal to noise ratio.

The pertinence of these approaches in a practical radio link is here tested by simulations. Two important issues are to be highlighted:

- The signal waveform, which will determine the bandwidth and spectral content, and will strongly affect the fading behavior of the radio link. We used a waveform specially determined to comply with FCC regulations for indoor communications.
- The channel model, which will obviously affect the link quality to a great extent. We used a stochastic Monte-Carlo channel model based on the definition of multipath amplitudes, delays, directions of departures (DOD) and directions of arrival (DOA), according to given statistical distributions.

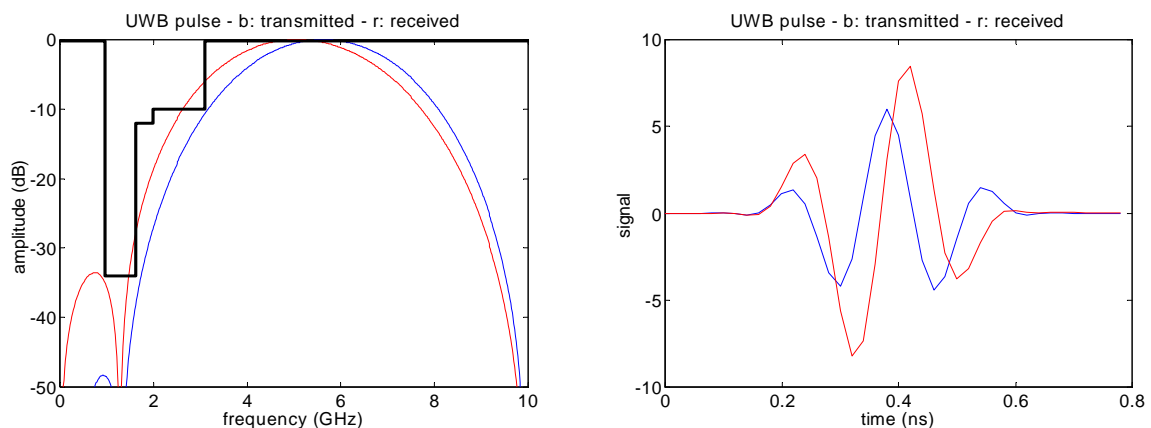


Fig. 1: left: spectra of the transmitted (blue) and received (red) signals; black: FCC mask; right: temporal waveforms

II Signal waveform and channel model

II-1 Signal waveforms

FCC issued on 14 february 2002 an authorization for UWB devices intended for a few applications, among which indoor communications. The FCC requires the EIRP to be at most -41.3 dBm between 3.1 and 10.6 GHz, and much less outside this range. This imposes a particular care to be exerted by designers of transmitters, in order to respect this spectral mask. We use here the spectral transmission waveform shown below, which was constructed from an initial rectangular spectrum (*sinc* function in the time domain), properly windowed.

Regarding the received signal, it should first be recalled that an "ideal" antenna, i.e. an antenna with constant complex gain irrespective of frequency, which is non dispersive (i.e.

phase linear vs. frequency) has an effective receiving area scaling with the wavelength squared. This means that for a flat transmission spectrum, the received spectrum has a fundamental downward slope of -6 dB per octave (fundamental receiving antenna filtering). In the plot below, this appears as a shift of the peaked received spectrum towards low frequencies, as compared to the transmitted spectrum. According to the parameters chosen for the simulations, the transmitted half-power bandwidth is 2.81 GHz, and the received half-power bandwidth is 2.94 GHz. The corresponding temporal waveforms are also shown, within a total duration of 0.8 ns. It is possible to find waveforms that make a better use of the spectral mask, however the duration of the pulse will generally increase because of Heisenberg relation.

II-2 Channel model

We use a space-variant discrete channel model. For a given position of the receiving and transmitting antennas, the channel is described as a discrete sum of paths, each characterized by its delay, its amplitude, its DOD and its DOA.

As compared to more usual wideband channel models, the present model has the following differences:

- Since we deal with *real* and not complex signals, the Channel Impulse Response (CIR) is real as well and not complex. This means in particular that the path amplitudes are real, positive or negative. According to physical intuition, the signs and amplitudes of the received paths are related to the elementary events experienced by the pulsed waves, i.e. specular metallic reflections, diffraction, transmission etc ...
- We expect a much greater number of paths, due to the extremely large bandwidth. The multipath density has been experimentally ascertained [2].

This model in particular assumes an identical number of DODs and DOAs, for a given channel realization. This is an approximation of possible reality, since "path junctions" may exist in certain circumstances, and eventually lead to keyholes [3].

The statistics and related parameters of path amplitudes, delays, DOD and DOA is obviously a crucial issue for the pertinence of the channel model. Here we have made the following assumption:

- Path delays are distributed according to a Poisson law in fixed delay bin durations, with a decreasing parameter as a function of the bin number. This allows to account for the rarity of significant paths with increasing delays.
- Path amplitudes are governed by a Ricean distribution, whose K factor is randomly generated within certain limits (uniform law); the signs of path amplitude are also randomly chosen (uniform law).
- Path DOAs and DODs are governed by a gaussian distribution in both azimuth and elevation

For a given channel realization, the knowledge of DOAs and DODs for each path allows to compute the additional path delay when either the transmitting or the receiving antenna is moved (small antenna approximation). This property will be used to compute the channel

variation from one sensor to another in an array, or from one antenna position to another intended to generate a large statistical set of channels.

In the simulations shown below, a few channel sets considered interesting to test the behaviour of multi-element UWB antennas have been generated, according to the following approaches:

case 1: channel with little temporal dispersion (well separated paths), and little azimuth angular spreads (10° standard deviation).

case 2: channel with little temporal dispersion but large azimuth angular spreads (60° standard deviation).

case 3: channel with strong temporal complexity (many close paths) and small azimuth angular spreads (10° standard deviation).

case 4: channel with strong temporal complexity and large azimuth angular spreads (60° standard deviation).

In all cases the elevation angular spread was kept constant (10° around 0°).

An example of a case 4 channel is shown in Fig. 2, both for the (infinite bandwidth) discrete path amplitudes, and for the finite bandwidth case when the transmitted waveform is filtered by the channel. It can be seen in the zoomed inset, that the signal waveform may strongly depart from the ideal received signal waveform of Fig. 1.

II-3 antennas

In the simulations, two types of "generic" elementary radiators/sensors were considered (see Fig. 3):

- an omnidirectional doublet-like elementary radiator, with a synthesized, real, frequency-independent radiation pattern (gain 1.7 dBi). Such an element was used as a reference radiator for SISO and SIMO schemes, and also within a circular array for SIMO and MIMO schemes. In this case, we assume that the radiating elements within the array are electromagnetically uncoupled, which is a realistic assumption even in UWB [4].
- a directional element for beam-switched SIMO or MIMO schemes, with the same elevation dependence as the doublet, and an azimuth dependence constructed by cubic interpolation over 5 points: the beam steering angle, the two half-power angles of the beam, and the beam boundaries where the gain cancels. The total beam width was chosen to be twice the half-power beam width in order to represent a realistic switched beam antenna, although secondary lobes are neglected however. We find a relative antenna gain comparing well with the ideal case of a perfect beam-switched antenna, i.e. for which the extra gain offered by beam formation is equal to the number of beams (e.g. 6 dB higher than the omnidirectional radiator for a 4 beams antenna).

Infinite BW amplitude Impulse Response - delay spread: 4.8711 ns

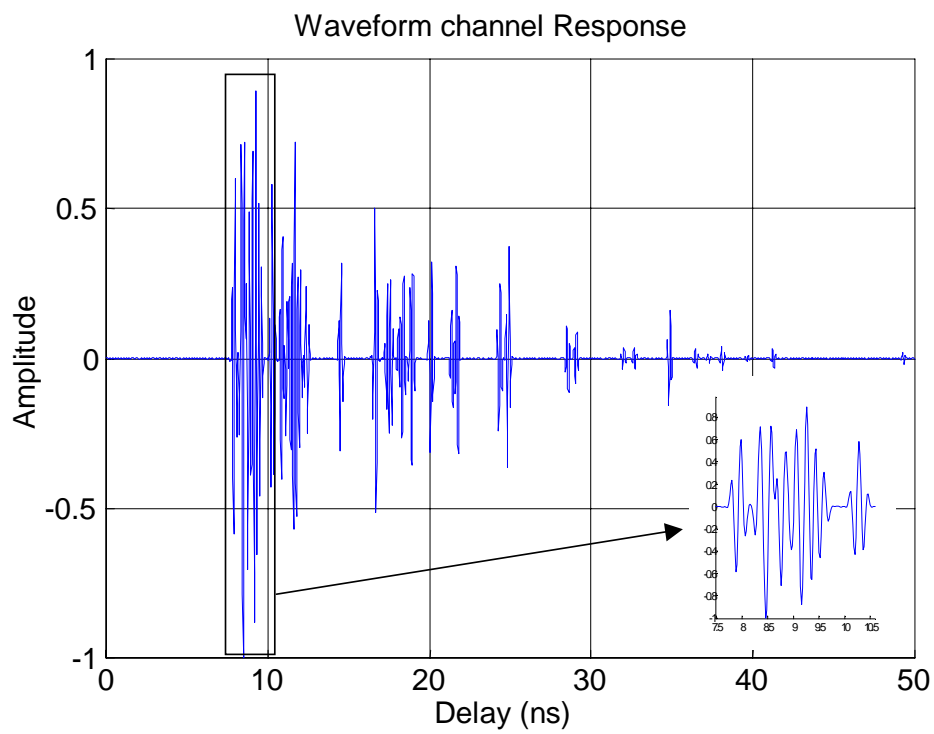
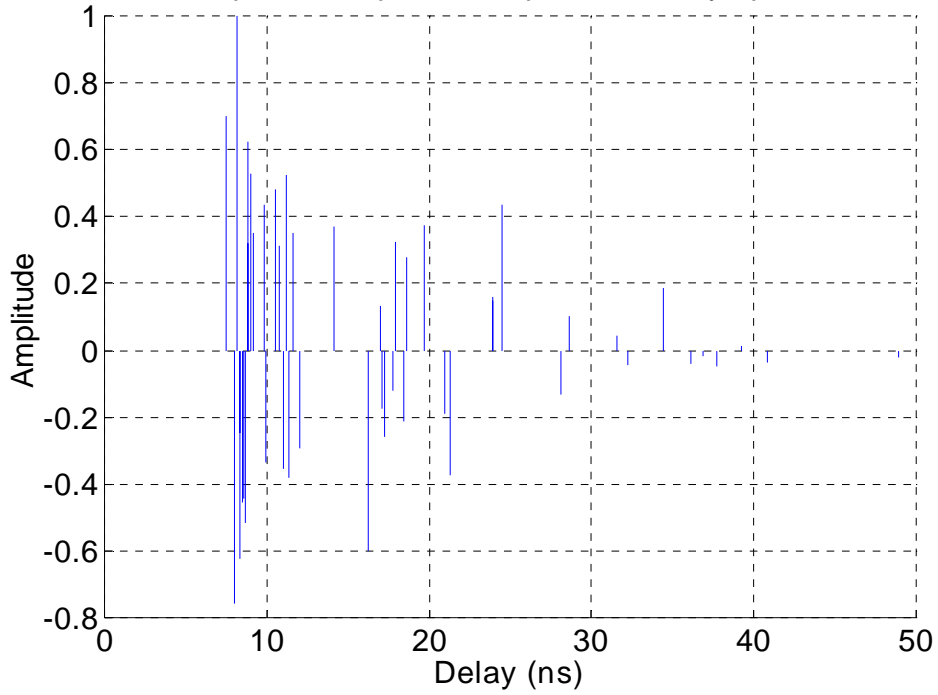


Fig. 2: example of a highly time-dispersive UWB channel (case 4 channel); up: infinite bandwidth; down: received signal resulting from the waveform filtered by the channel

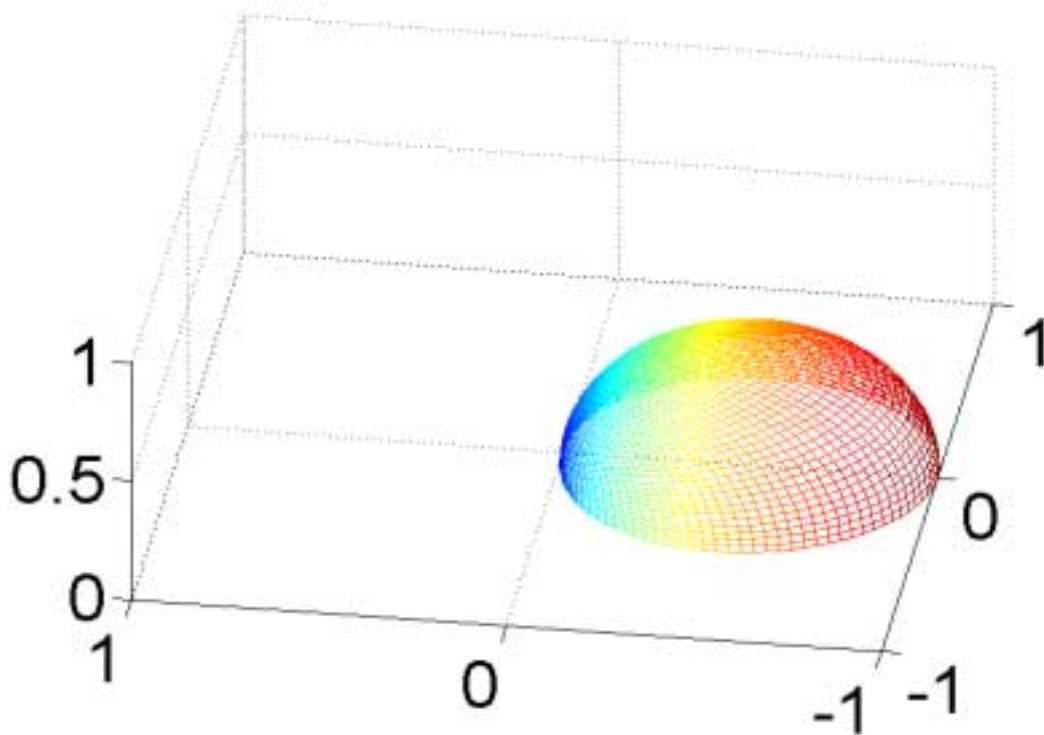
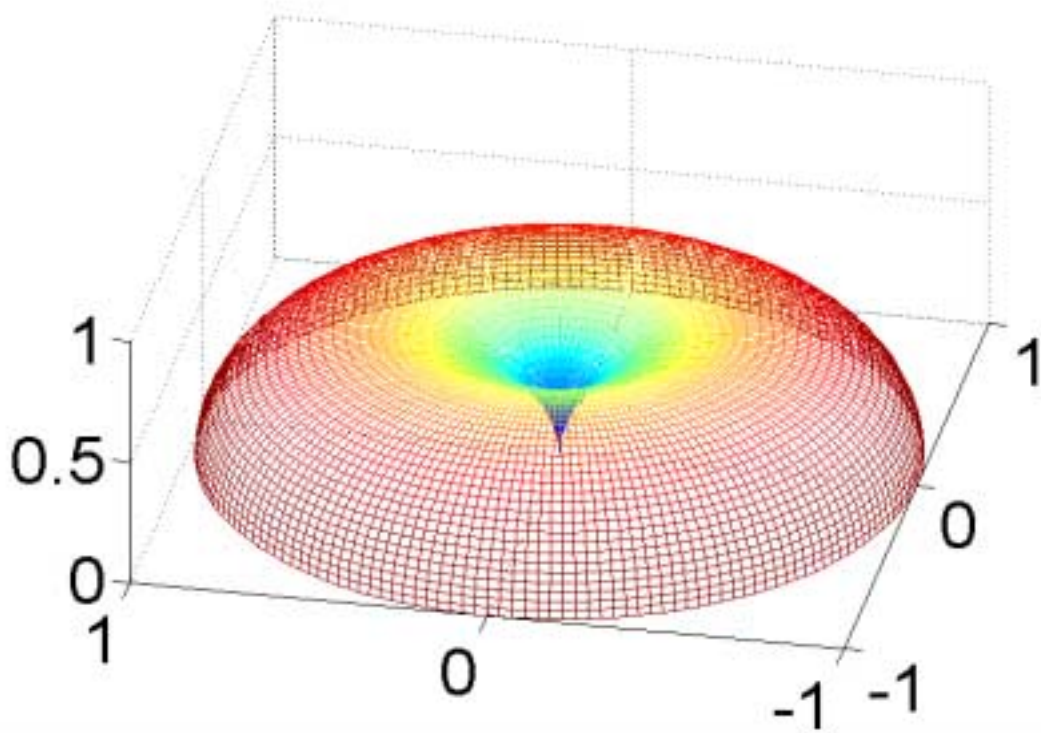


Fig. 3: "generic" sensors radiation patterns: omnidirectional (left) and directional (right; 90° half-power beam width for use in a 4 sensors circular array)

III SIMO and MIMO schemes

The transmitted pulsed waveform is expected to be considerably deformed by the propagation events, due to the dispersive character of the channel. At the receiver, the resulting signal is an addition of attenuated and time-delayed replica. This results in a received waveform which can considerably depart from the original one. We here consider a receiver architecture based on the existence of a correlator, where the received signal is correlated with the waveform which would be obtained with an ideal channel (i.e. taking into account the fundamental receiving antenna filtering). We restrict ourselves to a perfect synchronisation process, where the maximum absolute correlation is researched over the whole duration of the impulse response. In addition, we take advantage of the perfect reciprocity of the channel, assuming a perfect identity of the transmitted signals by the two radio equipments in the channel acquisition phase. This allows for instance to consider that downlink synchronisation is equivalent to uplink synchronisation.

The following SIMO and MIMO schemes are considered:

- Switched beam (angular) diversity on the receive side. In this case the transmitter antenna is a single omnidirectional radiator, and the receiving antenna is composed of as many sensors as the number N_r of beams, each beam having a half-power width of $360^\circ/N_r$. We optimistically expect the radio link to be improved by a diversity gain linear with N_r , and at best equal to it. This can be obtained only when the received waves are very closely aligned with the beam maximum, which obviously cannot be always achieved. One purpose of this work is to investigate what happens when the channel temporal and angular complexity is such that the received waveforms are intricately different from the nominal one.
- Switched beam diversity on the transmit side. This scheme may appear quite symmetrical from the previous one and therefore solely used to bring additional diversity gain. Although true, let us remember that regulations generally impose a maximum EIRP, which means that the total radiated power has to be reduced in the presence of antenna gain. Therefore the main exploitation of switched beam diversity on the transmit side is by reducing the total emitted power, undoubtedly an appealing advantage in the sensitivity context of electromagnetic pollution regarding UWB regulation in Europe and elsewhere.
- Switched beam diversity on both sides. In this case all radiator/sensor combinations in the arrays are considered, meaning a number $N_t \times N_r$ of evaluations of the channel matrix.
- Combining (spatial) diversity on the receive side, or on the transmit one, or on both. Synchronisation in the particularly complicated MIMO case is assumed in the following way:
 - the best correlation is obtained on a reference radiator/sensor n_{t0}/n_{r0} pair, both acquired by the nominal transmitter (in an acquisition phase where it would receive a signal emitted by the nominal receiver) and by the nominal receiver .
 - subsequently the best correlations for the n_t/n_{r0} channels are acquired, i.e. the nominal receiver sends an acquisition signal on n_{r0} , and each n_t antenna acquires the best synchronisation.

- subsequently the best correlation for the nr/nt_0 channels is acquired, i.e. the nominal transmitter sends an acquisition signal on nt_0 , and each nr antenna acquires the best synchronisation.
- finally both the transmitter and the receiver synchronize the signals of their radiators/sensors, and the communication link is established.

Such a protocol is probably sub-optimal, since the best correlation for a nr/nt pair is deduced from the synchronisation delays of nr/nt_0 and nt/nr_0 , which is only an approximation particularly in the presence of interacting multipaths. There is indeed no reason to think that these delays are additive, since they are not linear functions of the sensor number. This sub-optimality can be envisioned in a more rigorous manner: let us consider the simplest 2x2 MIMO UWB channel (Fig. 4), where propagation delays are τ_{ij} for the radiator i to sensor j link.

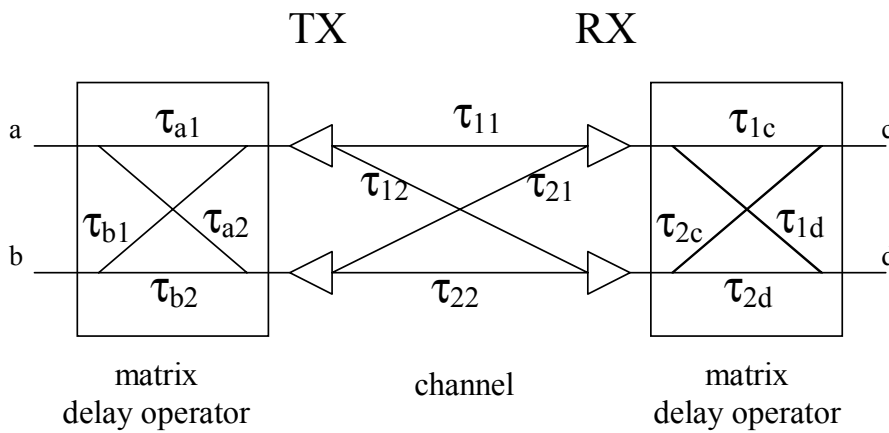


Fig. 4: hypothetical synchronisation by matrix delay operators of a channel of pure Dirac delay operators (does not work !)

We may imagine a perfect combining synchronisation scheme where two transmitted signals a and b would go through a matrix of delay operators, then through the channel, then through a second matrix of delay operators (Fig. 4), in such a way that all paths from a to c , a to d , b to c , b to d would be perfectly synchronised. However this is impossible, since it would imply $\tau_{11} + \tau_{1c} = \tau_{12} + \tau_{2c}$, i.e. $\tau_{11} - \tau_{12} = \tau_{2c} - \tau_{1c}$, but also $\tau_{21} + \tau_{1c} = \tau_{22} + \tau_{2c}$, i.e. $\tau_{21} - \tau_{22} = \tau_{2c} - \tau_{1c}$. Obviously these two requirements are contradictory as the channel delays are in general unconstrained.

We consider the following combining schemes:

- simple resynchronisation; i.e. the transmitted and received signals in the transmitter/receiver are simply added.
- resynchronisation and polarity correction; in this case the transmitted and received signals within the transmitter and the receiver are added after correcting for the sign of the best correlation found with the reference signal. Such a correction may be expected to be useful on account of the randomly positive and negative multipath amplitudes; a correlation signal on one nr/nt pair may destructively interfere with another, implying lower and not better combining performance of

the simple synchronisation scheme. This scheme corresponds in narrowband systems to “equal gain combining”.

- same scheme as above, with a correction factor equal to the ratio of the maximal correlation value to the correlation achieved for the reference n_{t0}/n_{r0} pair. This is a maximal ratio combining (MRC) combining scheme, which is known to be optimal for Rayleigh faded signals.

IV Results

In the simulations, all the schemes devised in section III will be compared, for all statistical set of channels devised in section II-2. Each of these sets contain 100 Monte-Carlo random realizations of the channel, and for each of them 4 positions of the Rx antenna on corners of a 10 cm square have been defined ("small-scale" statistics).

In all cases we compare the squared best correlation over combined noise ratio, to the one obtained in the SISO conventional scheme. This yields a gain, expressed in dB. The noise power is the sum of the receiver noise powers (assumed identical for all receiving sensors), eventually corrected for the square of the weighting factor (MRC).

Let us first concentrate on switched beam algorithms. In this case the simulations assume the array radius to be zero. Although this is unrealistic in practice (angular diversity is to some extent accompanied by spatial diversity due to non coincident phase centers [5]), this will allow to evaluate the effectiveness of angular diversity alone.

In the case of a 1x4 SIMO $N_t \times N_r$ architecture, we see that the diversity gain ranges between about 3 and 6 dB, the latter being the maximum gain we expect from this scheme as explained above. There is no great dependence on the channel type, which means that even in the case of an angularly and temporally dispersive channel the algorithm succeeds in achieving gain. Lesser improvement is therefore due to the sub-optimality of the discrete beam number, in other words the algorithm performance is limited by the discrete beam steering capability.

It might be questioned why in certain cases better than 6 dB gain is achieved. This is due to the fact that for certain channel realisations and antenna positions, the SISO correlation is not maximum, due to peaks of the CIR interacting within the pulse duration itself (deformation of the received pulse). In this case in addition to the 6 dB angular diversity gain, we may get more if the best beam reduces this deformation. Interestingly the effect is enhanced for the worst channel, as we may expect since such situations where the SISO channel is poor are more common. Actually this is simply the manifestation of fading, which although much less important in UWB than in narrow band, may still be present for particularly "complicated" channels with small delays between successive paths.

We basically find the same result in the case of the 4x1 architecture, i.e. the maximum gain is about 0 dB, going down to -3 dB typically in the worst case. Let us again state that since each beam has 6 dB antenna gain better than the omnidirectional radiator, the total emitted power is 6 dB less. Therefore the net diversity gain of this 4x1 switched beam scheme ranges between 3 dB and 6 dB, which is logically equivalent to the 1x4 architecture. There is no reason why it would not be the case, due to the symmetry of this scheme. Actually we can

recover a gain between 3 dB and 6 dB together with a power reduced by 6 dB, through a more complex 4x4 architecture (see below).

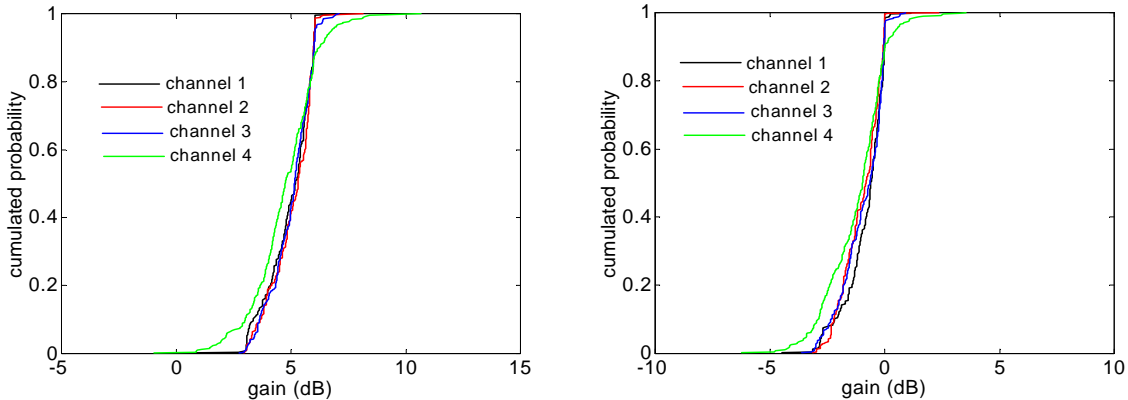


Fig. 5: beam switched scheme; 1x4 architecture (left) and 4x1 architecture (right)

Let us now compare beam-switched and the various combining schemes. In this case multi-element antennas are circular arrays of diameter 10 cm. This is considered large enough to provide effectively spatial diversity in indoor environments, and appears realistically achievable for certain UWB equipments.

It can be seen that for the best channel (channel 1: small angular and temporal complexity), any combining scheme performs much better than the switched beam case, and is close to the ideal.

However in the case of a time dispersive channel (channel 3 or channel 4), the situation changes somewhat, since the diversity gain is much more broadly ranged, e.g. about 3 to 8 dB in the case of channel 4 for a 1x4 architecture. The switched beam algorithm behaves about 1 to 1.5 dB worse than the other combining algorithms, with fairly parallel CDF curves.

It is unexpected that all three combining algorithms consistently yield almost identical results. It appears that allowing for variable polarity, although it improves the best correlation value for the SISO case, *does not improve the diversity*. For instance, for certain channel realizations and antenna positions, the improvement brought by polarity correction in the SISO case is such that the diversity gain is *less* than its value without polarity correction.

As Regards MRC vs. simple polarity correction, we only remark that in narrowband systems the improvement (MRC vs. EGC) is also quite moderate.

MIMO results exhibit a variety of behaviours. In the case of a moderately dispersive channel, the same general results as above are obtained, i.e. a better performance of combined vs. switched schemes. However the situation is reversed for highly dispersive channels, with much poorer performance whatever the combining scheme. The explanation is as follows: low-dispersive channels have multipaths that are well separated in delay, allowing the combining to occur on single paths in practice. In this case a single DOA and a single DOD is involved in the combined signal, so that the above MIMO synchronisation scheme works well. In the case of a highly dispersive and highly angularly spread channel, several multipath components are involved in the correlation signal, all with differing DOA and DOD, which makes the synchronisation scheme quite inefficient. This does not apply to the same extent to a SIMO case, for which the sub-optimality exemplified in Fig. 4 is irrelevant.

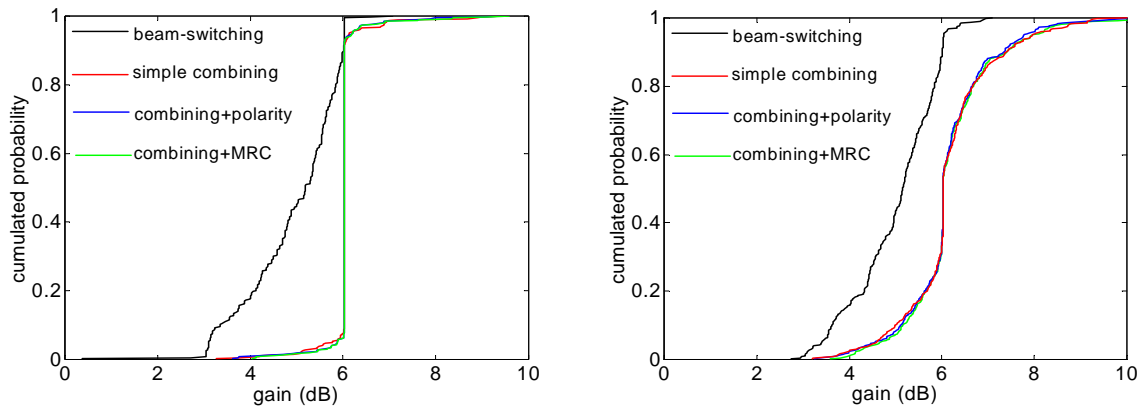


Fig. 6: 1x4 architecture. Comparison between the various algorithms.
Left: channel 1; right: channel 3.

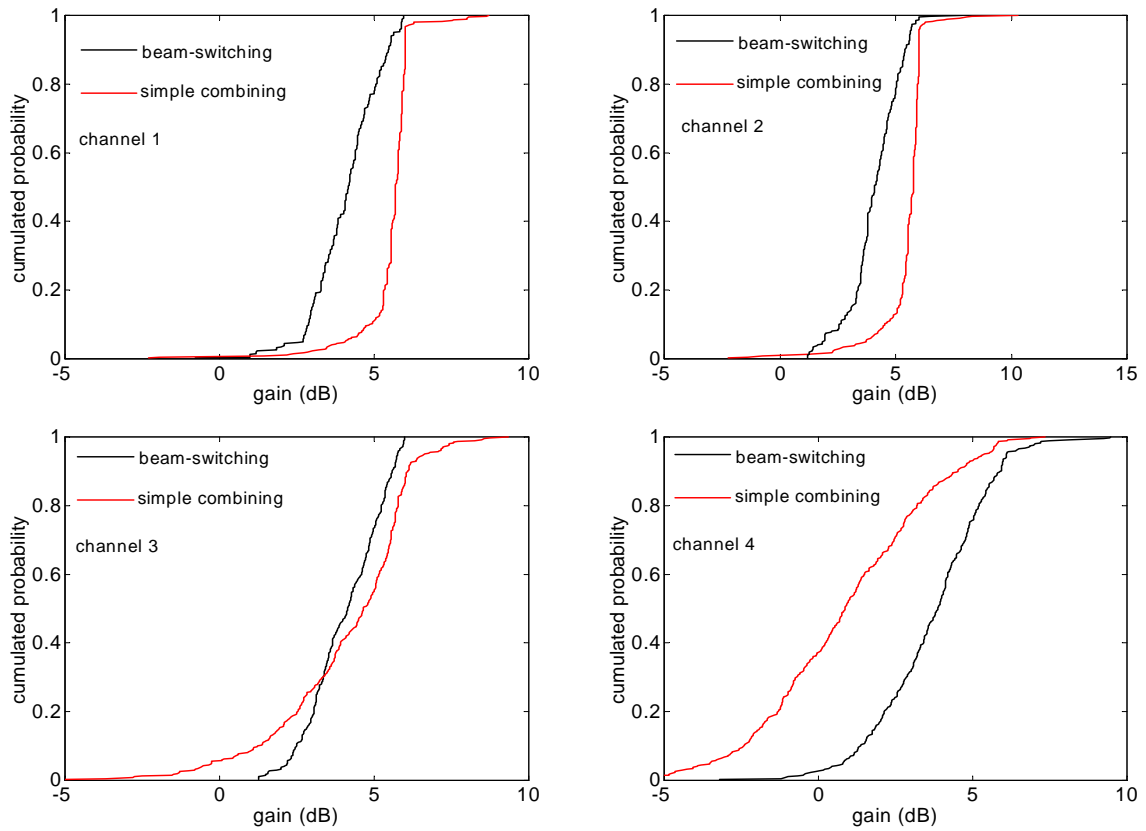


Fig. 7: 4x4 architecture. Comparison between switched beam and simple combining scheme, according to the channel type.

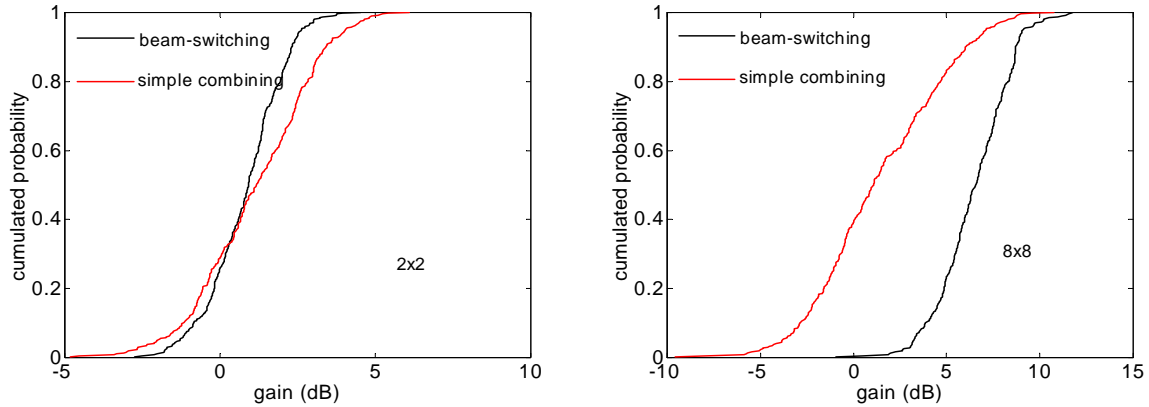


Fig. 8: Comparison between switched beam and simple combining scheme for a highly time and angular dispersive channel, according to the number of elements of an $N \times N$ architecture

This poor performance of the combining scheme actually occurs when the DOA and DOD globally exhibit a large angular spread. However in reality it is likely that the angular correlations originated from the physics of propagation will involve *clustering*, whereby the echoes will be grouped either in delay or in angle, both at their departure and at their arrival.

Since UWB detection is carried out in a narrow delay range, it is possible that much less angular dispersion will be involved in the detected signals than in the whole CIR. This can be easily simulated by creating clusters in the multipath channel, each of them being angularly narrow although the global channel is highly angularly dispersive. By comparing Fig. 9 and Fig. 7 (down-right plot), it can be seen that indeed there is a much better performance of the combining diversity performance of a 4×4 MIMO architecture for this clustered channel (

Fig. 10-Fig. 11) than for e.g. channel 4.

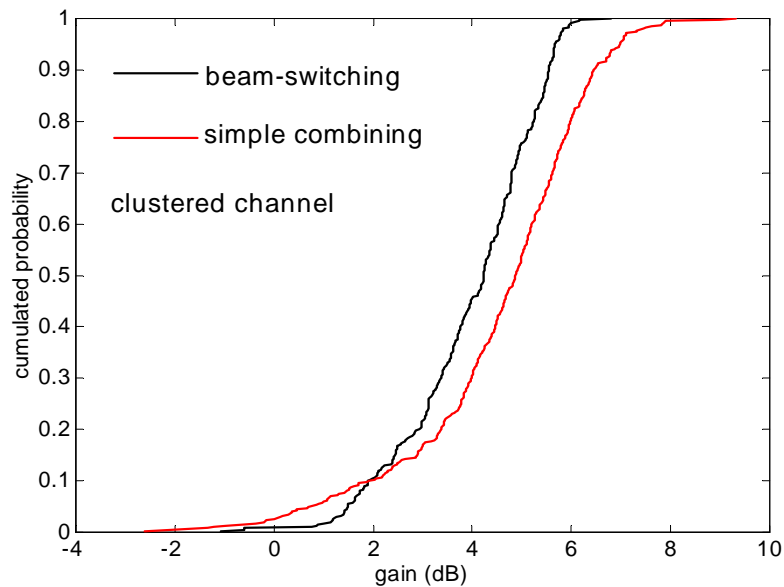


Fig. 9: Comparison : switched beam and simple combining scheme for a *clustered* highly time and angular dispersive channel (4×4 architecture)

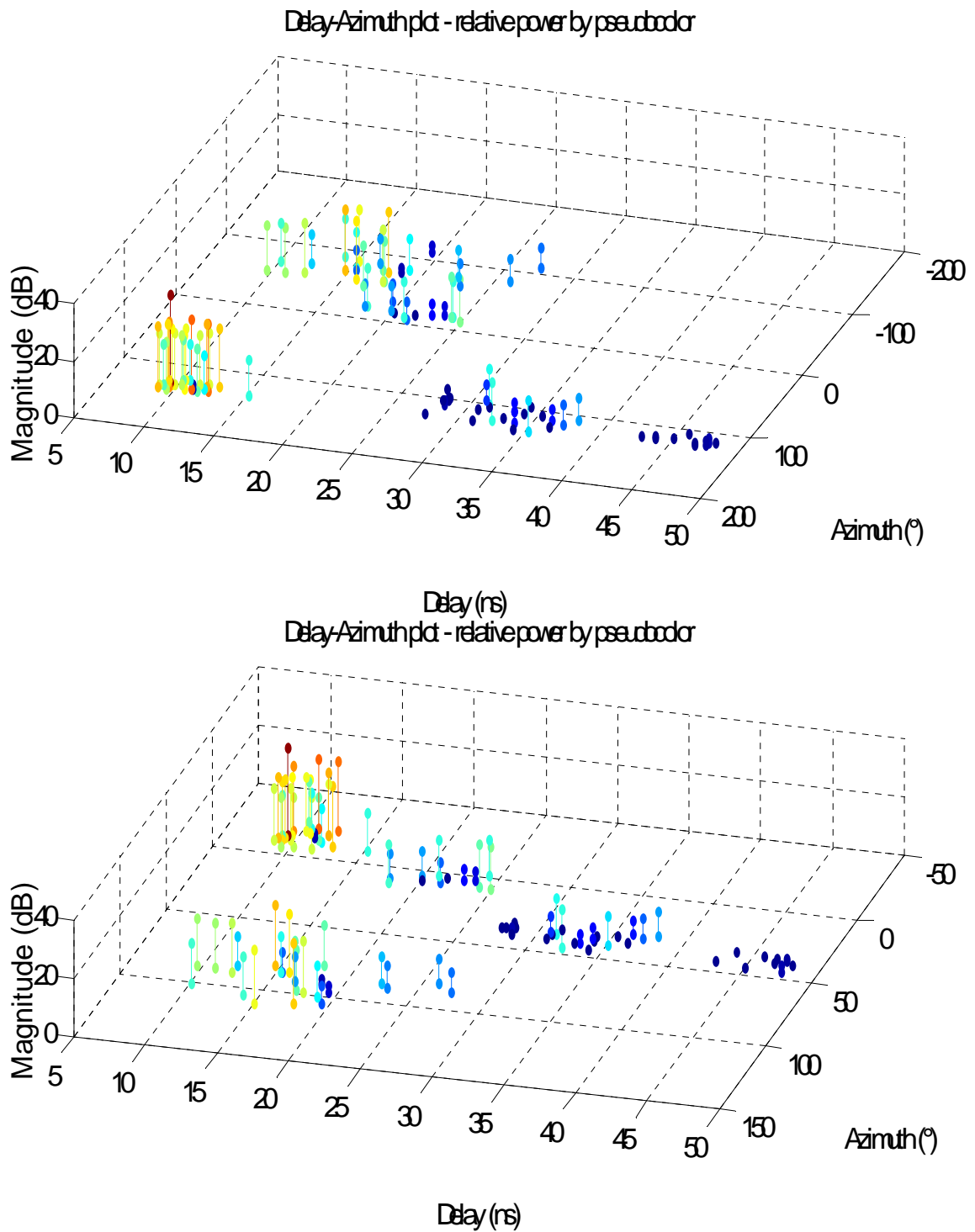


Fig. 10: example of a clustered UWB channel (4 clusters)

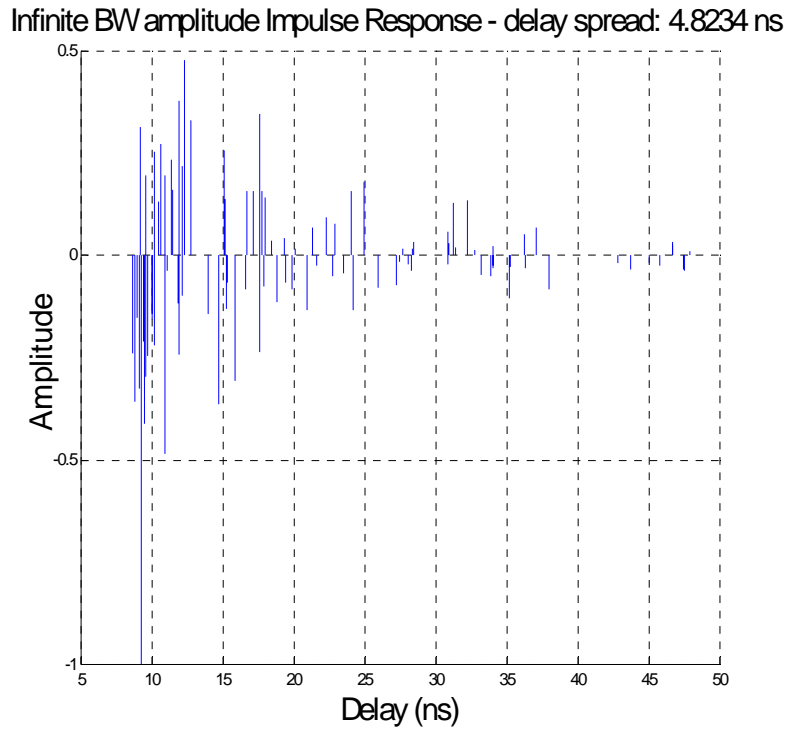


Fig. 11: discrete impulse response for the simulated channel of
Fig. 10.

V – Conclusion :

We have investigated and evaluated by simulations a few SIMO and MIMO diversity schemes which can improve the performance of a UWB radio link, in the hope to surmount the heavy constraints put by stringent regulations (small transmitted power). Using a stochastic channel model based on discrete waves and taking into account optimal waveforms intended to respect allowed spectral masks, we find that MIMO techniques may bring an improvement close to the $N_t \times N_r$ diversity order for N_t transmitters and N_r receivers, particularly by synchronising and combining the signals emitted by the various radiators and received by the various sensors. However the characteristics of the channel dramatically influence the diversity gain, and poor results for MIMO architectures are obtained for a highly time and angular dispersive channel, due to the deficiency of the synchronisation scheme. Beam-switching works fairly well, and might be an effective technique to obtain diversity gain for a moderate complexity cost.

Still these results rely on a rather simplistic channel model which should be tested against reality, in particular as regards the importance of clusters in the angular and delay domains. Also the existence of diffuse scattering, known to contain an important fraction of the radiated energy, has not been accounted for and might complicate the analysis of UWB MIMO effects. Another key issue is the performance of antennas, since dispersionless antennas are very difficult to design in UWB, especially under other current constraints. Finally these simulations assumed perfect channel estimation and synchronisation, obviously not an easy task in real time under complexity limitation constraints.

Acknowledgements

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