Spatial diversity for UWB communications

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Abstract

Spatial diversity is regarded as a possible mean to relax the stringent constraints imposed by regulations on link budget for Ultra Wide Band (UWB) communications. After general considerations on the pertinence of diversity for UWB signals, it is shown here by simulations on a test array, that electromagnetic coupling between sensors should be negligible, allowing to use diversity for improved energy capture. In addition, the computation of fading signal probability distributions shows good hope of fading mitigation by spatial diversity, in the case of a frequency mode UWB modulation.

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 for a great variety of scientific, public or commercial services. The FCC for instance imposes indoor communications a maximum EIRP of -41.3 dBm/MHz between 3.1 and 10.6 GHz, falling to much less outside this band and 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 about –8 dBm, will 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 of UWB communications systems.

In the present work we address diversity, as a possible solution to improve the UWB link robustness, or its range. We first discuss the general characteristics of diversity in the case of UWB, then we investigate the case of a two radiators array, from the point of the electromagnetic properties and diversity capabilities. In a first part we show that electromagnetic coupling is small enough to avoid reduction of the diversity gain due to this effect. In a second part we investigate the role of the frequency dependence of the correlation properties of the array. This shows that in the case of a frequency domain modulation, spatial diversity can be an efficient way to mitigate fading, just as in narrowband systems.

II Some considerations about spatial diversity in UWB arrays

Spatial diversity in reception is reputed to bring two complementary advantages: the first is improved radiated energy capture, since each sensor possesses a given antenna effective area, expressing the ratio between the power delivered to a (matched) load and the incident power density. The greater the number of sensors, the higher power can be captured from incident waves. Efficient combining techniques like maximum ratio combining (MRC) exploit this advantage and improve the SNR, proportionally to the number of sensors [1].

Another advantage of diversity in narrowband systems is enhanced robustness to fading, since the likeness of having all sensors experiencing fading rapidly decreases with the number of sensors. The diversity gain obtained from multiple sensors antennas and from performant combining schemes, is an increasing function of the fading depth, and can reach much higher values than those obtained for the average SNR gain. This is of course extremely useful in the hope to reduce the probability of link outage.

Diversity in ultra wide band systems will exhibit several significant differences. Although several alternatives exist for the physical layer of UWB communications, a main classification exist between those based on pulsed modulations (like PPM, CDMA and the like, etc ..), and those operating in a frequency mode (OFDM and related techniques, frequency hopping, etc …). In the case of pure OFDM for instance, each tone carries a narrowband or moderate band signal, while in the former all information carrying signals contain the full UWB spectrum. This generates a difference of behavior between both types of techniques, as regards diversity.

In the case of frequency domain modulations, and assuming the narrowband limit for each tone (i.e. negligible delay spread), the main difference with usual moderate band channels is the fundamental variation of channel/antenna parameters with the carrier frequency. Such effects like the carrier frequency dependence of the correlation coefficient, or the antenna preference for low frequencies should not be disregarded. They are the subject of section IV.

In the pulsed mode case, the main difference with narrowband cases is the reduction of fading. It is well known that wideband systems exhibit less fading than narrowband systems, and this is due to the enhanced delay resolution which allows to discriminate between the various paths of the channel impulse response (CIR). The UWB case is the extreme limit of wideband, and we can expect that fading will be totally absent. Apparently things are not so simple, experimental results showing clear spatial variations of the wave amplitudes [2]. It appears that in spite of the excellent delay resolution of UWB techniques, the peaks in the CIR possess an underlying structure related to their angular spectra.

Nevertheless it is not obvious in the absence of sufficient experimental data, that this residual fading will bring extra fading gain to motivate the complexity associated with diversity architectures. However another motivation may be found: it is related to energy capture, also a crucial feature when being aware of the stringent limits put by regulation on emitted UWB powers. This may be all the more valuable as many UWB devices should operate close to line-of-sight, i.e. under conditions of power decay dominated by a power law with exponent 2. A gain of 3 dB thus means an extra 41% of range.

Replacing a single electrical generator (the receiving antenna) by e.g. an array of two radiators intuitively seems to imply a doubling of the received power, provided suitable impedance matching by a network was achieved. This assumption is only true under the condition of electromagnetically uncoupled sensors. Otherwise electromagnetic short-circuiting reduces the useable power delivered to the loads. While two far away sensors deliver at most $2\times|E|^2/8R_a$ where $R_a = \mathrm{Re}(Z_a)$ is the antenna radiation resistance, in the extreme case of very strong coupling for instance, two short circuited sensors will deliver at most $|E|^2/8R_a$, i.e. there is no power gain. It is therefore crucial to identify precisely the role of electromagnetic coupling in a diversity application targeting energy capture. In the next section, this is done using full electromagnetic simulations and electrical network computations of a UWB array.

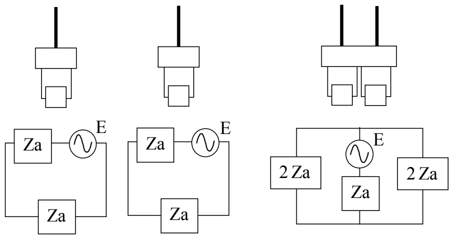

Fig. 1: Two isolated sensors (left) vs. two extremely coupled sensors (right)

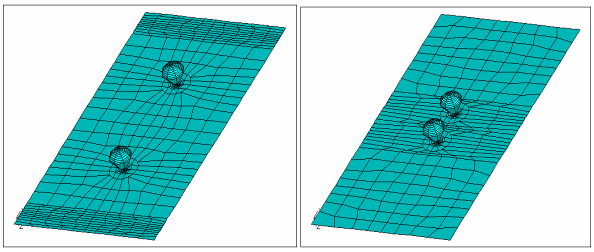

Fig. 2: schematic view of the dual UWB arrays, with intersensor distances of 12 cm and 4 cm

III Electromagnetic coupling of close UWB radiators

In order to investigate the influence of electromagnetic coupling in UWB arrays used for spatial diversity, a test structure composed of two UWB radiators was designed and simulated (fig. 2). The elementary radiator is a shaped monopole, intended for operation in the 3-6 GHz band with omnidirectional radiation in an horizontal plane. It was designed and optimised with an electromagnetic simulator based on the method of moments (WIPL), involving suitable de-embedding procedure to ensure reliable results for the antenna impedance. Each radiator is fed through an exponentially shaped transition region, between a feeding coaxial line and the monopole itself. The feeder together with the monopole shape are indeed critical issues for the proper impedance matching of the antenna to 50 Ω [3].

A fairly large ground plane of constant size 30x16 cm was used, in order to avoid any detrimental influence of its finiteness on the antenna impedance and for a fair comparison between arrays with varying inter-radiator distances. Three distances were chosen; namely 12 cm, 8 cm and 4 cm. The latter case is almost the minimum reasonable, on account of the radiator diameter 2.3 cm. This array electrically behaves as a linear two-port device, characterized by a scattering S matrix, or equivalently by an impedance or admittance matrix. In all cases, the presence of electromagnetic coupling between radiators is characterized by a off-diagonal entries. The matrices are also symmetric by virtue of reciprocity, and in addition the diagonal elements are here equal because of the presence of a symmetry plane between the radiators.

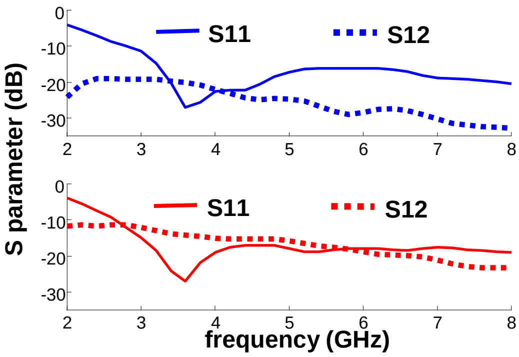

Fig. 3: S parameters of the arrays.
Up: 12 cm distance. Down: 4 cm distance

Several features can be seen in fig. 3:

i/ The return loss is basically below –15 dB in the 3-6 GHz band, which is traditionally considered to be an acceptable impedance matching for an antenna.

ii/ The transmission coefficient from one radiator to the other by electromagnetic coupling is below –20 dB for the most distant array, and rises to below –10 dB for the shortest distance.

iii/ The transmission coefficient decreases with increasing frequency, e.g. from –11 dB to –24 dB between 3 and 8 GHz for the smallest array.

Remark ii/ shows that even in the smallest array, electromagnetic coupling remains moderate. This is of course a favourable feature for spatial diversity applications. Nevertheless it is useful to analyse the effect of this residual coupling in a quantitative manner. For this purpose we have computed the power loss in two ways:

1/ *The array is operated in transmission*, i.e. one radiator is excited by a generator while the other behaves as a parasitic element delivering some loss power into its 50 Ω matched load. An efficiency can therefore be defined, equal to the ratio of the radiated power to the total power supplied to the excited radiator. It can be seen that even in the worst case of the smallest array, the efficiency is better than –0.4 dB at 3 GHz, rapidly growing to better than –0.1 dB at 6 GHz. This means that a very small power is lost to the load of the parasitic radiator (fig. 4).

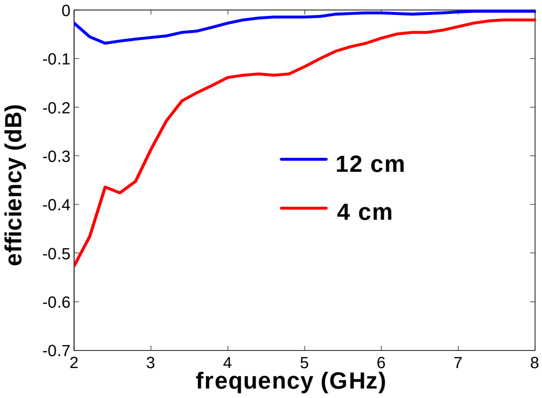

Fig. 4: efficiency of the dual sensor array operated in transmission, as defined in the text.

2/ *The array is operated in reception*. An arbitrary scenario was considered, in which waves of constant amplitude 1V/m are incident on the array between 0° and 90° elevation and 0° to 360° azimuth. The total received power delivered to the loads can be seen on fig. 5. There is virtually no difference between both arrays, meaning that the total received power is not affected by sensors proximity. Actually when comparing the average received powers for intersensor distances of 12 and 4 cm, the difference is less than 2%. As a matter of comparison, two λ/4 monopoles distant from λ/10 lose 45% of received power, as compared to monopoles distant from λ.

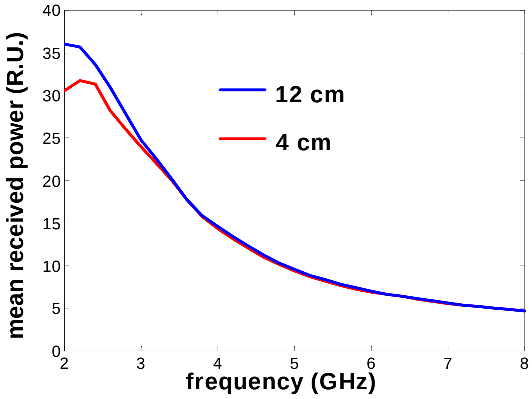

Fig. 5: Mean received power for a hypothetical omnidirectional scenario of incident waves

It is interesting to remark the decrease in frequency of the received power. This feature is typical of UWB, and is due to the frequency dependence of the antenna effective area for a constant gain antenna, scaling as λ^2 where λ is the wavelength. Obviously low frequencies are more favourable to the link budget. This characteristic explains remark iii/, since in the case of power fed to one radiator, the second behaves as a very close receiver.

In order to conclude this section, let us mention that the radiation patterns have also been investigated in detail. It turns out that the "shadowing effect" of one loaded UWB monopole on the other, although not negligible, is basically minor and does not change the general characteristics of the elementary radiators radiation patterns (fig. 6).

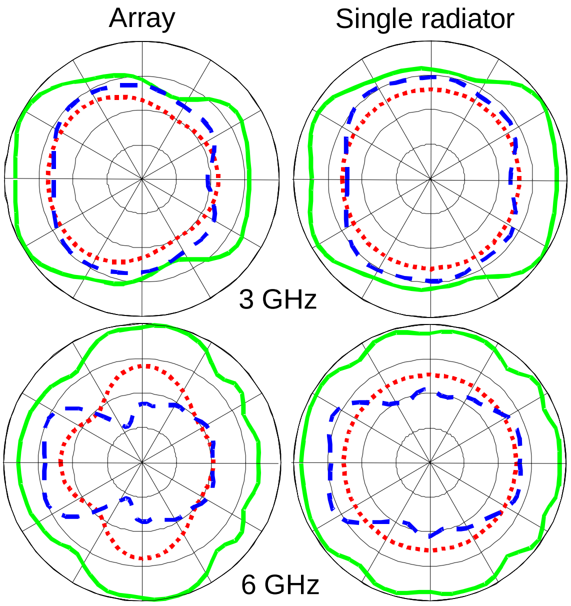

Fig. 6: copolarized radiation patterns showing the moderate modification due to the presence of the nearby radiator (dotted line: elevation 0°, full line: elevation 30°, dashed line: elevation 60°)

IV Evaluation of diversity performance in frequency domain UWB

In the present section, we attempt to evaluate the performance of a dual sensors array diversity performance, in the case of a hypothetical frequency mode UWB modulation, where each tone would be perfectly narrowband.

Diversity performance is limited by two effects: **i/** electromagnetic coupling on the first hand, as discussed above. The previous section shows that this effect is quite moderate even for very close sensors. We will therefore neglect coupling below; **ii/** correlations between the incident electromagnetic fields, due to spatial proximity of the sensors. We may expect these correlations to be enhanced at low frequencies, as the wavelength/inter-sensor distance ratio increases. On the other hand the improved effective area of sensors at low frequencies makes them less prone to fading. In other words in a frequency mode physical layer, spatial diversity will be particularly useful at the higher frequencies, where by chance it operates best.

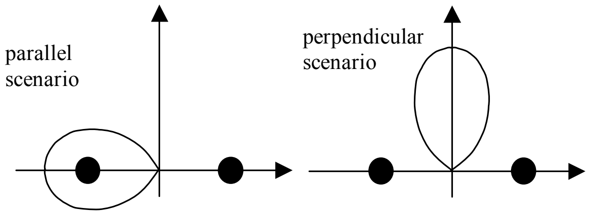

Fig. 7: hypothetical directional scenarios used in the computations of fig. 8

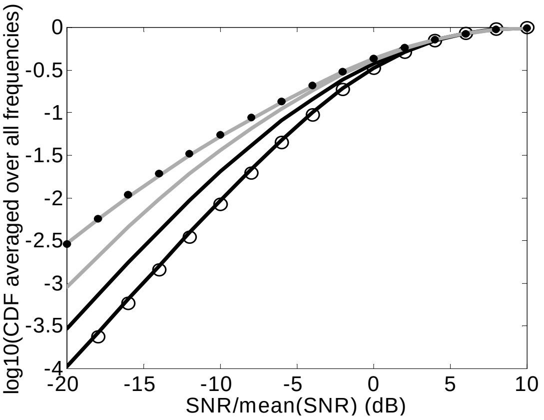

Fig. 8: averaged CDF for a dual UWB array. Black (grey): perpendicular (parallel) scenario; full (dash) lines: 10 cm (4 cm) sensor distance. open (full) dots: perfect decorrelation (perfect correlation).

In order to quantitatively evaluate diversity performance, we used a simple model in $\cos^n(\varphi-\varphi_0).\delta(\theta)$ between $\varphi=\varphi_0-\pi/2$ and $\varphi=\varphi_0+\pi/2$ for the angular spectrum of received power, where φ is the azimuth, θ the elevation, and φ_0 the mean direction of arrival (DOA). Assuming omnidirectional radiators, the complex correlation coefficient between the received signals can be computed as a function of inter-sensor distance *d*, for instance when $\varphi_0=\pi/2$ [4] we have:

$$\rho_c(d)=\int_{-\pi}^{\pi}\cos^n(\alpha).\exp(j.2\pi d\sin(\alpha)/\lambda).d\alpha$$
$$=\sqrt{\pi}\,2^{n/2}\,\Gamma((n+1)/2)\frac{J_{n/2}(2\pi d/\lambda)}{(2\pi d/\lambda)^{n/2}}$$

From this expression, we approximately obtain the *normalized* envelope correlation coefficient $\rho_e\cong|\rho_c/\rho_c(0)|^2$. In the case of correlated incident fields, the probability density for the MRC signal power has the following analytical expression [1]:

$$P(\gamma)=\frac{1}{2\rho_e\Gamma}\left\{\exp\left(-\frac{\gamma}{\Gamma(1+\rho_e)}\right)-\exp\left(-\frac{\gamma}{\Gamma(1-\rho_e)}\right)\right\}$$

where Γ is the mean SNR. This expression gives us the fading signal distribution function for each tone, the carrier frequency entering ρ_e through the above integral.

We show above an example of results, for a mean DOA either perpendicular ($\varphi_0=\pi/2$) or parallel ($\varphi_0=0$) to the array, and a fairly directional scenario of 30° half power width. Two inter-sensor distances of 4 cm (as modelled in section II) and 10 cm are considered. For clarity purposes, only the CDF of SNR *averaged over 4 frequencies* covering the band from 3 o 6 GHz is shown. In addition and prior to averaging, each frequency dependent CDF was computed with respect to the SNR normalized to its value *averaged over all frequencies*. This is necessary in order to take into account properly the decrease of the average SNR with increasing frequency, assumed proportional to F^{-2}. Such a curve gives an indication of diversity performance for the array. It turns out that a moderate intersensor distance of 10 cm already allows a good diversity performance, e.g. 6.2 dB improvement with respect to full correlation in the perpendicular scenario (very close to the optimum), and 2.2 dB in the parallel scenario. The 4 cm distance array on the other hand behaves poorly, with 4.2 dB improvement with respect to full correlation in the perpendicular scenario, but only 0.15 dB in the parallel scenario.

V Conclusion

Spatial diversity seems to be a useful technique for UWB radio link robustness improvement, by capturing more incoming power in the case of a pulsed mode UWB, and by mitigation of fading in the case of a frequency modulation UWB. Further experimental work is needed to verify these assertions.

VI Acknowledgements

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VII References

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