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About the role of antennas in UWB impulse radio

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About the role of antennas in UWB impulse radio

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Abstract

An analysis is carried out about the way antennas affect the performance of an impulse based UWB radio link, evaluated according to the captured energy as measured at the output of a correlator. Various normalizations are considered, in order to distinguish between the antenna gain and the antenna dispersivity in the time domain signals, or to take into account the EIRP limit imposed by regulations. It appears that the properties of the channel are paramount as regards the antenna performance in the radio link, mainly regarding the multipath density. Several simulations of radio link performance related to antennas are presented, both for real and simulated antennas, and for real and simulated channels. In addition it is stressed that using antennas as filters at the reception reduces the SNR.

I Introduction

Antennas constitute key elements in the communication chain, both at the receiver and at the transmitter, subject to performance requirements while at the same time supporting demanding constraints implied by their incorporation in terminals or network access points. The contradiction between requirements and constraints make the selection or the design of an antenna something difficult, particularly in the ultra wide band (UWB) case since the large bandwidth places additional needs in comparison to narrowband radio.

The second problem for the antenna designer is that he has no tools at his disposal to help him evaluate the performance of an antenna embedded in a radio system, apart from tools intended to determine the antenna gain, its efficiency, and its radiation patterns. These tools are of course quite important in order to say where most of the radiation would go or would be received, and what signal power can be lost due to antenna losses, but they say nothing about the "matching" between the antenna and the channel. For instance, it seems that a number of UWB applications will need very small, or very cheap antennas, implying a very poor performance. In this situation, it may be quite beneficial to be able to quantify the performance loss with respect to an ideal antenna beyond simple hand waving arguments.

It is well known that matched filtering is a necessary requirement for optimal signal reception, therefore since both antennas and channels are filters that are involved in the transfer function between the signal to be transmitted and the signal at the receiver output. This means we should analyse antenna performance and channel properties in a correlated manner, if optimization of the radio link performance is a goal to reach. Another trivial way to put it, is that we attempt here to answer the naïve question : "since the channel is so bad, does it make any difference if the antenna differentiates it to third, second or fourth order ?".

In the present work we attempt to analyse the radio link performance, from the point of view of the signal to noise ratio (SNR) under white noise assumption, and in the case of a pulse based physical layer scheme, by looking at antenna characteristics and at channel properties together. For this purpose we compute cumulative distribution functions of the SNR for various antenna/channel combinations, and for various normalizations of the signal intended to distinguish between the antenna gain and the antenna dispersivity, or to take into account the EIRP limit imposed by regulations. A selection of measured (monocone, log-periodic dipole array) and simulated (rectangular horn) antennas are considered, as well as simulated (IEEE 802.15.3a model, ENSTA model) and measured (within ENSTA premises) channels.

II System model and description of the approach

II-1 ?Generalities on the UWB architecture and signal aspects

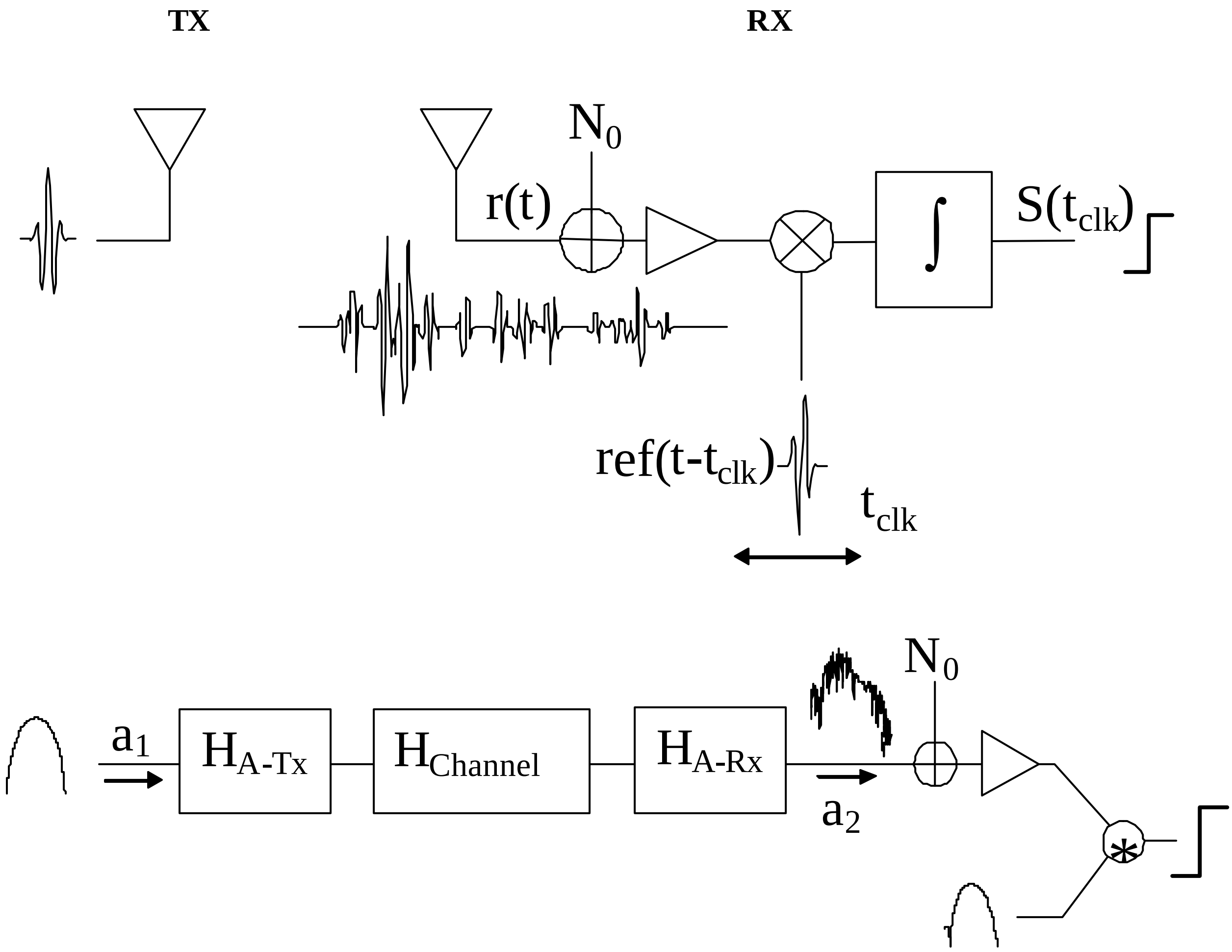

Fig. 1: up :schematic system model with the transmitter waveform and antenna (left), and the receiver antenna followed by the correlator (multiplier-integrator in temporal domain) and output decision operator.

Down : ditto in the frequency domain.

We consider the system model as depicted in the figure, where a pulsed signal waveform (finite energy) is sent to the transmitter antenna, radiated through the propagation channel, received by the Rx antenna, convoluted with a reference (template) waveform clocked at an adjustable delay, and passed through a decision operator for detection. Such a system model is general enough to describe pulse position modulation (PPM), pulse amplitude modulation (PAM), and direct sequence code division multiple access (DS-CDMA), by using the adequate template; Except for the last one, each of these operators is a linear filter susceptible to affect both the signal shape and its energy. In the present work we investigate the influence of both Tx and Rx antenna filters in relation with the channel filter, and also the influence of the correlator template.

In the case of free space propagation, the global transfer function writes $H_{21} = \frac{a_2}{a_1} = \frac{e^{-jkr}}{r}\left(\frac{-j\lambda}{4\pi}\right)H_{Tx} \cdot H_{Rx}$ in the frequency domain, and $H_{21} = \frac{c}{2r}\left(H_{Tx} * \partial_t^{-1} H_{Rx} * \delta_{r/c}\right)$ in the time domain. These formulas express reciprocity and here H_{Tx} and H_{Rx} in the frequency domain are dimensionless antenna transfer functions which relate, for either Tx or Rx antenna operating in transmission, the complex amplitude $\mathbf{A}(\mathbf{k})$ of the radiated electric field $\mathbf{E}(\mathbf{k}) = \frac{e^{-jkr}}{r}\sqrt{\frac{\eta_0}{4\pi}}\mathbf{A}(\mathbf{k})$ to the complex wave amplitude $a_1(\omega)$ of the incident signal : $H(\mathbf{k}) = \frac{\mathbf{A}(\mathbf{k})}{a_1(\omega)}$, ($k = 2\pi / \lambda = \omega / c$). In the case of a channel differing from free space, the term $\frac{e^{-jkr}}{r}$ should be replaced by the frequency domain channel transfer function [1].

We use a signal waveform at the transmitter level that is compliant with the FCC mask issued on 14 february 2002. 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. The spectral transmission waveform shown below, was constructed from an initial rectangular spectrum (sinc function in the time domain), properly windowed. However it is important to mention that this waveform will be filtered by the Tx antenna, and will therefore deviate from the spectrum shown below, as far as this antenna is not ideal.

Regarding the received signal, it should first be recalled as expressed in the above formulas 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.

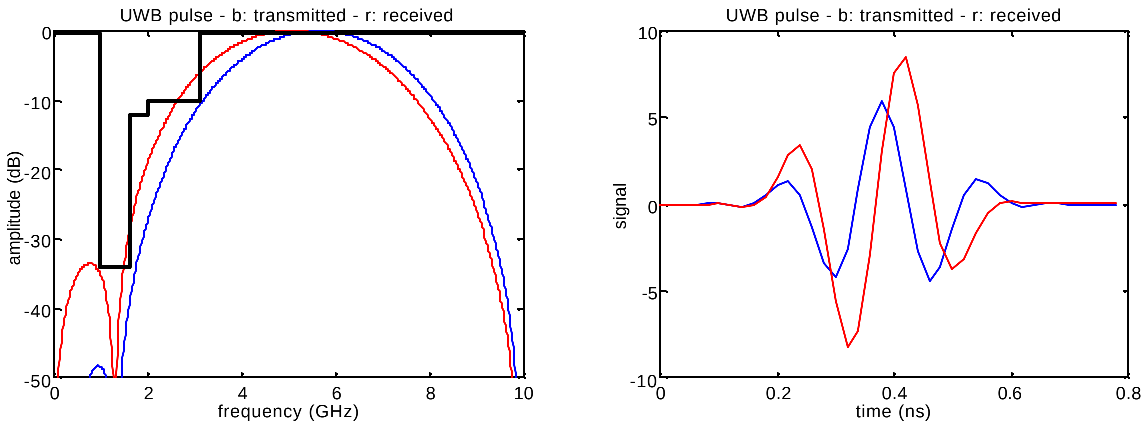

Fig. 2: left:spectra of the transmitted (blue) and received (red) signals; black: FCC mask; right: temporal waveforms

II-2 Approach followed to analyse the role of antennas

In order to evaluate the role an antenna has on the radio link performance, measured as the output SNR, the following analysis has been carried out :

Antenna combinations :

- We first determine the SNR for an ideal Tx antenna/imperfect channel/ideal antenna combination.

- Then we replace one of the ideal antennas by the imperfect one under investigation and compare SNR

- Then we replace both ideal antennas by the same imperfect one and again compare SNR.

We thus obtain two results, corresponding to only one or to two imperfect antennas. Let us stress that since the output signal only depends on the product of the antenna transfer functions, it is irrelevant to say whether the imperfect antenna is on the Tx or on the Rx. Of course in the real world everybody knows it is not equivalent to put a real antenna on Rx or on Tx. This is due to the scenario of radio waves, which differs at both ends of the link. Here however, we consider a *scalar* channel, in other words the channel is like a wired channel where all waves are guided along the same way. Of course this is totally unrealistic for radio propagation, but our present goal is to see quantitatively what happens on SNR when we replace an ideal antenna transfer function by an imperfect one, and this imperfect transfer function will affect all multipaths in the same manner. Therefore our analysis is at present only a primary one, in the sense that sooner or later the full angular dependence of the antenna and of the channel properties will have to be included if we want to have a complete evaluation of the change in radio link quality by replacing an ideal antenna by an imperfect one.

Another issue here is that we consider the waveform sent to the Tx antenna as unique (as given in Fig. 2), which may be contradicted on the basis that a UWB system designer will *ensure the respect of the spectral EIRP mask for radiated electric fields, not for the signal sent through the transmitter circuitry to the antenna*. Clearly, antenna dispersivity will indeed affect the radiated field spectrum. Our goal however is to investigate what can happen on signal output SNR, when antenna properties are not properly taken into account by the designer. This is a willingly practical-minded approach, in that it is probably impossible for a radio manufacturer to have a complete mastering of antenna characteristics, therefore it is useful to investigate performance loss when unwanted antenna characteristics come into play.

Transfer function normalizations :

We consider several normalizations of the transfer function :

- No normalization, which means that the ideal antenna transfer function $H_{ideal} = 1$ is replaced by the real antenna transfer function H_{Tx} or H_{Rx}.

- Normalization in order to ensure that in the case of an ideal (free space) channel, the energy of the output signal after correlation is unchanged with respect to an ideal antenna. This feature allows to remove the gain of the real antenna in the output signal, and to keep radio link performance affected only by the dispersivity of the antenna in combination with that of the channel.

- Normalization in order to ensure that at the Tx level, the EIRP is maintained identical to that of an ideal antenna. This feature is intended to evaluate the influence of the real Tx antenna while respecting the EIRP limitation imposed by regulations.

Reference template :

We consider two cases for the correlator reference template :

- The template (ideal template) is the received signal for an ideal (free space) channel and ideal antennas at each both Tx and Rx levels. In other words this template ignores the antenna characteristics.

- The template is the received signal for an ideal (free space) channel and the antennas under consideration at Tx and Rx levels (antenna filtered template). In other words this template takes into account the antenna characteristics. However it should be clear that in a realistic situation where the channel is angularly dependent at both sides, it is impossible to define a unique template that could include antenna dependences for all angles. Therefore the "academic" template choice considered here is only for the sake of a comprehensive study, and in order to grasp the influence of the template on the SNR.

II-3 Antennas and channels

Antennas :

Antennas need be characterized by a transfer function as defined above, covering the whole signal bandwidth involved in the transmitter signal waveform. This transfer function *includes mismatch effects*, Since we deal with impulse radio issues, the impulse antenna response equal to the Fourier transform of the transfer function may be a more intuitive way to envision the antenna imperfection.

We have used several antennas for our investigation :

- A genuine log-periodic dipole array, nominally designed to operate in the 1-18 GHz band.
- A genuine shaped monocone over a circular ground plane, designed to operate in the 3-10 GHz band.
- A poorly matched simulated rectangular horn, with an operation bandwidth 2-5 GHz.
- A fully synthetic antenna response, built from a main peak and delayed replica in the impulse response.

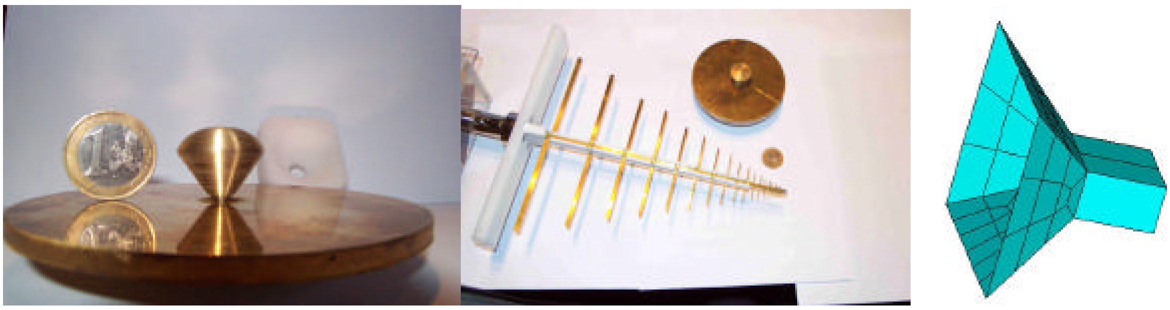

Fig. 3: left : shaped monocone over a ground plane; center : log-periodic array; right : simulated horn

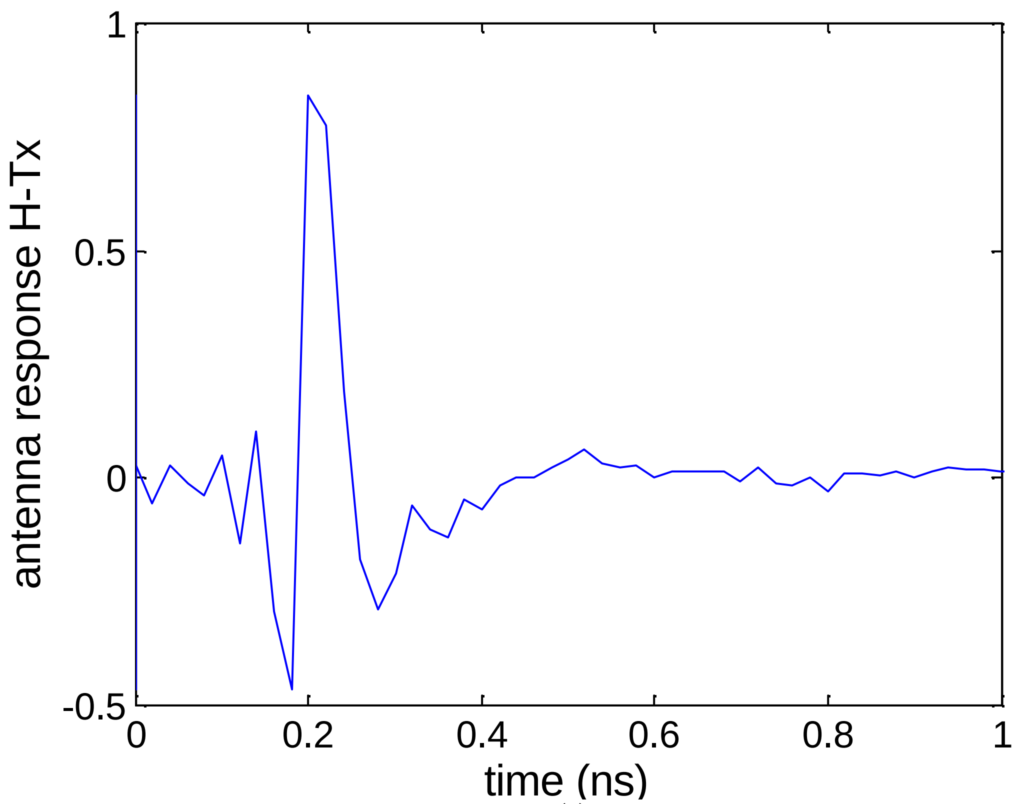

Fig. 4: impulse response $H_{Tx}(t)$ of the monocone in the main lobe

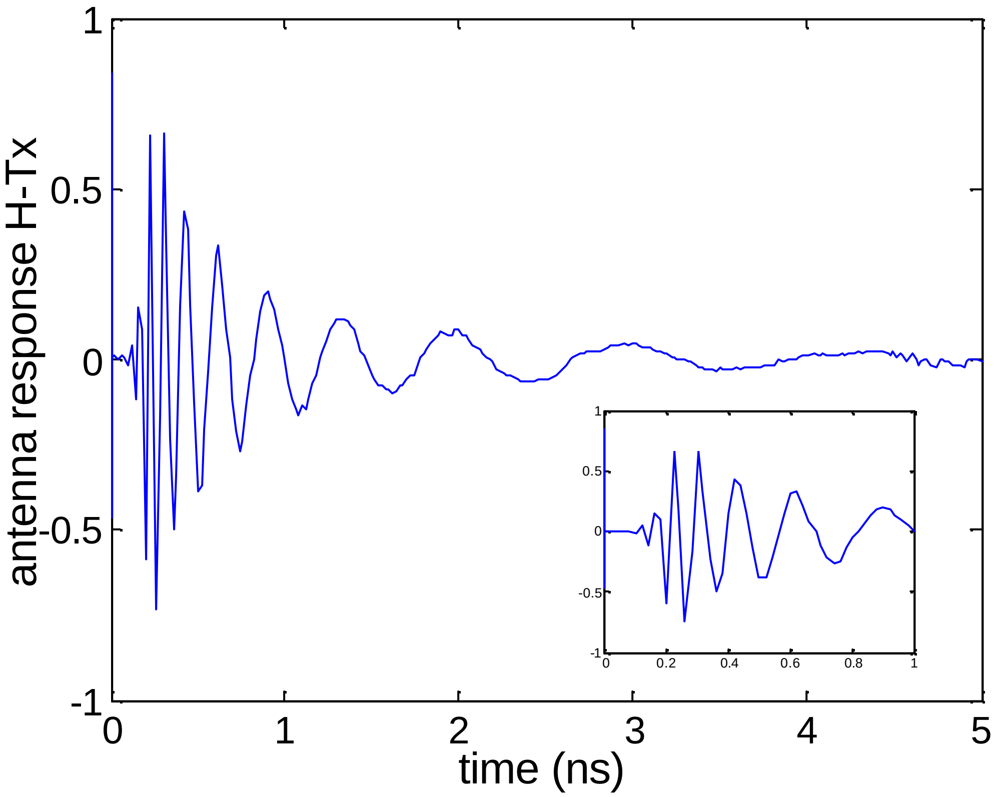

Fig. 5: impulse response $H_{Tx}(t)$ of the log-periodic antenna in the main lobe

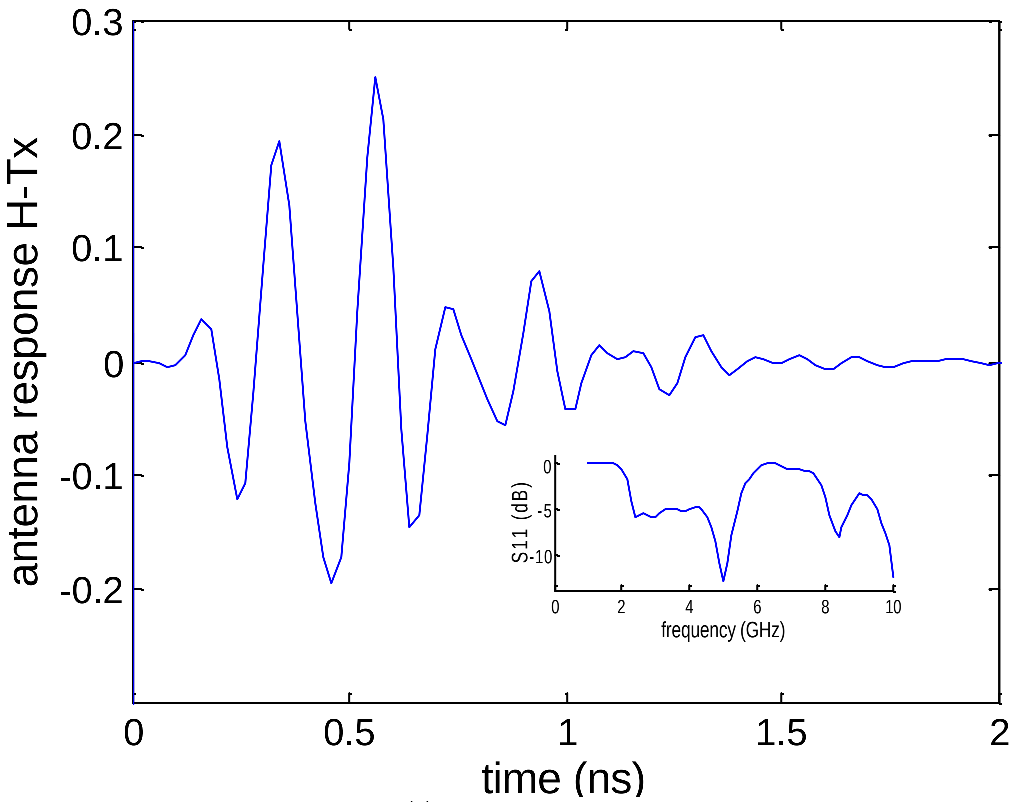

Fig. 6: impulse response $H_{Tx}(t)$ of the simulated horn in the main lobe; inset : return loss

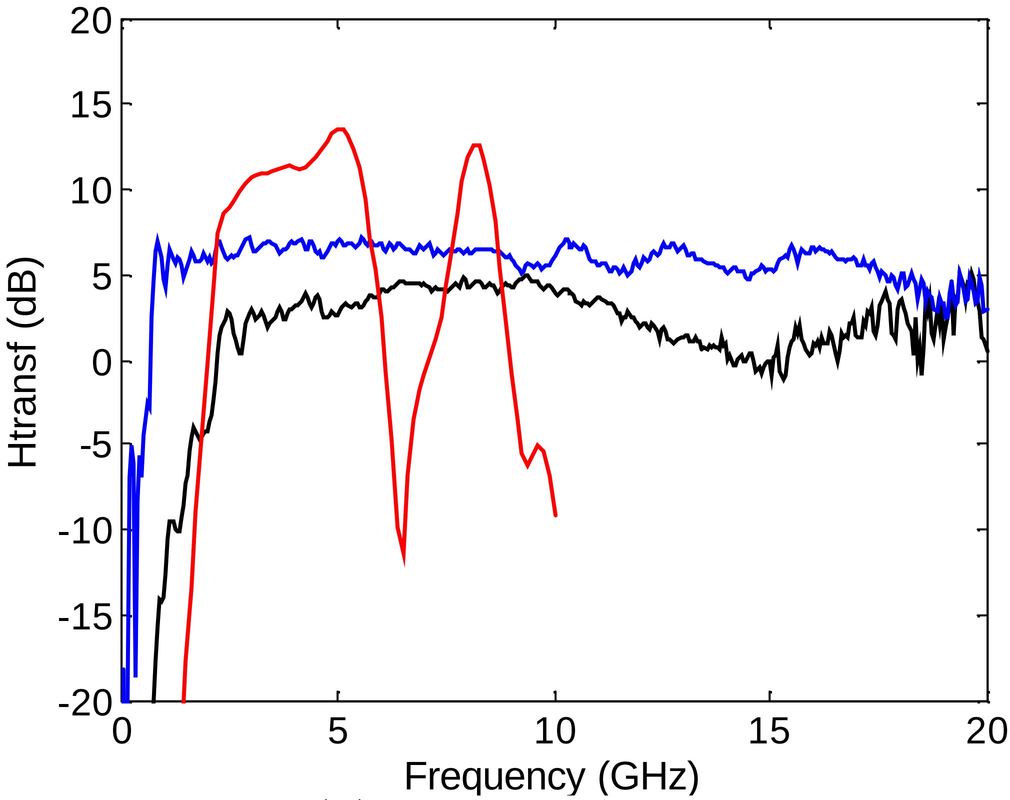

Fig. 7: transfer function $H_{Tx}(F)$ of the monocone (black), log-periodic antenna (blue), and simulated horn (red)

Channels :

We have used three kinds of UWB channels :

- IEEE-802.15.3a channel model [2], which is a discrete multipath model based on a clustered approach. 4 kinds of channels are categorized, with varying Tx-Rx distance and varying degree of obstructions (LOS/NLOS). The model is fully implemented in matlab code and is readily available.

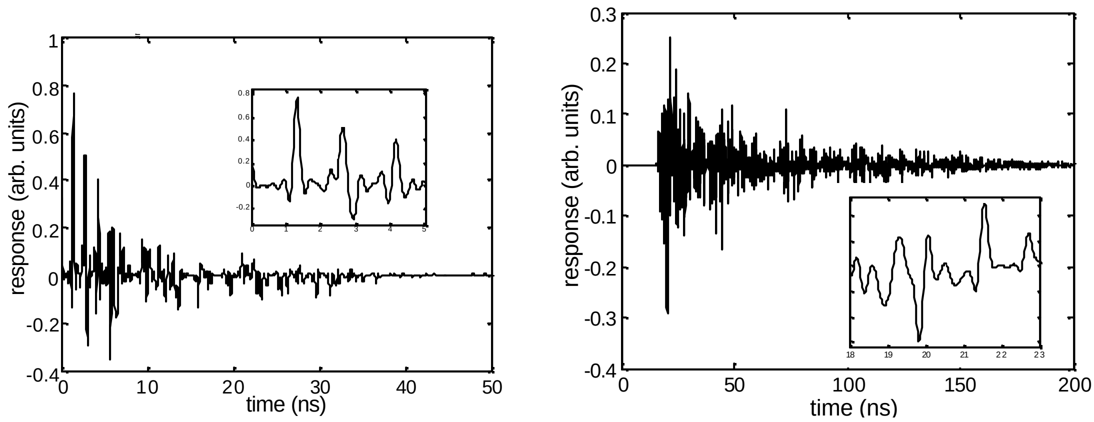

Fig. 8: examples of IEEE-CM1 (left) and IEEE-CM4 (right) channels

• A channel model previously developed at ENSTA and based on the same philosophy although with a different implementation [3]. This model is fully parametric and has been used in order to relate observed effects to parameters of the model. Below, we show results for a sparse channel (channel 1), and a denser channel (channel 2).

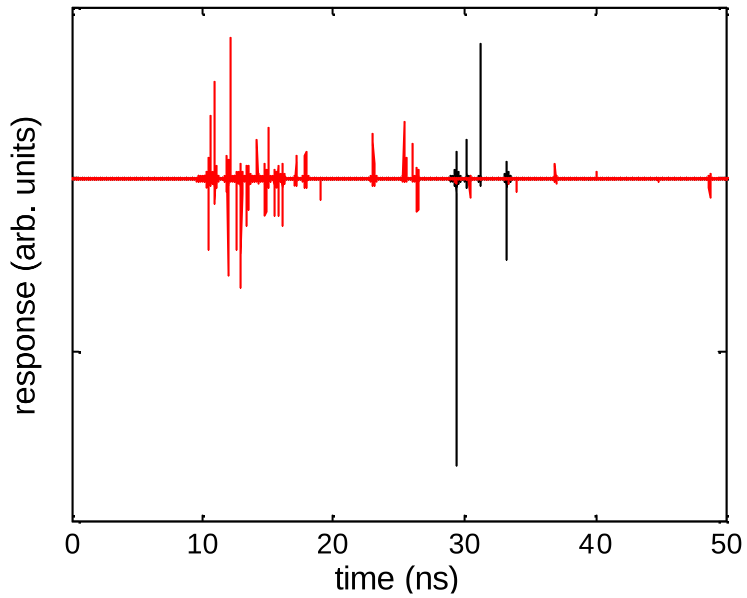

Fig. 9: examples of responses for channel 1 (black) and channel 2 (red)

• Experimental channel measurements carried out at ENSTA with a vector network analyser in the 2-10 GHz band. These measurements were made with a 3D automated positioner at one side of the radio link, enabling to obtain a small-scale space-variant statistical set of channels for each antenna position. Monocones on a ground plane were used for these measurements at both ends of the link. In the SNR simulations below for these channels, extra antenna transfer functions were added just like if the original ones were ideal, which obviously they could not be. This procedure is of course normally incorrect, since the true channel data is filtered twice per radio terminal, instead of once. This has the effect of reducing the channel+antennas bandwidth and increase the dispersivity, with respect to the true situation. However the channel “richness” and multipath density are apparently not strongly affected by this procedure, which has the advantage of providing true data rather than pure simulations based on channel models not intended to be used to the degree of detail we want to. Therefore we will provisionally consider the procedure pertinent.

We show below results for two channels, measured in the microwave laboratory of ENSTA : for the first the antennas are in unobstructed line of sight (LOS) at a distance of about one meter of each other. For the second (NLOS), the positioner location is unchanged, but the other antenna is placed in a neigboring room, only separated from the laboratory by a very thin windowed wall and a closet. The LOS distance is typically 3m. In both cases it can be seen from the pictures that the environment favours a rich multipath structure.

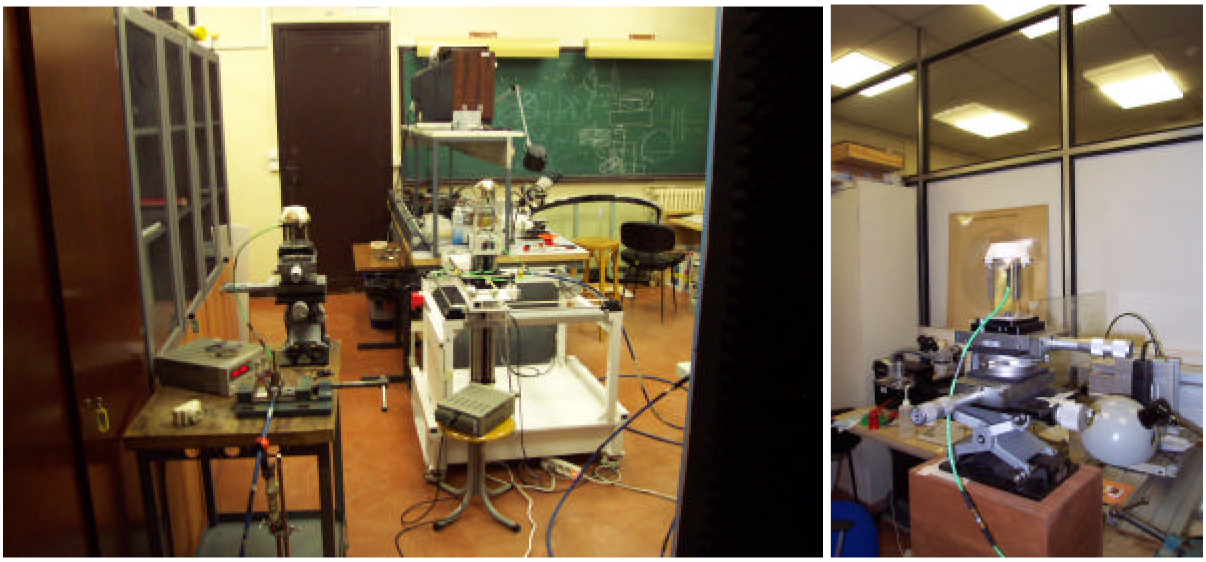

Fig. 10: left : LOS channel in the microwave laboratory of ENSTA ; right : the fixed antenna has been moved to a neighbouring room, while the positioner is unmoved (just behind the visible thin windowed wall), resulting in a NLOS channel.

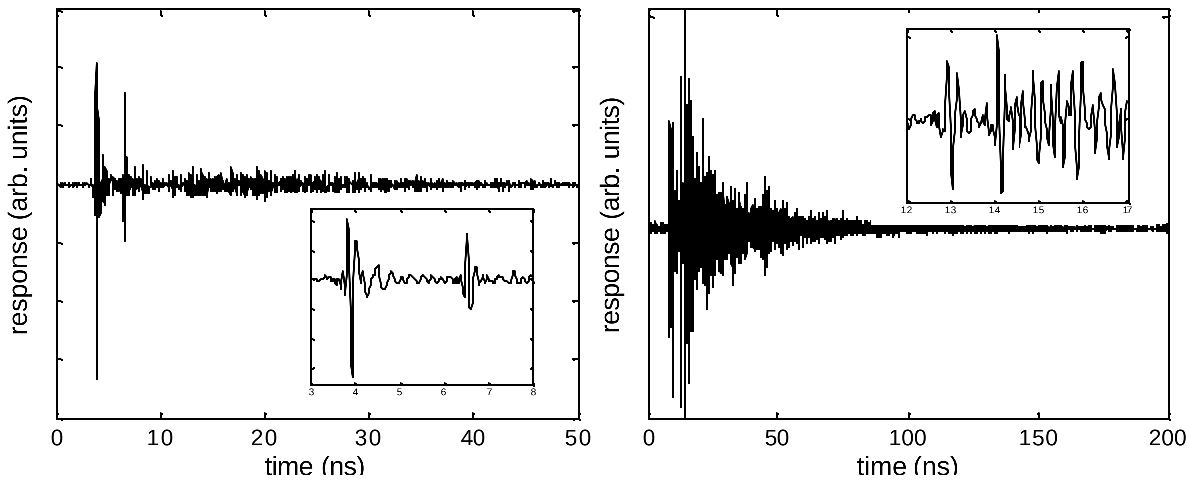

Fig. 11: left : LOS channel in the microwave laboratory of ENSTA ; right NLOS channel

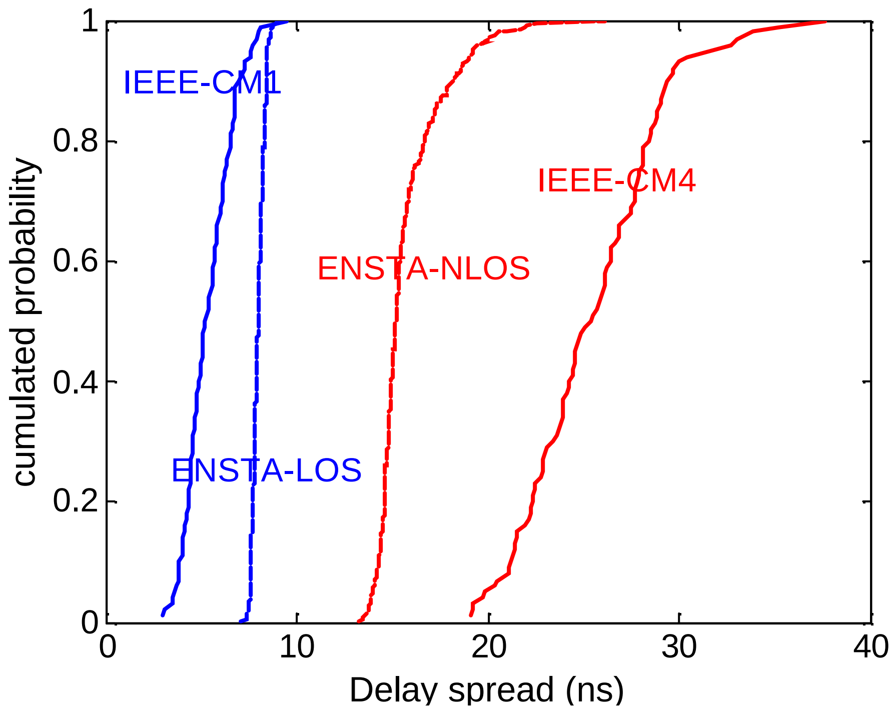

Fig. 12: distribution of delay spreads

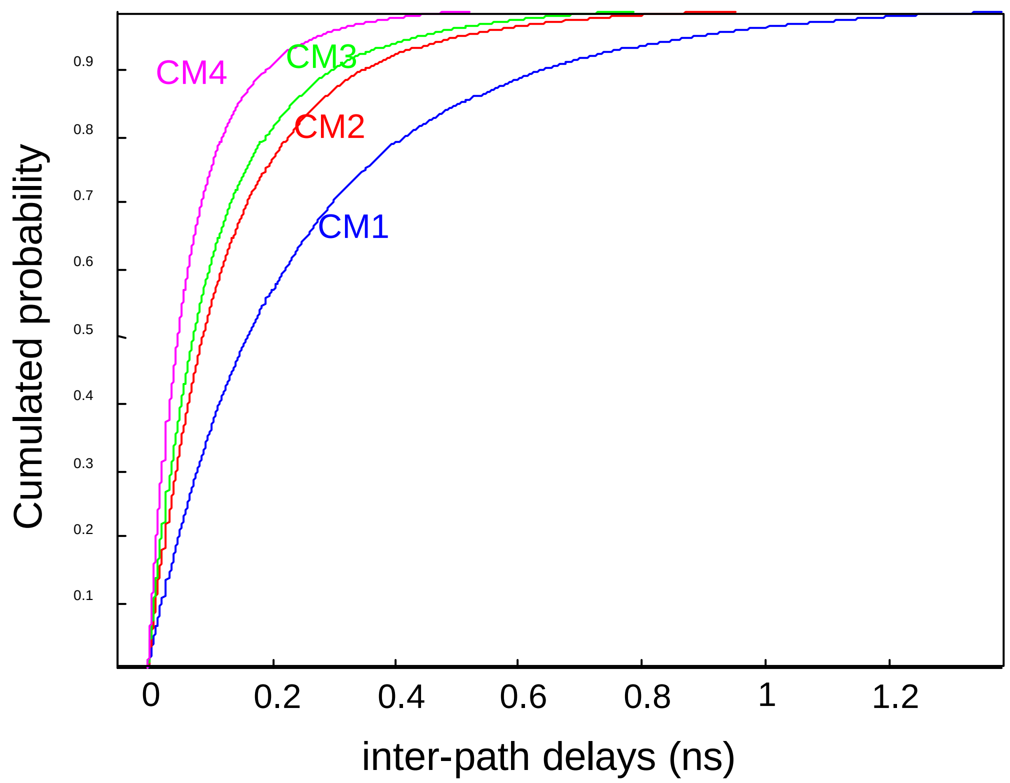

Fig. 13: distribution of inter-path delays for IEEE channels

III Results and discussion

Below are shown the statistical distributions of the modification of SNR by the replacement of ideal antennas by real antennas. with respect to ideal antennas.

First the effect of various normalization conditions can be appreciated on fig. 18. the antenna gain is directly visible on the SNR (black curves). When a constant EIRP is imposed, this gain disappears when a real antenna is placed at the transmitter side. When a constant received power is imposed for an ideal (free space) channel, the antenna gain of both antennas is removed. Still the SNR is different from its value for ideal antennas, which stems from the influence of antenna dispersivity. In spite of the fact that the same antennas are used on both sides (right part of figure 14), the SNR loss by imposing constant received power on an ideal channel is not twice that the SNR loss by imposing constant EIRP. Again this results from the complicated interplay between antenna dispersivity and channel dispersivity. Such a difference is not seen in channels with less dense multipath.

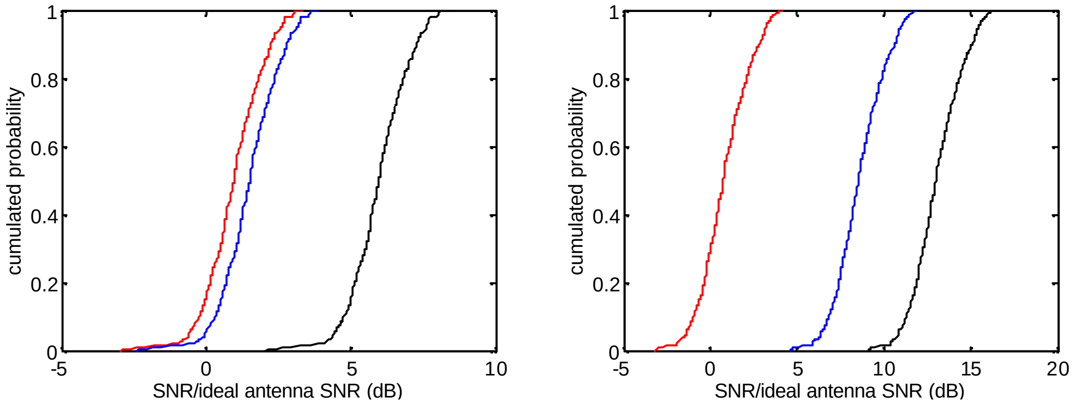

Fig. 14: distribution of SNR with respect to ideal antennas and various normalization conditions; simulated horn and ENSTA NLOS channel; black : antenna gain included; blue : EIRP limitation at the transmitter; red : received power unchanged for an ideal channel; left : real antenna at the transmitter only; right : real (identical) antennas on both sides.

In fig. 15 are shown the distributions of SNR in the case of normalization by constant received power (all antenna gains removed), in order to highlight the role of antenna dispersivity vs. channel dispersivit, for the three antennas and IEEE channels CM1 and CM4. Several remarks can be drawn :

- The SNR is almost always worse than for ideal antennas, with the notable exception of the horn. See comment below.
- In general, the SNR is degraded when the ideal reference template is used, and less or not degraded when the antenna filtered template is used. The exception is essentially for CM4 channel, which is also the densest in terms of multipaths as shown by the distribution of inter-path delays (see fig. 13). It is rather remarkable that the log-periodic is nearly perfectly “equalized” by the antenna filtered template, less or much less so for the other two antennas.
- There is a greater dispersion of the SNR for the log-periodic antenna and the horn than for the monocone. This antenna tends to have a SNR closer to that of the ideal antennas than the other two.

- Generally the SNR degradation is larger for two real antennas than for a single one, but not necessarily by a factor two.

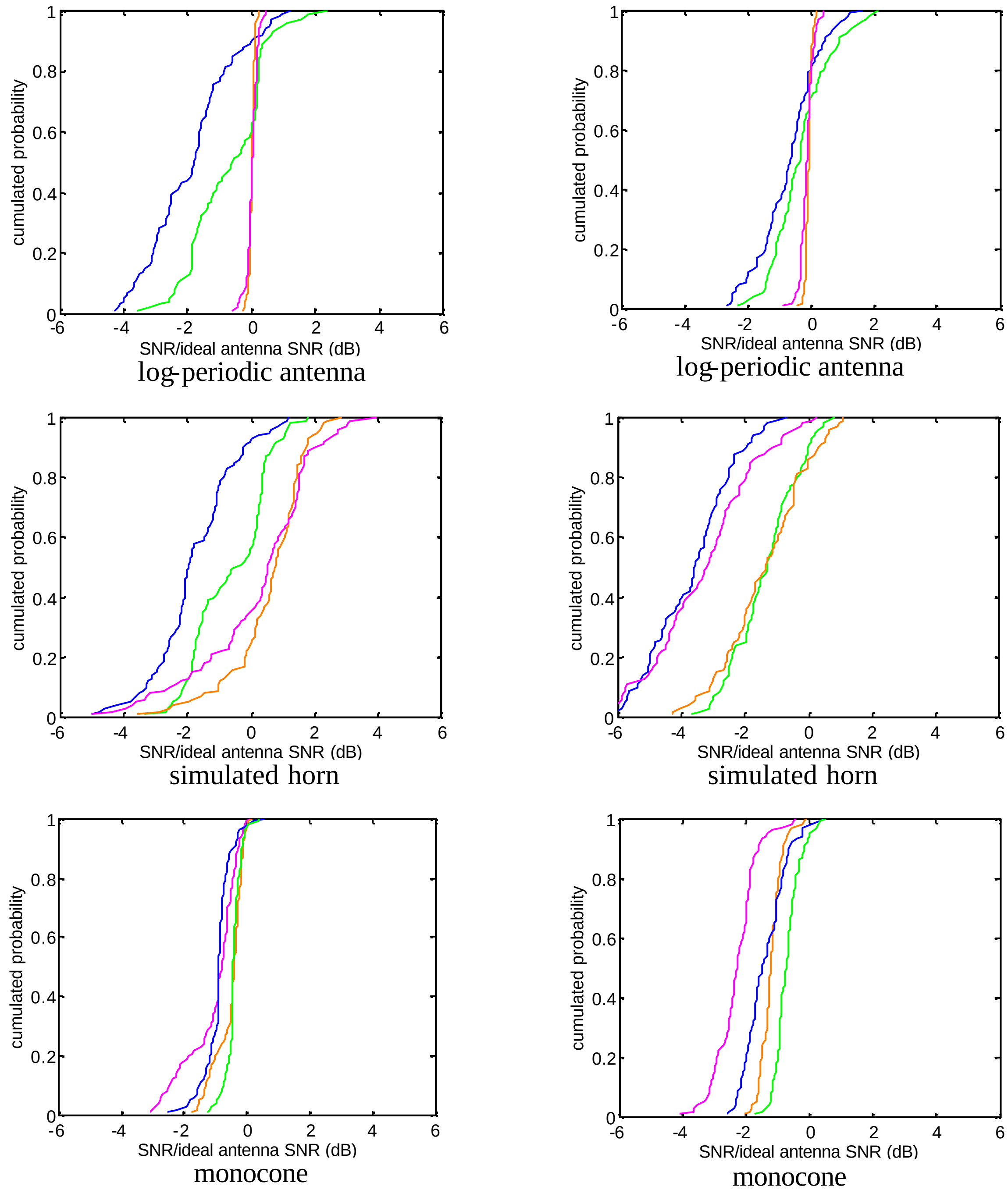

Fig. 15: distribution of SNR with respect to ideal antennas; IEEE channels; left : IEEE-CM1; right : IEEE-CM4;

green :	one real antenna, ideal template
blue :	two real (identical) antennas, ideal template
orange :	one real antenna, antenna filtered template.
magenta :	two real (identical) antennas, antenna filtered template.

The results in the case of ENSTA LOS and NLOS channels are basically on the same line, with some closeness between LOS and IEEE-CM1 on one hand, and NLOS and IEEE-CM4 on the other. Although the distributions of delay spreads do not fall exactly in the same ranges (fig. 12), IEEE-CM1 is indeed a LOS channel and IEEE-CM4 a NLOS one.

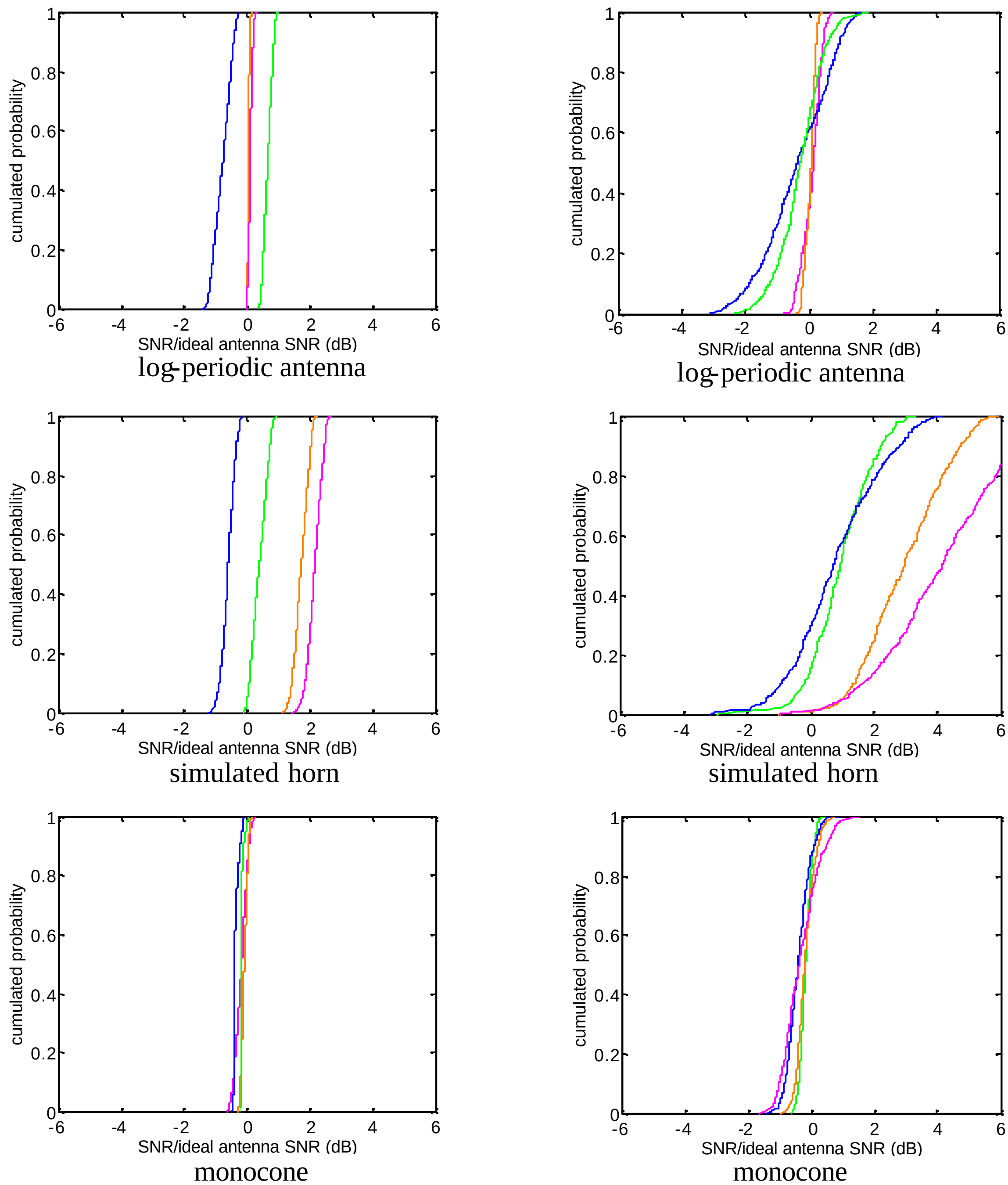

Fig. 16: distribution of SNR with respect to ideal antennas; ENSTA channels; left : LOS; right : NLOS;

green :	one real antenna, ideal template
blue :	two real (identical) antennas, ideal template
orange :	one real antenna, antenna filtered template.
magenta :	two real (identical) antennas, antenna filtered template.

A confirmation of the unexpected feature mentioned above is the *improvement* of the SNR in the case of the horn, especially in the NLOS channel, for antenna at both sides, and with the antenna filtered reference template where the improvement can reach 8 dB. It is not expected to improve so much the SNR by replacing an ideal antenna by a “poor” one and additionnally removing its antenna gain (constant receive power normalization) ! The explanation to this enigma is simple and is related to the frequency behaviour of the antenna (figs. 17-20). It can be seen that the received spectrum is much narrower for the horn than for the other antennas, due to its smaller bandwidth. This improves the SNR by reducing the noise power. This effect is further enhanced when horns are used at both ends of the radio link.

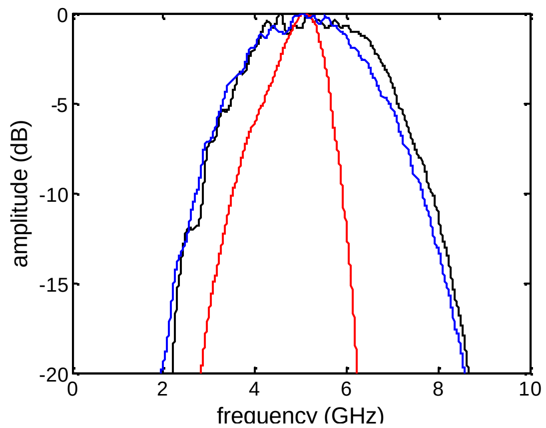

Fig. 17: received spectrum (normalized) in the case of an ideal channel, after convolution with one real antenna : monocone (black), log-periodic antenna (blue), and simulated horn (red)

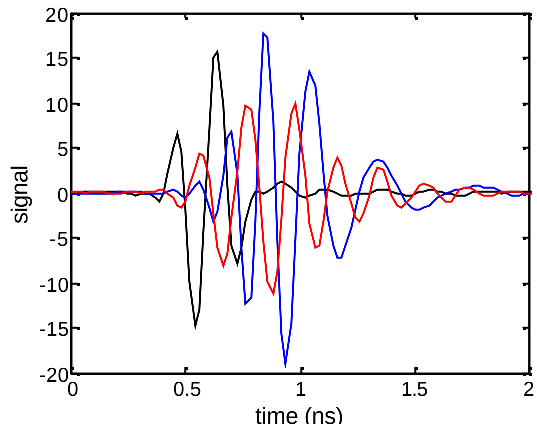

Fig. 18: same as the previous figure, in the time domain. The antenna gain has not been removed.

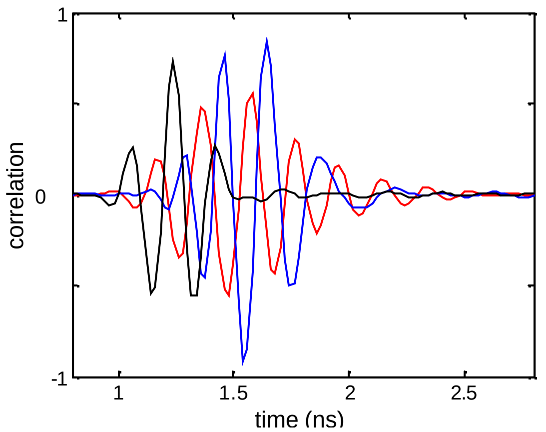

Fig. 19: correlation between the reference (ideal) template and the received signal, for one real antenna : monocone (black), log-periodic antenna (blue), and simulated horn (red); antenna gain not removed.

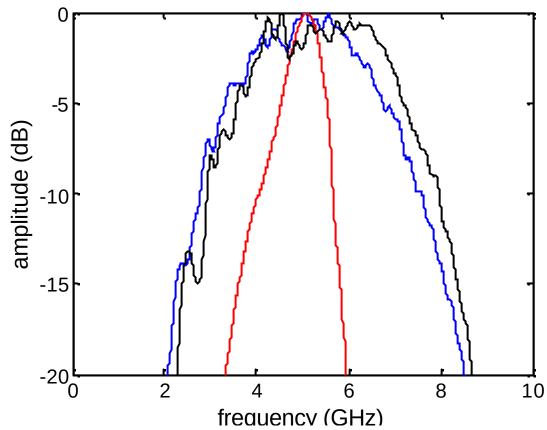

Fig. 20: received spectrum (normalized) in the case of an ideal channel, after convolution with two identical antennas : monocone (black), log-periodic antenna (blue), and simulated horn (red)

Finally the «elementary» effect of channel dispersivity on the SNR can be seen in fig. 21. For a very little dense channel, steps are clearly visible o the CDF curve, corresponding to one, two or more multipaths interacting within the effective antenna convoluted pulse duration. This discreteness is no more visible for more complicated channels where a great variety of number of multipaths interact within the effective duration..

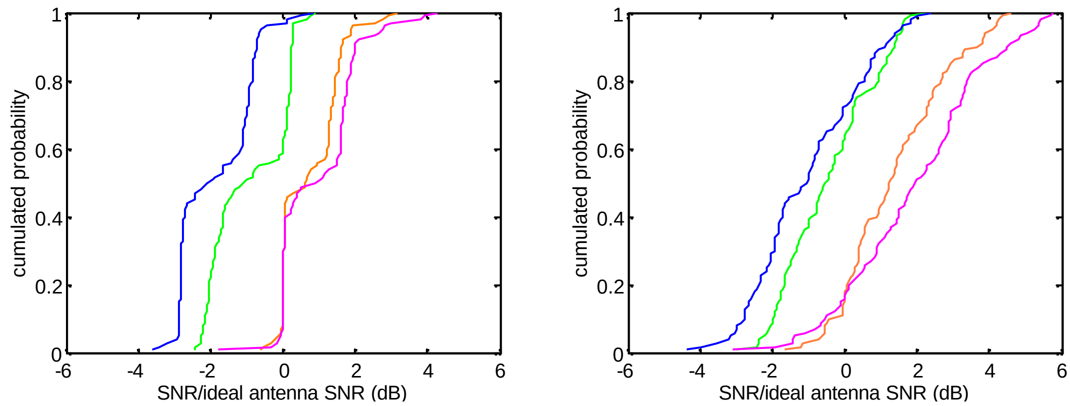

Fig. 21: distribution of SNR with respect to ideal antennas; ENSTA channel model; left : channel 1; right :channel 2; horn antenna.

green : one real antenna, ideal template
blue : two real (identical) antennas, ideal template
orange : one real antenna, antenna filtered template.
magenta : two real (identical) antennas, antenna filtered template.

IV About the filtering role of antennas

One of the original motivations for developing UWB technologies is their supposed cheapness potential. This results from a smaller number of costly components, like mixers. Without entering such a debate, it is obvious that reducing the number of components is favourable both for cheapness, consumption and compactness purposes. Regulations impose drastic spectral requirements on UWB electromagnetic emissions, requiring such filters at the transmitter, which are currently implemented with suitably designed analog filters. The question may arise whether the antenna itself, with its limited bandwidth, could not play such a role and eliminate this particular component. The calculation below show this is a sub-optimal solution in terms of SNR, when implemented at the receiver.

Coming back to Fig. 1, we can write for the output of the correlator :
$S(t)=\int r(t).ref(t-t).dt$ and $N(t)=\int N_0(t).ref(t-t).dt$ with $t=t_{clk}$

Assuming white Gaussian noise, the expectation of noise power comes as follows, with $H_{ref}(w)$ the Fourier Transform of $ref(t)$:

$$E\left(N^2\right)=E\left(\left|\int N_0(t).ref(t-t).dt\right|^2\right)=E\left(\left|\int N_0^*(w).H_{ref}(w).\exp(-jwt).dw\right|^2\right)$$
$$E\left(N^2\right)=E\left(\left|\int N_0^*(w_1).N_0(w_2)H_{ref}(w_1)H_{ref}^*(w_2).\exp\left(-j(w_1-w_2)t\right).dw_1.dw_2\right|\right)$$

$$E(N^2)=E\left(\left|\int N_0^2 d(w_1-w_2)H_{ref}(w_1)H^*_{ref}(w_2).\exp(-j(w_1-w_2)t).dw_1.dw_2\right|\right)=N_0^2\int\left|H_{ref}(w)\right|^2.dw$$

$$E(N^2)=N_0^2\int\left|H_{ref}(w)\right|^2.dw=N_0^2\int\left|ref(t)\right|^2.dt$$

where N_0 is the noise power spectral density.

The SNR can be written $Max_t\left(S^2(t)\right)/E(N^2)=Max_t\left(S^2(t)\right)/\left(N_0^2\int\left|ref(t)\right|^2.dt\right)$.

Let us consider an ideal receiving UWB antenna, i.e. verifying $H_{Tx}(w)=1$. In this case the matched filter reproduces the received signal temporal profile, and thus obeys $ref(t)=r_{ideal}(t)$; then :

SNR= $\left(\int\left|ref_{ideal}(t)\right|^2.dt\right)^2/\left(N_0^2\int\left|ref_{ideal}(t)\right|^2.dt\right)=\int\left|ref_{ideal}(t)\right|^2.dt/N_0^2$

Let us now consider an imperfect receiving UWB antenna (transmission antenna unchanged), i.e. verifying $H_{Tx}(w)\leq 1$ and varying with ω. Then the matched filter is chosen such as $ref(t)=r_{ideal}(t)*H_{Tx}(t)$, i.e. the template involves the filtered received signal. Then :

SNR= $\int\left|ref_{ideal}*H_{Tx}(t)\right|^2.dt/N_0^2=\int\left|Href_{ideal}(w)H_{Tx}(w)\right|^2.dw/N_0^2$

SNR= $\leq\int\left|Href_{ideal}(w)\right|^2.dw/N_0^2=\int\left|ref_{ideal}(t)\right|^2.dt/N_0^2$ =SNR(ideal antenna)

In other words antenna filtering at the receiver reduces the SNR, simply because at reception part of the incident energy is filtered by the antenna while the noise at the amplifier input is not filtered by this same antenna..

On the other hand using the transmitting antenna as a shaping filter is not detrimental in terms of SNR. However in most applications this same antenna will also be used in the receiving mode, and reciprocity implies that it will perform filtering in the same way. Therefore SNR degradation will also occur.

Still it may be useful to use "moderate" antenna filtering, inducing only a small SNR degradation, and allowing to simplify the downstream filter architecture.

V – <u>Conclusion</u> :

In this work it has been attempted to analyse and evaluate the role of antennas in a UWB radio link, in terms of gain vs. dispersivity. For this purpose several normalization conditions have been used, and both ideal and antenna filtered reference templates considered.
It appears that aside from "normal" antenna gain, dispersivity is responsible for a degradation of the SNR which ranges between a few tenths of dB and a few dBs for a single antenna, which is not enormous whereas some antennas exhibit strong dispersivity (e.g. the log-periodic antenna). A low dispersivity antenna such as a suitably shaped monocone [4] also has the smallest dispersion of SNR in general. In certain cases, a small improvement of the SNR is effectively observed, unless the small antenna bandwidth was responsible for a reduced noise power with a consequently much improved SNR.

Finally by analysing the possibility to use the antenna as an input signal shaping filter at the receiver, it has been shown that it would lead to a reduction of the SNR, not a desirable feature.

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