Diversity combining for enhanced Multi-user throughput in pulse based UWB communications

Alain Sibille
ENSTA/UEI, 32 Bd Victor, 75739 Paris cedex 15, France
alain.sibille@ensta.fr

***Abstract* - We investigate a simple protocol for multi-user synchronous high data rate communications between a central node and several terminals, in the case of a pulse based ultra wide band physical layer. Using RAKE combining with or without multiple antennas at either or both sides helps improve the signal to interference ratio (SIR) by typically 10 dB for 3 users in a LOS or NLOS channel. The protocol makes use of a simple iterative algorithm to maximize the SIR.**

1. Introduction

Ultra wide band signalling provides an attractive alternative to conventional narrow band signalling for short range/high data rate communications [1]. However much work is still required in order to extend usual signal processing techniques to UWB, and to exploit the potential of UWB through new approaches. Due to the stringent limitation of transmission power imposed by regulation authorities [2], achieving high data rates at radio distances of interest for contemplated applications needs a real effort on transmitter/receiver architectures and hardware. In the European project ULTRAWAVES [3], work has been carried out in order to construct a UWB multimedia communication system based on a pulsed physical layer scheme. The application scenario consisted in the simultaneous transmission of several video streams, and their aggregation into a single high resolution movie with three projectors. Achieving such a goal with three wireless links means some form of multi-user operation, each projector being one user, receiving one video stream from a central UWB node in the downlink connection.

In the present work we investigate the possibility to achieve simultaneous UWB transmission to or from several terminals, by exploiting the enormous multipath diversity of realistic UWB channels through proper combining of time delayed replicas at either or both ends of the radio link. This can be achieved either with single antennas (RAKE combining), or with multiple antennas. This scheme differs from the one proposed in [4], where the simultaneous operation was obtained by reverse filtering the various transmission channels through all-RAKE combiners. Here, by evaluating the multi-user interference, we show that a high signal to interference ratio (SIR) can be achieved, allowing simultaneous multiple data streaming under proper coding. This scheme is compatible with various pulse based modulations, like pulse amplitude modulation (PAM) with single pulses or multiple pulses (direct sequence coded, DS-UWB) or pulse position modulation (PPM).

The principles of the proposed scheme are introduced in section II. The signal and channel models are described in section III, followed by the presentation and discussion of results.

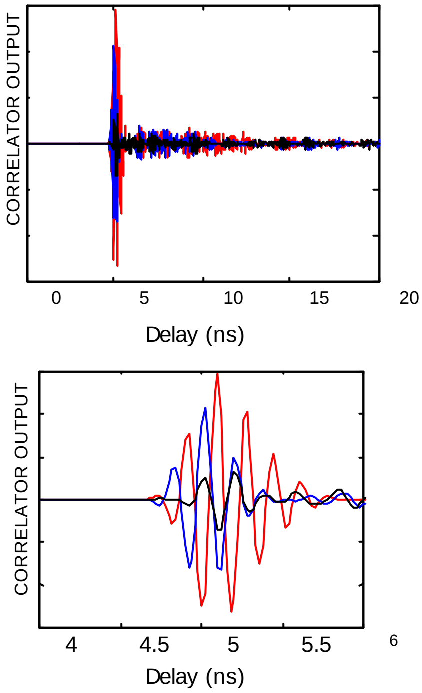

Figure 1: correlator ouput signal for 3 different users (simulated LOS channel, single pulse)

2. System model and multi-user operation principle

We consider a correlator based architecture, where a reference waveform (template) is correlated with the received signal. In the case of an ideal (free space) channel and a single user with Gaussian noise, the optimal template is identical with the received signal. Depending on the modulation scheme, the transmitted (and template) may be a single pulse, or a coded sequence of pulses modulated by +1/-1 (DS-UWB), or a double pulse of opposite polarity (2 states PPM).

Owing to the very high band width considered in UWB communication systems (FCC requires 20% relative BW, or 500 MHz), the radio channel exhibits a very fine temporal resolution, which can be usefully exploited. In Figure 1 can be seen the received signal for two users for a single pulse modulation, at the correlator output. The basic idea of the present multipath diversity scheme, is to benefit from the difference between channels to carry out combining of delayed and optionally spatially separated versions of the received signal, with user specific parameters so that discrimination between signals was properly achieved by simple (linear) means. We will specialize the approach to the case of a centralized node, communicating with several user terminals, and distinguish the uplink (user to node) from the downlink (node to users). In the communication protocol leading to establishing a fully parallelized multiple data stream to the users, a first phase achieves uplink multi-user operation, which is subsequently followed by the second phase to establish the downlink. The following sub-sections propose a simple iterative protocol to achieve a satisfactory link quality, but obviously variants of this protocol may be designed.

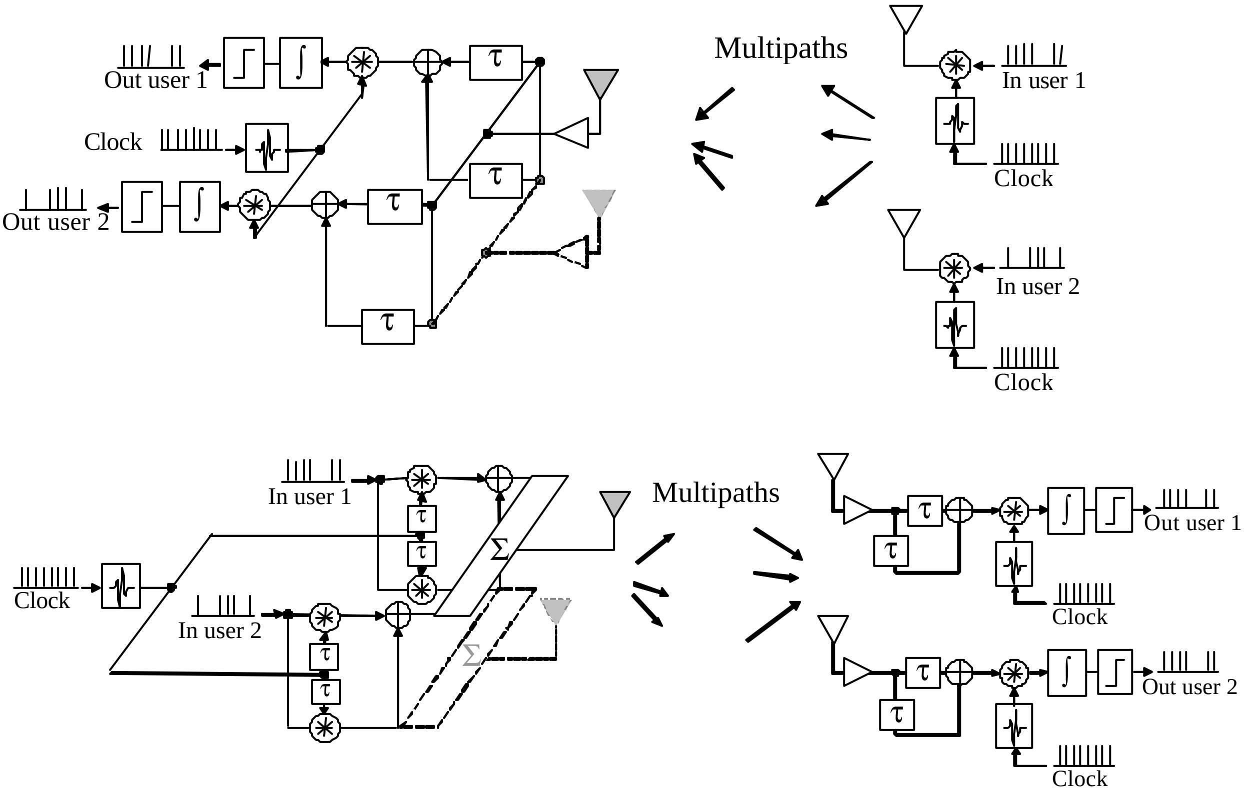

Figure 2: up : System model for a 2 users scheme in uplink. The dashed line antenna can optionally be used ; down : System model in downlink

2.1. Uplink phase

The schematic system architecture for the uplink communication is depicted in Figure . In this phase, successively each user makes use of a single (reference) branch (or antenna) to transmit a preamble to the central node. This allows the latter to acquire synchronization on its own reference antenna, for each separate user. In the following part of the uplink phase, the central node will adjust the timing delays of its other antennas in order to maximize the SIR for each user. The SIR for user i is defined as follows :

$$SIR(i) = corr(S_i, ref)^2 / \sum_{j \neq i} corr(S_j, ref)^2 \qquad (1)$$

where $corr(S_i, ref)$ is the signal at the receiver correlator stage output when user i is transmitting, for the chosen set of delays on the various rake finger (or antenna) combining branches, and $corr(S_j, ref)$ is the receiver correlator stage output when user j is transmitting. We thus need to select the most adequate set of these delays, one set per user, so that for this set the SIR was maximized. This is a multivariate non convex optimization problem, for which we propose the following simple iterative algorithm, assuming that only discrete delays are possible within a finite set of values. This assumption is based on the fact that a continuous variation of delays is neither technically simple, nor necessary. In the algorithm, all branch delays are initialized to the reference branch best symbol synchronization delay. Subsequently the best synchronisation delays are searched on the successive antenna elements one after the other in a regular order (Figure 3). Because we have a multivariate non-convex optimisatio, it is not sure that maximization over successive dimensions produced the best results Therefore the algorithm can loop after a first round of synchronisation on all elements. In practice however, this refinement turned out seldom necessary. At each iteration step for user i, $SIR(i)$ is computed and the set of delays is memorized whenever the result exceeds its previous value.

In a practical implementation, the delays can be truly applied in hardware and the SIR computed with effectively measured output signals. However this will take a fairly long time since the repetition of the preambles of all users successively will be needed to compute the SIR. Alternatively, the initial acquisition of the correlator output signal sequences enables the central node to virtually replay the combining for any set of delays by software, resulting in a reduced duration of the whole adaptive process.

After the obtention of all users delay sets, each user specific set is applied on one of the parallel layers of the central node receiver, as depicted in Figure 2, allowing the simultaneous transmission of the uplink signals. In order this to be possible of course, it will be required that $SIR(i)$ for each user was sufficiently high to allow bit decoding with few errors.

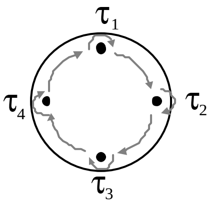

Figure 3: principle of the iterative synchronisation algorithm on a 4 sensors array

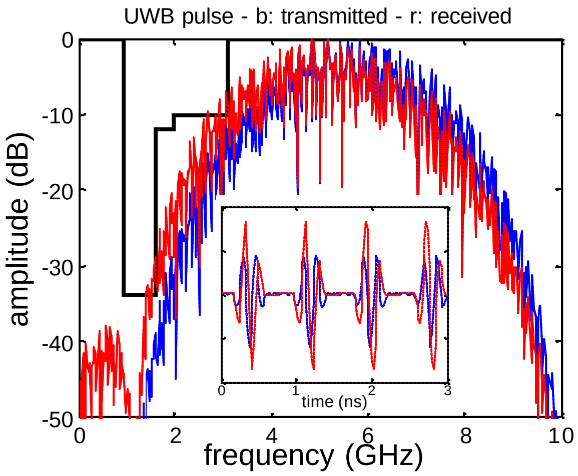

Figure 4: spectra of the transmitted (blue) and received (red) signals for a 31 pulses PN code ; black: FCC mask; inset : temporal waveforms

2.2. Downlink phase

The goal of the downlink phase is to achieve a high SIR for each user, where $SIR(i)$ is again defined according to eq. (1). This time however $corr(S_i, ref)$ is the receiver correlator stage of user i when the central node is transmitting towards this user, while $corr(S_j, ref)$ is the receiver correlator stage output of user i when the central node is transmitting towards user j.

Owing to reciprocity of the UWB radio link (same transmitted signals and BW in both senses), it could be expected that the set of delays maximizing $SIR(i)$ in the uplink would also maximize $SIR(i)$ in the downlink. However in spite of the apparent symmetry in the formulas this is not true. Therefore an additional step is needed in order to achieve adequate signal to interference ratio in downlink. This time the set of delays is adjusted in the user terminals, according to the same algorithm as for the uplink phase, where the central node successively sends a preamble to the various users Figure 2).

3. Simulation results

3.1. Signal and channel models

In the following simulations, we systematically made use of the same transmitted signal, occupying a 3 dB bandwidth close to 3 GHz for a single pulse (Figure 4). In the present work, we assume ideal antennas at both transmitter and receiver, which means here that these antennas are frequency independent when operated in transmission with no gain (isotropic antennas). It is well-known however that any antenna obeys the relation $A_{em} = l^2 G / 4p$ between the gain G and the effective antenna area in reception A_{em}, for an impedance matched load and a wavelength l. This implies such an ideal antenna to act as an integrator in the time domain, and also that the transmitted and received signals differ. In addition the antennas are here assumed electromagnetically uncoupled.

We base our analysis on 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 plane wave multipaths, each characterized by its delay, its amplitude, and its direction of arrival (DOA). The channel impulse response (CIR) writes vs. delay t and receiver antenna position $\vec{r}$ as follows :

$$h(\vec{r}, t) = \sum_i A_i d\left(t - t_i(\vec{r})\right)$$

with $t_i(\vec{r}) = t_{i0} - \vec{r} \cdot \vec{u}_i / c$

where t_{i0} is a fixed path delay, $\vec{u}_i$ is a unitary vector along the DOA at the receiver, and c is the velocity of light. The statistics and related parameters of path amplitudes, delays and DOAs are obviously crucial issues for the pertinence of the channel model. For the purpose of the present work we make simplifying assumptions :

- We specify fixed delay bins in which the number of occurrences of times of arrival (TOA) is distributed according to a Poisson law. The TOAs in each bin are randomly distributed.
- Path amplitudes are governed by a Ricean distribution with randomly generated K factors within certain limits (uniform law) ; the signs of

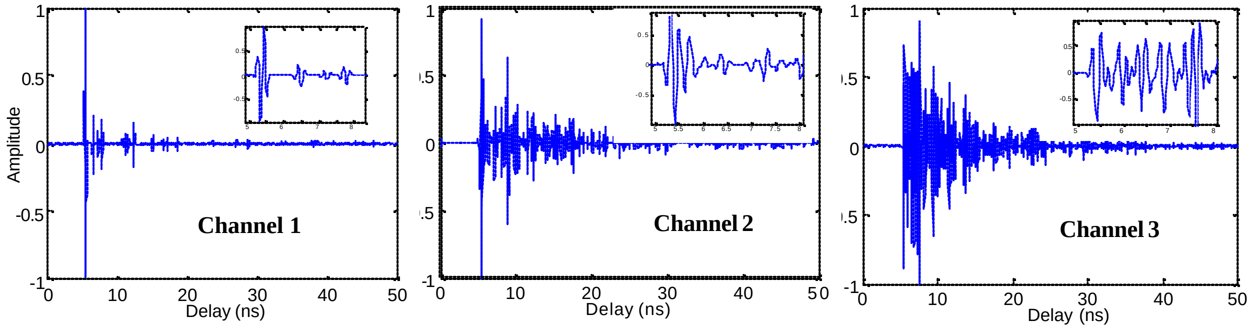

Figure 5: typical realizations of a LOS gentle channel (left), LOS dense channel (centre), NLOS dense channel (right)

path amplitudes are also random. Amplitudes decay with delay (i.e. with path length) according to an attenuation exponent.

- Path DOAs are governed by a gaussian distribution in both azimuth and elevation.
- Paths can be grouped in clusters, with cluster specific statistical parameters. This allows to generate a great variety of channels, and reproduce known channel behaviours [5].

In the simulations, a statistical set of channel realizations is constructed in order to generate cumulated distribution functions (CDF) of the SIR. A few exemplary channels have been chosen in order to show the potential and characteristics of the proposed approach (Figure 5) :

- LOS “gentle” channel (channel 1) with rather few multipaths, made of two clusters among which the first (large magnitude, small angular spread) represents the dominant LOS multipaths, and the second one is smaller in magnitude and highly spread in azimuth
- LOS dense channel (channel 2), with the same parameters as above, except for a much higher multipath density
- NLOS dense channel (channel 3), made of a single cluster fully spread over 360°.

3.2. Results of SIR statistics

We show below results obtained with the set of channels described above, and up to 4 antennas arranged in a circular array at either central node (N_C antenna elements), user terminals (N_U antenna elements), or both. A zero array radius simply means a conventional RAKE combining of signals from a unique antenna. The users are randomly oriented with respect to the central node. Thus the angular locations of users with respect to the central node are uniformly distributed independent random variables. On the other hand the distances are identical for all users, implying approximately identical channel attenuations.

The SIR improvement brought by the previously described algorithm is shown in Figure 6, for channel 2 and for 3 users. For a single antenna (no combining) the SIR CDFs are very generally quite similar for the uplink and downlink phases. In the latter single antenna case, only proper symbol level synchronization ensures a reasonable SIR. With multiple antenna combining, the typical gain on the SIR median is 12 dB at uplink and 8 dB at downlink. It can be seen that the uplink improvement is specifically brought by multiple antennas at the central node, and downlink improvement by multiple antennas at the user terminals, both gains being achieved in the MIMO case. In the following, results are shown for the typical configuration N_C=4, N_U=1, where the mere SIR difference between the uplink and the downlink SIR suffice to show the performance improvement brought by combining of signals in the central node. We see on Figure 7 for channel 3 that the same general behaviour is obtained as for channel 2. The improvement specifically brought by multiple antennas with respect to single antenna RAKE combining is channel-

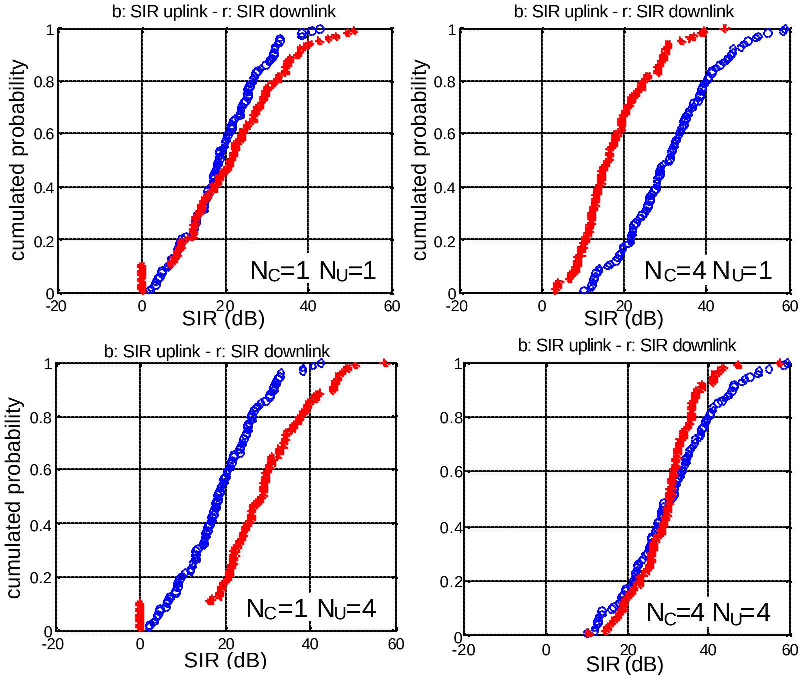

Figure6 : SIR statistics with 1 or 4 antennas at central node and user terminals (channel 2, array radius : 5 cm)

dependent (Figure 8). In the case of a low density channel such as channel 1, it is very effective to use multiple antennas which allows beamforming and improvement of the SIR by placing nulls in the unwanted DOA. In the case of a dense UWB channel, this is less necessary as the very strong multipath diversity allows to reduce SIR by exploiting the signal distortion due to the combining process. The iterative algorithms describe above achieve this because they do not use any specific directional information.

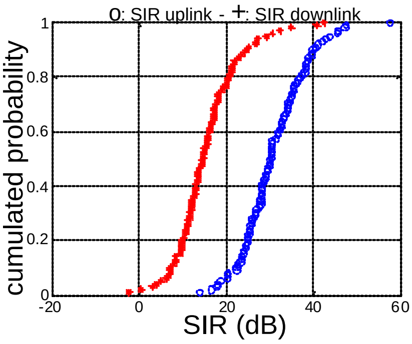

Figure 7: SIR statistics with N_C=4, N_U=1 (channel 3, radius 5 cm)

In a practical case, it is possible that not only interference but noise as well was responsible for the link quality and corresponding throughput. The relevant quantity to maximize is the signal to interference+noise ratio (SINR), which can be defined by the previous formula suitably modified in :

$$SINR(i) = corr(S_i, ref)^2 \Big/ \left(\sum_{j \neq i} corr(S_j, ref)^2 + noise\_energy \right)$$

where *noise_energy* is the input noise power integrated and filtered by the correlator. The algorithm behaviour can be appreciated in Figure 9 for channel 2, with an average received SNR of 0 dB. The median improvement by multiple antennas signal combining is around 5.5 dB, which approaches 6 dB corresponding to standard diversity gain due to enhanced energy capture [6]. We thus recover the expected gain when noise dominates the link quality.

From a practical point of view, the convergence time is a key issue in the algorithm performance, and it can be adjusted through the number of allowed (discrete) delay steps. In the previous plots a temporal excursion of ±0.6 ns by steps of 0.02 ns was used for the delay values tested in the optimization loop, typically resulting in several hundreds of iteration steps for the whole array. This is however quite excessive, as can be seen on Figure 10 : for only 45 iterations on the average the uplink performance is not much reduced, and even down to 25 iterations on the average the performance improvement is still very good (about 10 dB median) with respect to the SIR determined for the single antenna (or no RAKE) case in the same synchronisation precision conditions. Here in terms of convergence time the price to pay for RAKE or multiple antennas combining is the multiplication of the number of iterations by the number of RAKE fingers or of antennas. Of course this is not a negligible price, but in the contemplated multimedia indoor applications the channel is reputed nearly static and long convergence times may not be a serious problem.

4. Conclusion

The present work has described a single (RAKE) or multiple antenna diversity combining technique at either or both central node/user terminals, for enhanced aggregated throughput at uplink or/and downlink for UWB high data rates communications. The proposed approach attempts to reduce multi-user interference, so that the simultaneous transmission between the central node and several users was made possible. An iterative algorithm using successive trials of antenna or Rake finger delays is used. Simulations for a DS-UWB modulation with a “realistic” channel model either in LOS or NLOS have shown that a SIR gain of 10 dB typically for 4 antennas was possible, resulting in a net SIR beyond 10 dB in almost all cases. Since the channel attenuations were basically here taken identical for all users, all practical situations are not covered. A perspective of further improvements would thus be to take into account power control for the distant users.

In terms of complexity, the approach described in this paper is not very much processing power greedy, however it requires as many parallel layers in the transceivers as the number of antennas or fingers, and combiners operating at RF level over the UWB bandwidth. A comparable approach was used in the single antenna case in [7].

Acknowledgements

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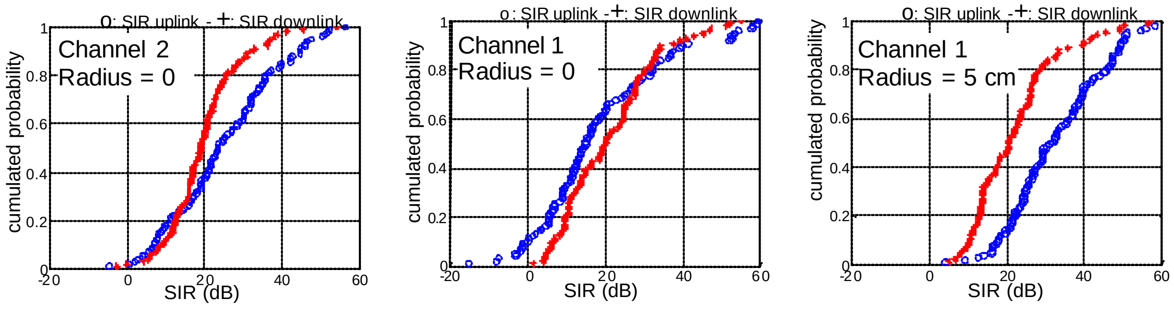

Figure 8: SIR statistics with N_C=4, N_U=1

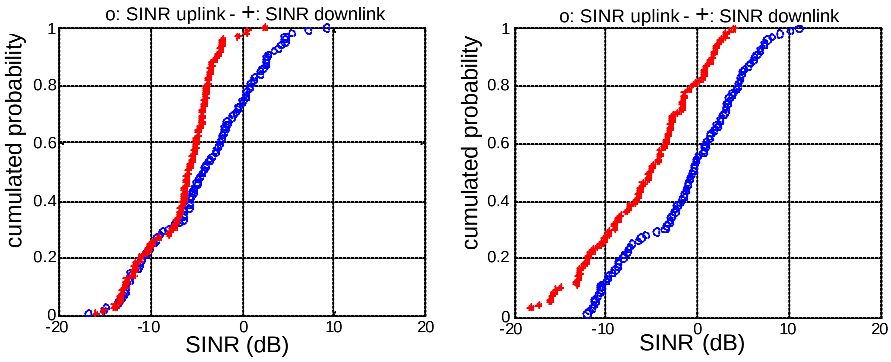

Figure 9: SINR statistics at 0 dB average SNR (left : N_C=1, N_U=1 ; right : N_C=4, N_U=1)

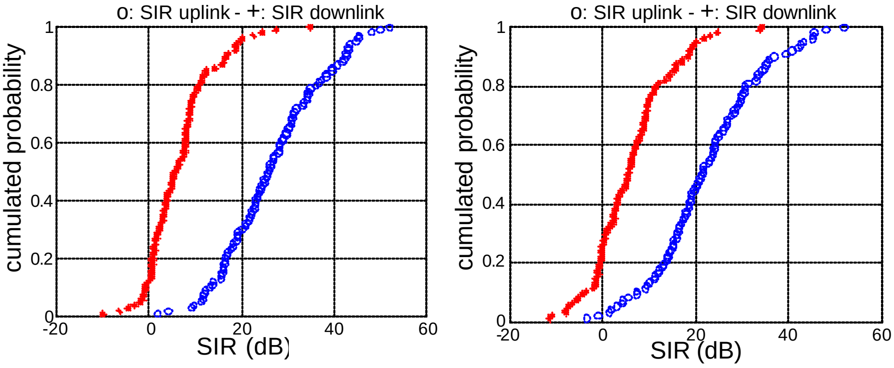

Figure 10 : SIR statistics (N_C=4, N_U=1) with 45/25 uplink average iteration steps (left/right)