FROM THE USE OF MULTI-USER DETECTION ALGORITHMS IN A WIDEBAND AIRBORNE COMMUNICATION NODE

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ABSTRACT

The Airborne Communication Node (ACN) demonstrator has been developed by EADS for the French MoD (DGA/SPOTI) in order to enhance telecommunication and network capabilities, providing up to 40 Mbps capacity on the IP standard, for both civilian and military applications (Network Centric Operations concept).

The ACN has been developed considering the fact that a SDR platform should support more than multi-mode and multi-standard communications but should also support “reconfiguration services” like QoS, FEC codes, detection...

Nevertheless, no special detection schemes/services have been implemented at the present time but studies have been done concerning the impact of Multi-User Detection (MUD) algorithms on the system. This paper shows a significant capacity impact that could have MUD algorithms for the future Airborne Communication Node. The demonstrator, upgraded with these algorithms will offer a higher data rate capability for wireless IP network over a wide coverage area and could be a part of future Network Centric Operations.

1. INTRODUCTION

In the demonstrator phase, the ACN is only composed of 10 ground mobile gateways but for the final system it would be able to provide IP connectivity for up to 50 gateways. Considering this and knowing that the noise coming from the other gateways is completely unknown and non-deterministic if you do not have the spreading and scrambling codes (due to the WCDMA Waveform), we could think that the use of more and more gateways would highly decrease the signal to interference ratio and thus degrade the global capacity performance.

The use of Multi-User Detection Algorithm not only allows us to reject the most part of the noise introduced by the other gateways, but also, thanks to this rejection of the multi-user noise, allows us to increase artificially the global capacity of the system by increasing the signal to interference ratio.

In this paper, we will first describe the ACN system, its waveform and its SDR approach. Then, we will give a description of some MUD algorithms and the results of the application of these algorithms to the ACN system.

2. DESCRIPTION OF THE ACN SYSTEM

The Airborne Communication Node (ACN) demonstrator has been developed by EADS for the French MoD (DGA/SPOTI) in order to enhance telecommunication and network capabilities, providing up to 40 Mbps capacity on the IP standard, for both civilian and military applications (Network Centric Operations concept).It is based on an airborne node which covers a 100km diameter area for up to 10 ground mobile gateways.

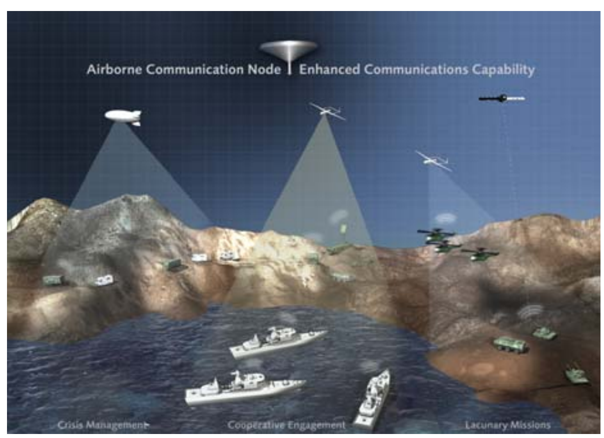

Figure 1 : illustration of the ACN system

A very high data rate is then simultaneously provided to all the forces (ships, mobile ground vehicles) and civilian actors along with a very high level of Quality of Services (QoS) whatever we are in peace time or not. This service is possible thanks to the use of a proprietary and very robust (noise, jamming) waveform.

3. THE ACN WAVEFORM

The waveform used in the ACN system uses Wideband Code Division Multiple Access (WCDMA), thus offering a natural low probability of interception and detection.

In a WCDMA system, we assign a code (called spreading sequence) to each user sending a scrambled transmission of the encoded data over the air and reassembling the transmitted data to its original format thanks to the knowledge of the code used at the emitter. The major benefits of WCDMA is increased capacity and more efficient use of spectrum.

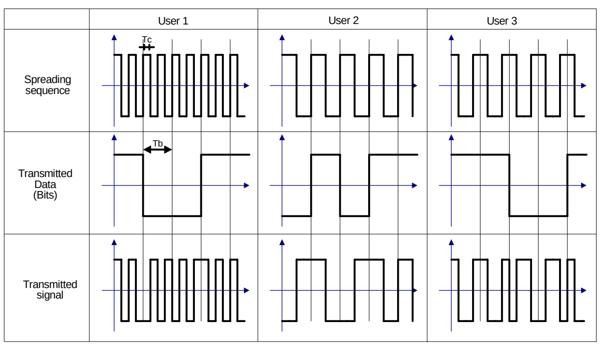

Figure 2 : illustration of the spreading process

The spreading operation in the example given in Figure 2 is the multiplication of each user data bit (±1) with a sequence of 4 code bits (called chips). User data is here assumed to be a BPSK-modulated sequence of rate R, R being the code rate of the global system (FEC, …).

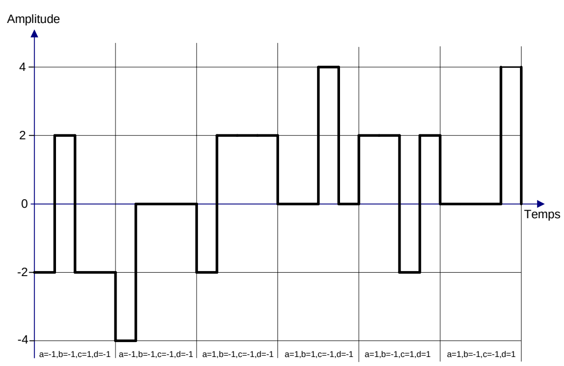

Figure 3 : e.g. of the received signal (without noise)

This spread spectrum technique results in a signal which occupies a much greater bandwidth. By assigning a unique correlating code to each transmitter, several simultaneous communications can share the same frequency allocation.

WCDMA supports highly variable user data rates, in other words the concept of obtaining Bandwidth on Demand (BoD) is well supported. Each user is allocated frames of few ms duration, during which the user data rate is kept constant. However, the data capacity among the users can change from frame to frame. This fast radio capacity allocation will be controlled by the system so that the network can achieve optimum throughput for IP services.

The system has been designed with robust and efficient algorithms along with advanced channel turbo decoding. In the ACN demonstrator, the signal power is very low for each gateway and is far below the noise level. So that the detection itself need the use of tricky algorithms to be able to extract the information from the noise. The noise comes from the environment, we would consider only Additive White Gaussian Noise, but also from the other gateways which all transmit using the same frequency resource at the same time.

4. SDR AND THE ACN NETWORK

Nowadays, it doesn't exist a perfect and unique standard which described and defined exactly what is "Software Defined Radio" (SDR). This term is often used to described a multi-mode and multi-standards communication platform using a multi-band transceiver.

Nevertheless, SDR terminals means more than that. Indeed, Mobile Wireless system are intended to support more than just multi-mode and multi-standards but also to be extremely flexible (at the highest level) while achieving a high spectrum efficiency. These means that these terminals should be able of software reconfiguration first between different standards but also within a specific standard. Then, we will talk of "Service reconfiguration" to increase spectrum efficiency.

The set of reconfigured parameters of a system may include (non exhaustive list):

- Services : Data rate, QoS, encryption/decryption parameters, …
- Error Control : CRC, FEC codes, coding rates, number of turbo decoding steps, …
- Modulation : constellation, …
- PN sequence : Spreading codes, spreading factor, PN acquisition and tracking schemes, …
- Interleaving : Interleaving parameters, adaptation to jamming, …
- Detection : coherent or non-coherent detection schemes, channel estimation/equalization, Multi-User Detection, …

In the ACN system, only one waveform is implemented (a wideband proprietary waveform) but nevertheless, a very large number of parameters could be reconfigured to increase spectrum efficiency and to provide a full “service reconfiguration” scheme. For instance, QoS, Data rate, FEC codes, spreading codes & factors, interleaving parameters are already reconfigurable on the fly (in real-time) to enhance the capabilities of the system.

This is not the case of the detection parameters which are for the moment static, but which could be completely dynamic using Multi-User Detection algorithms. Indeed, considering that we have a WCDMA waveform, this will be the only mean to increase spectrum efficiency just using a parameters “reconfiguration service”.

5. DESCRIPTION OF THE MUD CONCEPT

From this section, the performance improvements with ACN Multi-Used Detection are discussed. The target of section 5 & 6 is to give an overview of different MUD algorithms. Simulations and results are shown in section 6 & 7.

In a WCDMA system, like the ACN system, the maximum capacity that we can achieve depends, for a given bandwidth, exclusively on the signal to noise ratio (SNR). Nevertheless, the system seems also to be interference limited. This means, that if the number of users is large enough, an increase in signal-to-noise ratio yields no improvement in bit or frame error rate.

Considering that, thanks to the use of a power control algorithm, the received power of users are equal (no near-far effect) and the number of interfering users is large (>8), it can be shown that the interference can be approximated by Additive White Gaussian Noise (AWGN). This approximation has led to the fact that the matched filter is the optimum receiver for WCDMA system.

In fact, we can find in [1] & [2] that WCDMA is not interference limited and that this is exclusively due to a limitation of the conventional matched filter receiver. This means, that it is possible to find similar techniques which are able to detect and apply good correction to the multiple access interferences. These techniques will provide different performances depending on the fact the signals are synchronous or not. Anyway, we can classify these algorithms in two types:

- the linear filters
- the subtractive interference cancellation filter

We can see in figure 4 a modelisation of the multi-user access technique and a modelisation of the channel in the ACN system.

The received signal is then :

$$y(k) = \left(\sum_{i=1}^{n} A_i . PN_i(k - T_i) . Bit(i, k - T_i) \right) + n(k)$$

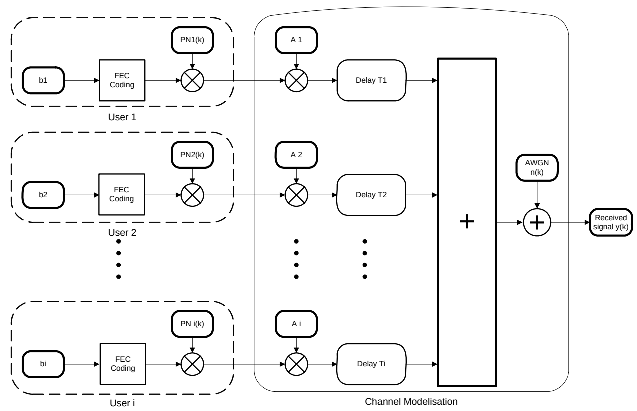

Figure 4 : Multi-Users access and channel modelisation

After correlation, we obtain the non-normalized expression for user 1:

$$Estimated\_Bit(1) = \sum_{k} PN_1(k) . y(k)$$

Then we can estimate the noise coming from the other users as:

$$MUD\_noise = \sum_{k} \left(\sum_{i=2}^{n} A_i . PN_i(k - T_i) . PN_1(k) . Bit(i, k - T_i) \right)$$

As the sequences used by the other users are not completely orthogonal, this term is not equal to zero. Its impact on the good estimation of the value of the transmitted bit can be relatively huge and then, the aim of MUD algorithms is to reduce or to completely eliminate this term.

5.1 The linear filters

The most widely used linear filters are decorrelating detectors or minimum mean square error (MMSE) detector. We will not describe all the methods and sub-methods (synchronous, asynchronous, exact decorrelating detector, …) in this article, but we will provide to the reader the basis of these two techniques so that you can appreciate the complexity of each methods and understand the results given in section 6 & 7.

5.1.1 decorrelating detector

This technique consist in using the correlation properties and the knowledge that we have at the node concerning the spreading sequence used by each user to estimate the exact value of the multi-user noise and to subtract it to the signal.

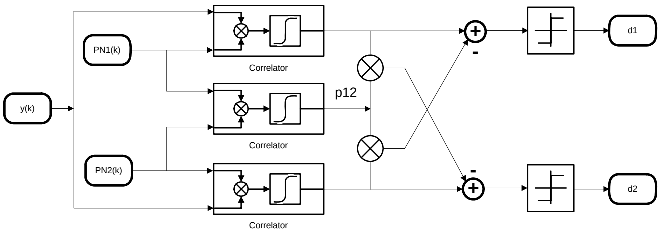

Figure 5 : decorrelating detector for 2 users

Considering the two users case shown in figure 5, we have:

$$Estimated\_Bit(1) \approx A_1(1-\rho_{12}^2)Bit(1,k)$$

with:

$$\rho_{12} \approx \sum_k PN_1(k).PN_2(k)$$

So, in this case, the perturbation is coming from the cross-correlation term ρ_{12} that we have to suppress to find the exact value of the transmitted bit.

This can be easily generalized to a n users scheme. Nevertheless, it is easy to understand that more users you have, more complex will be the detector and you will rapidly have to cope with resources limitations. And so, we can easily show that for more than 4 users approximation are compulsory and it is not anymore possible to compute the exact value of the interference term caused by other users. We can see in Figure 6 a matrix representation of the decorrelating detector where:

$$R = \begin{pmatrix} 1 & \rho_{12} & \rho_{13} & & \rho_{1n} \\ \rho_{12} & 1 & & & \\ \rho_{13} & & 1 & & \\ & & & & \\ \rho_{1n} & & & & 1 \end{pmatrix}$$

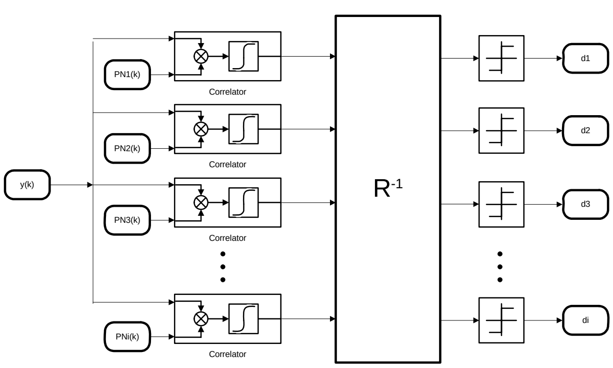

Figure 6 : decorrelating detector with use of matrix

5.1.2 MMSE detector

Here, the principle is exactly the same that the decorrelating detector using a matrix representation except that we replace the matrix R by R' with:

$$R' = R + \sigma^2.diag\{A_1, A_2, ..., A_n\}$$

where σ^2 represent the noise variance.

To conclude concerning these two methods, the different users are made uncorrelated by a linear transformation. This linear transformation is computed by measuring all cross correlations between pairs of user codes and then inverting the resulting huge matrix of cross-correlations. Since in practical systems each user is assigned a very long pseudonoise (PN) code, each bit has essentially a random code assigned to it. Thus, in this case, the above procedure would have to be repeated for each bit in succession.

5.2 The subtractive interference cancellation filter

This filter attempt to explicitly estimate the multiple access interference term and then subtract it from the received signal. This can be performed in parallel to all user, resulting in parallel interference cancellation (PIC), or serially, resulting in serial interference cancellation (SIC).

5.2.1 PIC detector

Parallel processing of multi user interference simultaneously removes from each user the interference produced by the remaining users accessing the channel. In this way, each user in the system receives equal treatment insofar as the attempt is made to cancel multiple user interference.

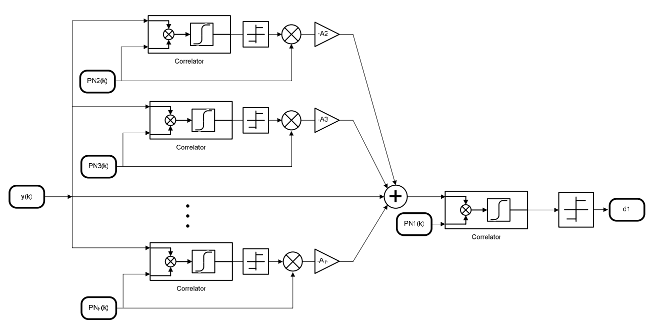

Figure 7 : PIC detector principle

5.2.2 SIC detector

The main disadvantage of this scheme has to do with the required delay necessary to fully accomplish the interference cancellation for all the users in the system.

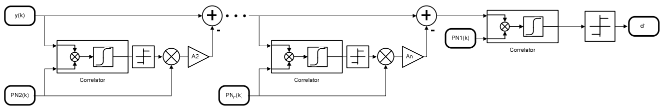

Figure 8 : SIC detector principle

The parallel processing is to compared with the serial processing scheme, since the interference cancellation is performed in serial for all the users. Otherwise, the technique is exactly the same that for the PIC. In this case, the delay required to complete the operation is at most a few bit times.

5.2.3 Two stages SIC detector

The approach successively cancels strongest users using SIC detector along with the power of correction of the turbo product code (TPC) channel decoder used in the ACN system and then re-encode the decoded bits to improve the multiple access interference detection. Then, the interfering signal is recreated at the receiver and subtracted from the received signal before to be again decoded by the channel TPC decoder.

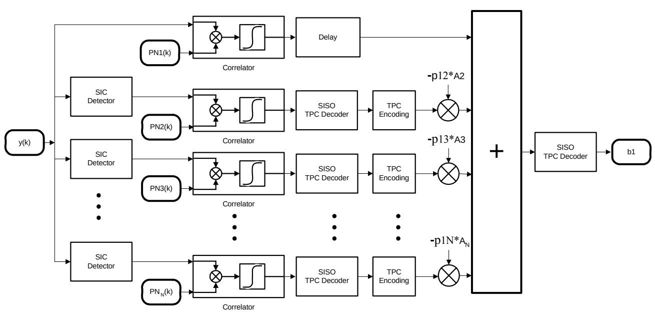

Figure 9 : principle of the two stages SIC detector

6. SIMULATIONS

This section presents the simulations that we have done and helps the reader to compare the different algorithms. All the simulations have been done using the Matlab/Simulink tool.

The simulation were done first using 1 user and 3 interferers, all using the same data rate on the channel and AWGN was added progressively to simulate the impact of an increasing noise on the system and the gain of each algorithm. All the curves are functions of the BER after hard decision and of the AWGN E_b/N ratio added to the user of interest. The ACN modulation is an M-PSK like modulation.

The decorrelating filter as been tested using the approximation form and not the exact one in order to improve the simulation time. Anyway, the exact form could not be implemented at the present time in a real device due to the important resources which are required. The matrix form has also been implemented.

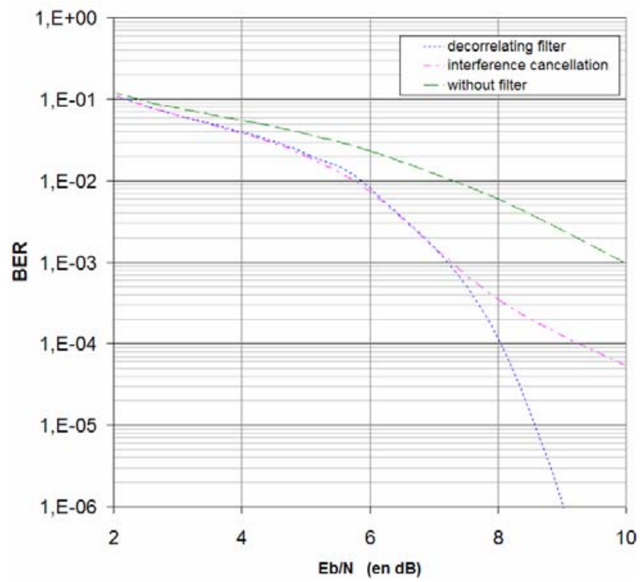

Figure 10 : BER vs Eb/N for different filters (synchronous mode)

Here, we can observe that when the noise power is high, all the algorithms tend to have the same behavior, but nevertheless, as far as E_b/N increase, the decorrelating detector shows clearly how it can reduce the noise coming from the interferers.

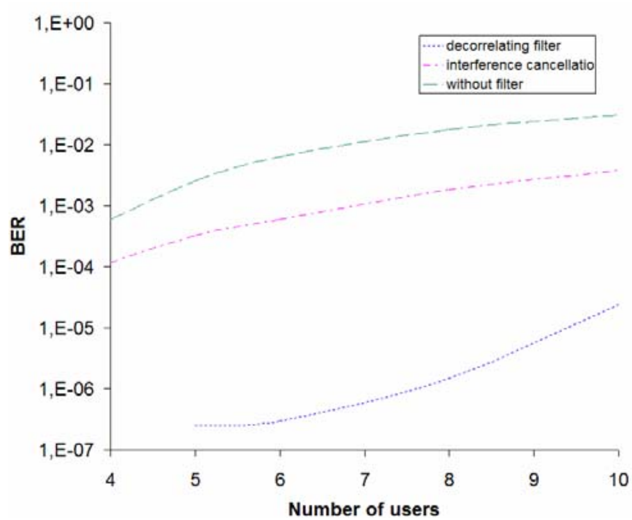

Figure 11 : impact of the number of users on the BER for different filters (synchronous users)

Here, we can see that for 10 users, the impact of the interference cancellation is at least of 1 decade on the BER after decision compared to the unfiltered form, and more than 3 decades for the decorrelating filter.

Nevertheless, these simulations have been done with synchronous users.

Then, the simulations have shown that even if for a synchronous communication the decorrelating filter is the most suitable algorithm to use, for asynchronous communication, this is not anymore the case when the noise level is high. For asynchronous communication, the results depend clearly of the value of the delay between each users.

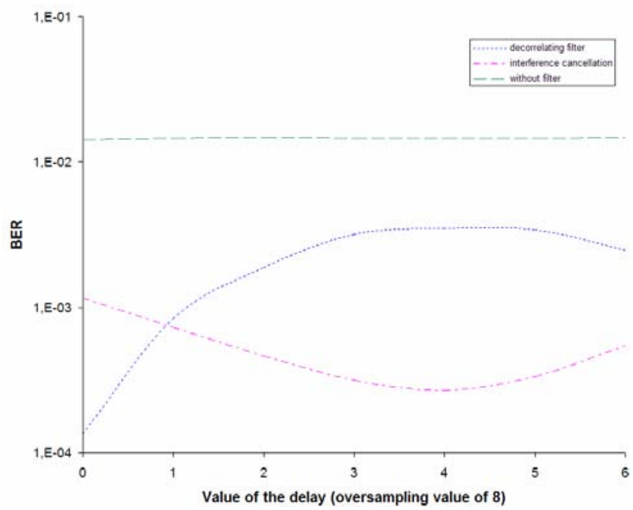

Figure 12 Variation of the delay for asynchronous communication with an Eb/N of 10 dB

If we do the same simulation with different values of E_b/N and that we represent the mean value of the BER, we have the result shown in figure 13.

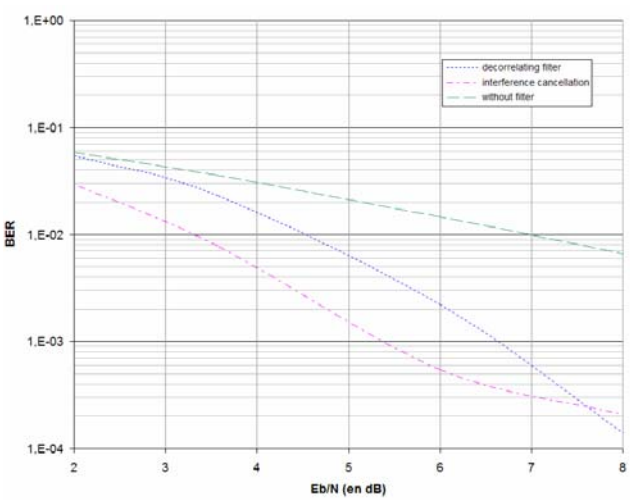

Figure 13 : BER vs Eb/N for different filters (asynchronous mode)

Then, we can check the impact of the 2-stages SIC detector using TPC correction. The simulation are shown for the synchronous mode in figure 14.

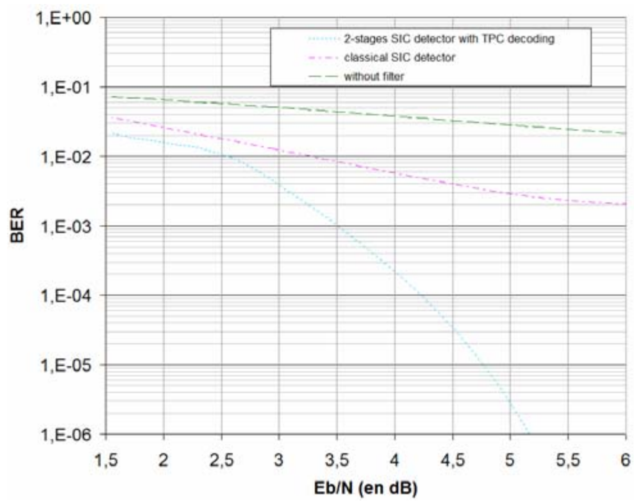

Figure 14 : Impact of the use of the 2-stages SIC detector with TPC decoding

7. RESULTS

Different algorithms have been tested to find the more suitable for the ACN Waveform, such as decorrelating filters, successive interference cancellation or MMSE. They have been implemented in software in a Matlab/Simulink environment and tested using the global simulation model and so the real waveform of the system. The impact of the information coming from a SISO Turbo-Product Code Channel decoder to improve the global performances of the algorithms has also successfully been tested.

Lower computation and hardware related structures are the main advantages of PIC/SIC methods beside the main advantage of lower BER or better capacity than linear multi user detectors (decorrelating detectors, MMSE) in synchronous case. This is not anymore the case for asynchronous communications as in the ACN system. So, we can see than in the ACN environment, the most powerful algorithm to use would be the 2-stages SIC detector with TPC decoding. This algorithms should be implemented in the future ACN network to increase again the global capacity of the system.

9. REFERENCES

[1] Verdù, Multiuser Detection, Cambridge University Press, Cambridge, UK, 1998

[2] Holma & Toskala, WCDMA for UMTS, Wiley, England, 2002