The spatio-temporal blind equalizer TRIDENT
Interest of real-time acoustic communication for mine and antisubmarine warfare.

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Abstract: **There is no doubt about the growing interest in underwater acoustic communications. Among all existing applications, the objective of the Groupe d'Etudes Sous-Marines de l'Atlantique (GESMA) is to develop a sufficiently robust high data rate acoustic link, named TRIDENT. A real-time receiver, based on a spatio-temporal blind adaptive decision feedback equalizer, developed and patented by ENST Bretagne was designed to cope with all perturbations induced by such harsh channels. Some sea trials were realized on 2002. The first results are clearly convincing since most of the 48 sequences of 5 minutes are successfully demodulated by the DSP in real-time.**
This acoustic system allows the transmission to data rate from 8 to 25 kbps in horizontal configuration and stand for an important step in the design of future operational acoustic communications.

I- INTRODUCTION.

The evolving roles of underwater vehicles are presently constrained by the lack of reliable underwater communication systems. Nevertheless, for safety reasons, it could be useful to send an autonomous underwater vehicle (AUV) in underwater mine countermeasures (MCM) operations. Such a vehicle aims to take underwater images, transmit them acoustically and present to the surface vessel from which further decisions may be made. For that purpose, a real-time high data rate acoustic link is currently developed by GESMA. The objective of this project, named TRIDENT, is to design and test a solution allowing wireless communications between an underwater vehicle and a surface vessel.

As a consequence, an acoustic link has been developed in order to test the whole communication from the acquisition of useful data to the restitution. The transmission part has been realized by ORCA Instrumentation, a French company specialized in acoustic modems. The receiver was realized by ENST Bretagne. The core of this receiver is a blind spatio-temporal decision feedback equalizer (DFE) which is able to track the strong variations of the underwater acoustic channel (UWA).

This paper is organized as follows. The second part provides some recalls about the interest of blind equalization. The third part consists of an overview of this equipment called TRIDENT. Finally, two examples of the first results of the last sea-trials realized in 2002 are presented.

II- INTEREST OF BLIND EQUALIZATION.

Multipath propagation and noise are responsible of most of the effects on acoustic communication. In coherent communication systems, maximum likelihood sequence estimators (MLSE) cannot always be implemented because of their computational complexity, especially when the delay spread and/or the order of the modulation is high. For those reasons equalizers represent a good trade-off between performance and complexity. In addition, even if channels can often be considered as stationary, they may suffer from an important frequency drift between local oscillators and/or a Doppler effect. That is why, in practice, equalizers need to be adaptive and, for this purpose, the minimum mean squared error (MMSE) criterion is commonly used with the stochastic gradient least mean squares (SGLMS) algorithm. Most of the time, transmitted symbols are organized in frames built with a probe to synchronize the receiver, a period of training sequence to allow convergence of the equalizer and finally true data. As coherence time (duration over which the channel is considered as stationary) is generally unknown, training sequence has to be periodically repeated in order to satisfy worst case conditions. Finally, this strategy drastically decreases the maximum reachable throughput data rate. The blind approach consists on using the *a priori* knowledge of transmitted data statistics. This method proves to be very efficient on severe channels, such as UWA ones. The main goal of this paper is to highlight the relevance of adaptive blind equalization for continuous data flow systems. At first glance, this solution may seem unrealistic since blind equalization is well-know to exhibit low speed of convergence. Nevertheless, the blind (single or possibly multiple input) decision feedback equalizer (DFE) described in [1], [2] is particularly well suited. Hereafter, it will be called the SOC-MI-DFE for self-optimized multiple inputs configuration DFE. Basically, this equalizer is characterized by the existence of two specific running modes. In the acquisition mode, it acts as a linear equalizer while in the tracking mode it acts as the conventional DFE. The main idea of this receiver is to combine the advantages of these two structures to define a decision feedback equalizer with an adaptive configuration. Thus, in period of convergence, the linear structure is selected in order to benefit from the stability and speed of convergence. When trust in decided data is sufficient, the structure turns into DFE. Better performances could be reached. Usually, a measurement of the MSE is used to define the mode of the SOC MI DFE.
Some details on the architecture and performances of this blind equalizer could be found in [3], [4] and [5].

III- SYNOPTIC OF THE ACOUSTIC LINK.

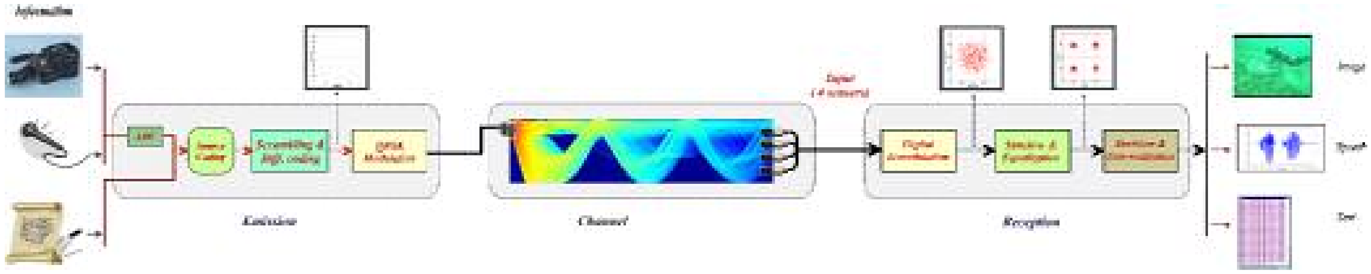

Figure 1 : Description of the acoustic system TRIDENT.

Figure 1 depicts a conceptual schematic of the acoustic system TRIDENT. A low-data rate link is first used to fix all parameters of the expected high data rate communication. Among parameters which could be fixed, one can select:

- The kind of information : TRIDENT is able to transmit various data (CCD camera snapshot, text, recorded pictures, MLBS[1] and voice);
- The kind of transmission : digital information could be scrambled and differentially encoded. Resulting information are then transmitted using 2, 4 or 8-PSK modulations.
- The data rate up to 25 kbps according to spectral bandwidth of the transducer [30;40] kHz.

The acoustic level is approximately 185 dB@1µPa\1m. Transmitted signal is received on a 4-sensors antenna, each sensor location on the antenna being adjustable.

The core of the receiver platform is an acquisition card with a Texas Instruments (TI) DSP, namely the TMS320C3201. Most of the signal processing is written in assembler language in order to reduce the processing time. In fact, there is an important gap that can reach more than 90 % in execution time depending on whether functions are written in assembler language or in C-language.

Only signal amplification, gain control and prefiltering are performed in an analogical way. Then, each input signal is synchronously sampled. Demodulation, timing-recovery and equalization are realized by the DSP. Demodulation is carried out by sampling every input signal at a clock frequency 4fo, fo denoting the carrier frequency. That is why symbol duration T was chosen in such a way that the product fo.T is an integer. Timing recovery is performed with the Gardner algorithm.

After that, T-spaced equalization can be performed. Detected data are then decoded and displayed into the GUI.

IV- DESCRIPTION OF THE SEA-TRIALS.

The first sea-trials were carried out in the bay of Brest in June and October 2002. Acoustic transmissions were performed on different ranges, 300, 1000 and 2000 meters. Three hundred meters stand for a distance where UWA channel is characterized by a harsh structure of multipath while one and two thousand meters correspond to the nominal range for desired applications.

Various areas were tested in order to evaluate the reliability of this acoustic transmission.

(1): Bay of Brest: Surf zone (minus 20 meters water depth with mud)

(2): Basse du Lis: Shallow water zone (minus 50 meters water depth with rock)

(3): Pierres Noires: Shallow water zone (minus 50m water depth with sand).

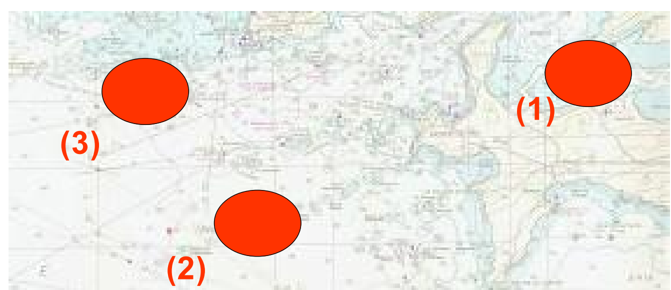

Figure 2: Area of the sea trials.

Figure 4 illustrates the procedure of sea trials. The system TRIDENT is buried at sea and recovered once a day. The transmission part is located approximately at 7 m depth. The antenna is deployed since the BEE Langevin. The space between hydrophones is 20 cm (around 5 acoustic wavelengths). The first hydrophone is deployed at 7m depth (approximately 3m below the ship's draught).

[1] Maximum Length Binary Sequence

Figure 3 : TRIDENT sub-surface equipment.

Visualization of the transmitted signals showed more or less deep fading, responsible for most of the decision errors. Approximately, 150 shots of 5 minutes and 15 shots of 15 minutes were thus transmitted.
The platform of reception TRIDENT processed in real-time received data and thus displayed decoded information.

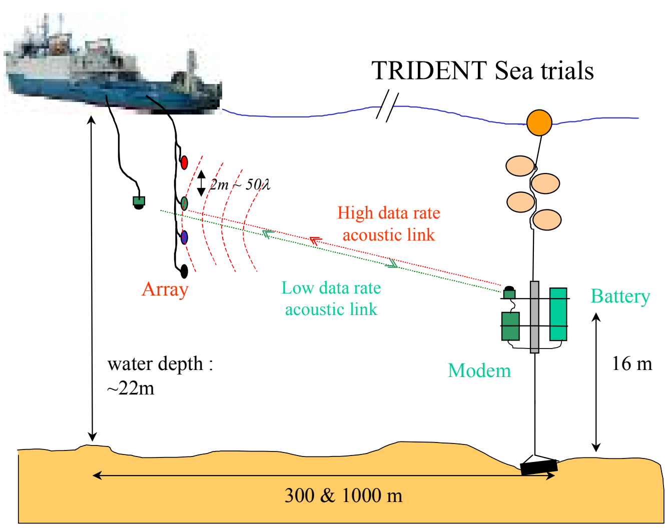

Figure 4: Configuration of transmission.

V- SOME RESULTS

Presented results correspond to a real-time UWA communication system in shallow water. The distance between transmitter and receiver was about 1000m and the depth around 20m.

The symbols were transmitted using QPSK modulation with a carrier frequency of 34 kHz and a bit rate of 11,7 kbps (12 samples within a symbol duration).

The different parameters of the SOC-MI-DFE equalizer are the followings : the transversal filter B held 10 coefficients in which 2 were for the causal part. The recursive filter A had 50 taps regards to the impulse response duration.

Table 1 depicts the evolution of impulse responses between the emitter and the four hydrophones. One can note the time-spreading around 40 symbols duration. The acoustic channel seems to be quite stable regards to the main path. Theses channels exhibit minimum phase behavior. Two main paths are visible.

Table 1 : Evolution of the impulse response.

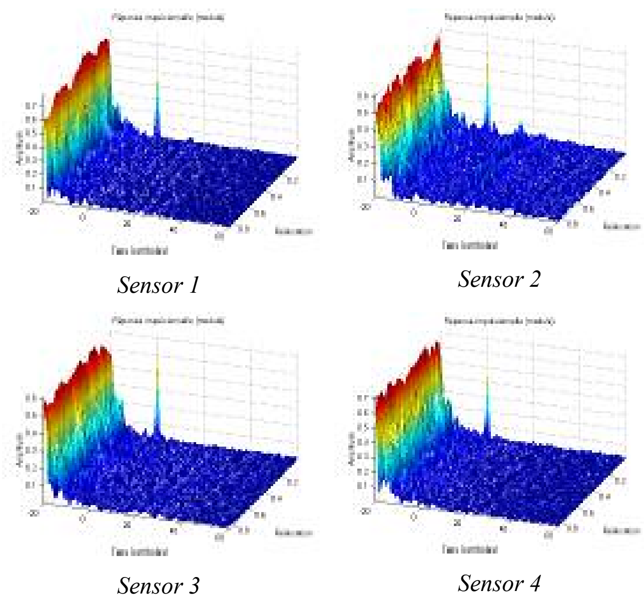

Figure 5 shows the evolution of the estimated mean square error (MSE) of the SOC-MI-DFE for 1, 2, 3 and 4 sensors. Processing is realized on more than 45 000 symbols. One can note the contribution of antenna processing. It lies in the possibility of using spatial diversity brought by various sensors. Advantages lie mainly in the reduction of probability of simultaneous fading.

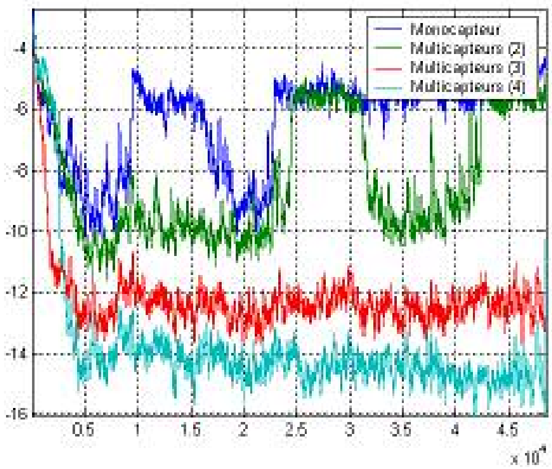

Figure 5 : Evolution of MSE regards to the number of sensors.

Figure 5 shows the evolution of the estimated mean square error (MSE) of the SOC-MI-DFE for 1 sensor (in blue), 2 sensors (green), 3 sensors (red) and 4 sensors (cyan). 4 minutes (more than one and a half million of symbols) of transmission are also successfully demodulated which proves the robustness of this receiver. Even if estimated MSE are relatively low whatever the number of sensors used, one can note that performances of the SOC MI DFE with one sensor (named in that case SADFE) can greatly fluctuate according to the position of the sensor. The interest of using multiple sensors clearly appears in that case providing more stability and sufficient safety margin. The gain brought by 4 sensors can reach more than 5 dB. More over, the time required to reach the running mode (DFE structure) is also reduced when multi-sensors are considered. Figure 7 shows the output equalizer between 20000 and 25000 symbols. It clearly highlights the gain brought about by use of 4 sensors.

Figure 6: Evolution of MSE during transmission.

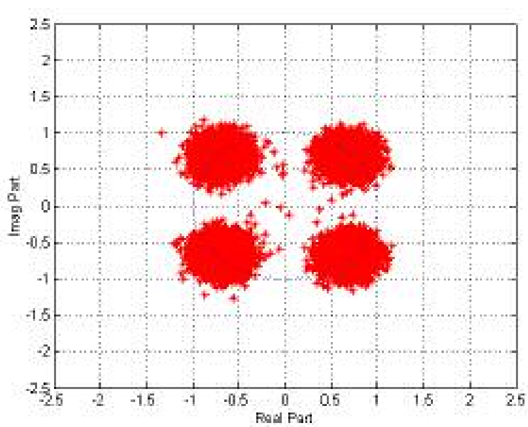

Figure 7: I-Q constellations.

Figure 8 depicts the distribution of errors during transmission. Each line draws the difference between the error-free sequence and decided sequence to within $\frac{\pi}{2}$. This is a well-known phenomenon due to the invariance of input signals statistics by a rotation of $\frac{\pi}{2}$, π or $\frac{3\pi}{2}$ for 4-PSK signals. As a result, such an approach absolutely needs differential encoding in order to solve this problem.

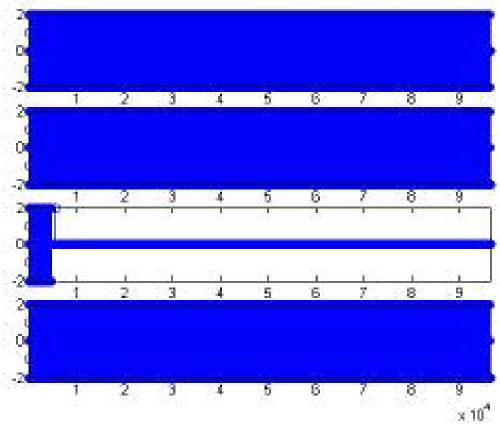

Figure 8: Distribution of binary errors during transmission.

The second example represent the transmission of a CCD camera taken by a diver. Imagery is a very important aspect in MCM, especially when the counter measures involve human divers. In that case, a diver simulated the recognition of a mine (MANTA). The distance between transmitter and receiver was about 1000m and the depth around 20m.

The symbols were transmitted using QPSK modulation with a carrier frequency of 34 kHz and a bit rate of 10 kbps (14 samples within a symbol duration). Decoded picture present some errors during JPEG packet decoding. This result could be improved with some channel coding and more dedicated image compression algorithms..

From a general point of view, this equipment is clearly able to transmit high data rate information over a long duration (more than 15 minutes during our sea-trials).

Figure 9 : Result of the transmission of picture with acoustic communication.

VI- INTEREST FOR MILITARY APPLICATIONS

Underwater acoustic communications are known to be highly dependent on undersea environmental conditions. The acoustic system TRIDENT overcome the effects of multipath by the use of a multiple inputs equalizer. The effect of fading on transmission is reduced. Real-time transmission is possible up to 20 kbps. The time required for symbol processing (from acquisition to restitution) is lower than 67% of the symbol duration. As a consequence, there is more than 33% time left. Further operations like channel coding could be integrated. Consequently, reliability would be once again improved.
Impact of blind approach is clearly shown in this project. Robustness during transmission is one of the main characteristics of the TRIDENT system. Probe and training sequences are no more needed. Efficiency is optimized.
With this digital communication, a new technology is becoming available. Transmission of data, text, voice and images are possible. Phase Shift Keying Modulation (PSK) exhibits the best spectral efficiency. Nevertheless, throughput could be improved using greatest spectral bandwidth.

In the context of MCM, AUVs are planned to realize missions such as environment assessment or mine reconnaissance. In that case, information have to be transmitted to command centers for further decisions. Collected data by buoys on large areas or imagery taken by camera need high data rate communications.
In the context of anti-submarine warfare (ASW), the ability to support high data rate communications stand for the future challenge. This must be satisfied with an other constraint : keeping submarine stealthy. Acoustic communication could bring an improvement in terms of interoperability with submarines, undersea vehicle, buoys or surface platforms. Digital phone should be one of the first operational application of high data rate acoustic communication.

VII- CONCLUSION.

In this paper, a real time acoustic link developed by GESMA, ENST Bretagne and ORCA Instrumentation is presented. Based on a patented blind equalizer, this system, named TRIDENT, shows some interesting performances in terms of MSE, Bit Error Ratio (BER) and convergence speed. Most of the transmitted sequences were successfully detected during several minutes. The robustness and adaptability of its receiver is clearly shown.
Interest of spatial diversity is confirmed. Even if mono sensor equalization exhibits a good behavior, spatio-temporal equalization offers a safety margin and an improved stability.

These first sea trials will be followed by other evaluations, the aim of which will be the evaluation of Doppler immunity. The TRIDENT equipment will be carried out by a ROV in order to test a typical mine hunting mission.

This project aims to develop a reliable solution to ensure real-time high data rate acoustic transmissions. An importatn stage was reached. Improvements have to be brought to lead to operational product (channel coding in particular). Acoustic network, multi-user theater and covert communications must be taken into account for the future of ASW operations.

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