An Overview of Channel Coding For Underwater Acoustic Communications

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***Abstract*— The TRIDENT (TRansmission d'Images et de Données EN Temps réeel) project was launched a few years ago by GESMA (Groupe d'Etudes Sous Marine de l'Atlantique). The initial objectives were to develop a multiple-rate underwater acoustic link for images, text and data transmission. Later, the speech option was added, and more recently channel coding options have been introduced to the TRIDENT platform. Convolutional codes (CC) and Reed Solomon (RS) block codes were then checked, but these simple codes were not able to significantly improve the Bit Error Rate (BER) at the channel decoding output. For this reason, GESMA decided to introduce turbo codes options, more specifically the Reed Solomon Block Turbo Codes (RS-BTC), to enhance the channel decoding efficiency. The data transmitted are interleaved and frame recovery is performed in reception. After system validation in static conditions, in the Penfeld river in Brest, France, sea trials were conducted in the Bay of Brest in dynamic conditions. This paper presents various possibilities offered by the platform for images and speech transmissions and the RS-BTC channel coding options.**

Keywords- Underwater acoustic communication; BER, Convolutional codes (CC); Reed Solomon (RS) block codes; Reed Solomon Block Turbo Codes (RS-BTC).

I. INTRODUCTION

The initial objective of the TRIDENT project (TRansmission d'Images et de Données EN Temps réel) was to equip Autonomous Underwater Vehicles (AUVs) with an acoustic communication link. This system had to be able to transmit continuous information such as images, speech, data and text. The TRIDENT system (Fig. 1) [1] can use four carrier frequencies (11.2, 17.5, 20.0 and 34 kHz) with a Quadrature Phase Shift Keying (QPSK) modulation and different bit rates, ranging from 2.8 to 23.3 kbps. Multipath propagation, Doppler effect and noise bring a lot of perturbation on underwater acoustic communication, such as time dispersion and variability to the received signal. It should be noted that carrier frequencies and available bandwidths are much lower than those of radio communication channels. A blind spatio-temporal equalizer [2] is used to reduce these various perturbations. GESMA also aimed to increase the link's reliability with the goal of lowering the Bit Error Rate (BER) from 10^{-2} to 10^{-4}. In order to do so, channel coding was integrated into the system. Two kinds of error correcting schemes had been tested, namely Convolutional Codes (CC) and Reed Solomon (RS) block codes [3-4], both hard and soft decoding versions. These two channel coding schemes did not provide an adequate level of correction. To improve the symbol correction with a higher code rate, Reed Solomon Block Turbo Codes (RS-BTC) were recently tested, in both static and moving conditions. The iterative decoding process based on the Chase-Pyndiah [5-6] algorithm uses a soft decoding version with eight iterations. Berlekamp [7] and Chien algebraic algorithms are also used to correct symbols during the iterative process. Synchronization words are wisely included in the coded frame to synchronize the interleaver and recover the information frame at the receiver. A differential coding/decoding is used to solve phase ambiguities.

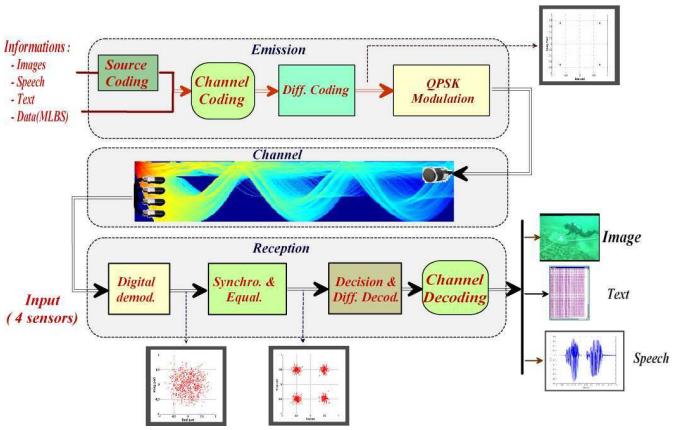

Figure 1. TRIDENT platform

This paper provides an overview of the high data rate acoustic link. Firstly, we present the TRIDENT platform and channel coding strategies, including the CC and RS options, with the RS-BTC extension. Then we present the sea trials and show the acoustic communication results in the 2.8 to 14 kbps range, applied both to images and low bit rate speech (2400 bps) transmissions.

II. CHANNEL CODING STRATEGIES

The signal is received on four hydrophones, coming from the same source of emission and demodulated. Timing and carrier recovery, equalization are then processed before making the decision upon the transmitted symbol. The equalizer is a multiple-input self-adaptive Decision Feedback Equalizer. This equalizer is able to run in one of two modes: a convergence or starting mode, in which the equalizer is self-controlled, and a tracking mode, where it is controlled by its own decisions. Switching between the two modes is performed in an automatic and reversible way by comparing the Mean Square Error (MSE) with a threshold.

In order to improve the acoustic link, channel coding may correct remaining errors. The goal is to decrease the BER from 10^{-2} down to 10^{-4}. Different channel coding have been tested, including Convolutional Codes (CC), Reed Solomon (RS) block codes and Reed Solomon Block Turbo Codes (RS-BTC).

A. Convolutional Codes (CC)

Convolutional Codes are generally specified by three parameters (*n, k, m*), where *n* is the number of output bits, *k* represents the number of input bits and *m* corresponds to the number of memory registers. The code rate $R = k/n$ is a measure of the code efficiency. Commonly *k* range from 1 to 8 and *n*, from 2 to 10. Usually CC is specified by parameters *(n, k, l)*, where *l* is the code constraint length defined by $l = k(m-1)$ and represents the number of bits in the encoder memory that affect the *n* output bit generation. Two Convolutional Codes were evaluated, namely CC (7, 5) and CC (35, 23).

The decoding process uses the Viterbi algorithm with a trellis representation, with 4 or 16 states according to the CC coder. Decoding is performed with hard or soft options. Hard decoding uses only binary values, whereas the soft option uses real values coming from the output equalizer. In order to close the trellis, zero tail bits are added at the end of the frame, respectively two for CC (7, 5) and four for CC (35, 23). Synchronization words (respectively set to 16 and 14 bits) are included to retrieve the 54 bits of data (speech frame). Whatever the CC in use and including the trellis tail bits, the information frame is a 72-bit length. With a code rate *R* equal to 0.5, the emitted coded frame is 144 bits in length. The whole correcting rate is then 0.375. After the coding process, the synchronization word is 32 bits (respectively 28) long.

CC (7, 5) is defined by (1) and (2) and its synoptic is represented in Fig. 2. The scheme for CC (35, 23) is shown in Fig. 3 and this code is defined by (3) and (4).

$$s_1(x) = (1 + x + x^2)e(x). \quad (1)$$

$$s_2(x) = (1 + x^2)e(x). \quad (2)$$

$$s_1(x) = (1 + x + x^2)e(x). \quad (3)$$

$$s_2(x) = (1 + x + x^2 + x^4)e(x). \quad (4)$$

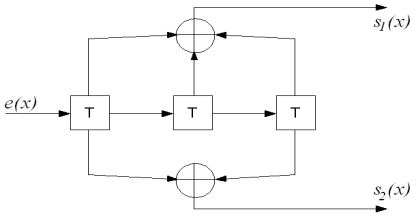

Figure 2. Convolutional Code (7, 5)

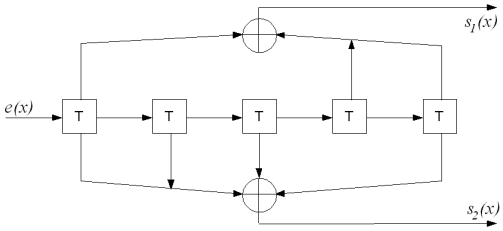

Figure 3. Convolutional Code (35, 23).

B. Reed Solomon (RS) block codes

Reed Solomon codes *(n, k, t)* are cyclic codes, built from *n* symbols with a maximum of $n = q - 1$, where *q* is the number of elements in the Galois field (GF^q) ($q = 2^n$) and *t* is the power correcting code, so the number of control symbols is *2t*. $k = n - 2t$ represents the number of information symbols that can be transmitted. The decoding process can be hard or soft. Based on the Chase algorithm, the soft decoding process uses the Berlekamp and Chien algorithms to correct received symbols. In our case, we are looking for four unreliable bits and checking among 16 possible code words. Two Reed Solomon codes were evaluated, namely RS (31, 29) and RS (31, 27). A synchronization word *S* is included in the frame to retrieve the data (speech frame) at the receiver side. According to RS power correcting code *t, S* is 29 bits in length ($t = 1$) and 27 ($t = 2$). To match the chosen RS code size, the information matrix processes over two speech frames (108 bits). The whole correcting rate *R* is equal to 0.7 of whatever the correcting power is. The Underwater Acoustic (UWA) channel is characterized by burst errors coming from multipath and noise. Writing and reading matrix strategies are likely to improve the correcting process by working like an interleaver.

C. Reed Solomon Block Turbo Codes (BTC-RS)

The concept of product codes is a simple and efficient method to construct powerful codes with a large minimum Hamming distance, δ_p, using conventional linear block codes [6]. Let us consider a systematic linear block code *C* having parameters (n,k,δ) as illustrated in Fig. 4. The parameters *n* and *k* stand for the code length and the number of information symbols, respectively. The product code $P = C \times C$ is obtained by placing k^2 information bits in a matrix of *k* rows and *k* columns and encoding the *k* rows and *k* columns using the code *C*. It can be shown that all *n* rows and all *n* columns are code words of *C*. Furthermore, the parameters of the resulting product code *P* are given by $n_p = n^2$, $k_p = k^2$, $\delta_p = \delta^2$. The code

rate R_p is given by $R_p = R^2$ with $R=k/n$. Thus, it is possible to construct powerful product codes based on linear block codes, such as RS codes. Working in the Galois field GF^q, RS codes are a class of linear cyclic block codes that have capabilities for multiple error detection and correction.

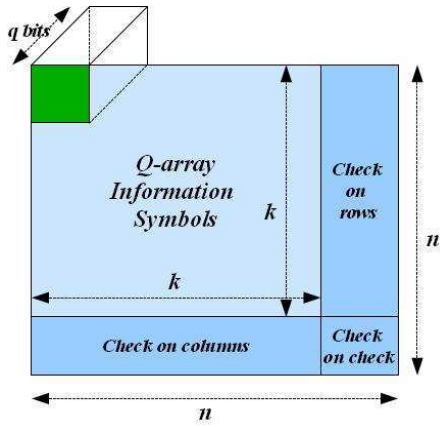

Figure 4. RS product codes with Q-ary symbol concatenation

Product code decoding involves sequential decoding of rows and columns using a Soft Input Soft Output (SISO) decoding algorithm (Fig. 5). The block turbo decoding process repeats this soft decoding for several iterations. Each decoding process computes soft information $R'_{(it+1)}$ from the channel received information R and the information computed in the previous half iteration, $R'_{(it)}$. The extrinsic information $W_{(it)}$ is obtained by subtracting the soft input information $R'_{(it)}$ from the soft output information $F_{(it)}$. The soft information $R'_{(it+1)}$ is given by $R'_{(it+1)} = R + \alpha_{(it)}W_{(it)}$, where $\alpha_{(it)}$ is a scaling factor that reduces the effect of the extrinsic information in the soft decoder during the first decoding steps.

In 1972, Chase proposed algorithms that approximate the optimum Maximum-Likelihood (ML) decoding of block codes with low computing complexity and small performance degradation. In 1994, Pyndiah *et al.* presented a new iterative decoding algorithm for decoding product codes, based on the iterative SISO decoding of concatenated block codes.

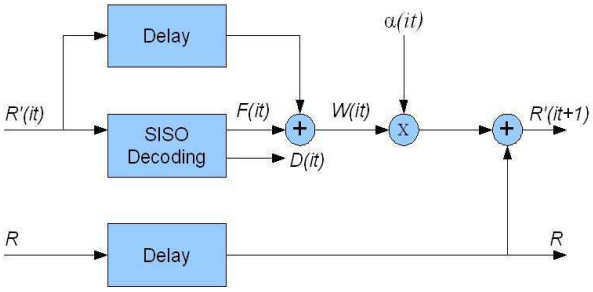

Figure 5. Iterative block turbo decoding principle

So far the TRIDENT system has used the $RS^2(31,29,1)$ = RS($n = 31 = 2^q-1$, $k = 29 = n-2t$, t) BTC channel coding ($q = 5$, $t = 1$; t being the correcting power). Three different synchronization words S_i ($i \in \{1,2,3\}$) are included to retrieve the frame, at the receiver side. S_1 (or, respectively, S_2 or S_3) is used to detect the frame start (respectively middle or end frame). The emitted coded frame, with S_i in (or respectively out of) the frame, is 4805 bits in length (respectively 5084), thus the whole correcting rate R is equal to 0.82.

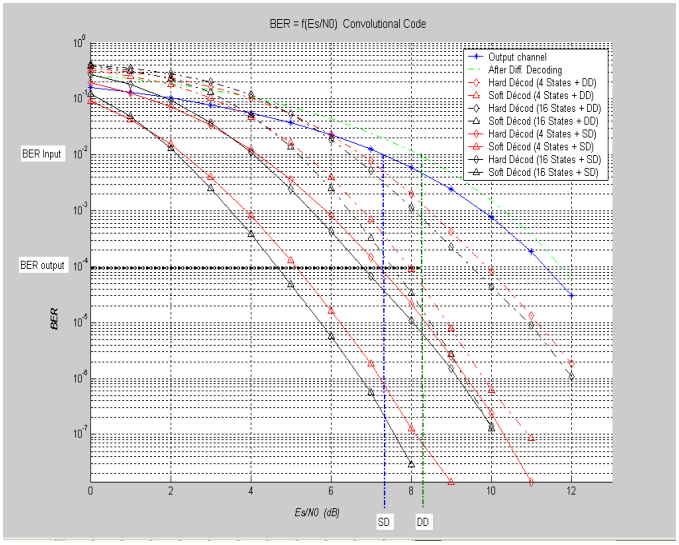

Figure 6. Convolutional Code 7,5 and 35,23 comparison

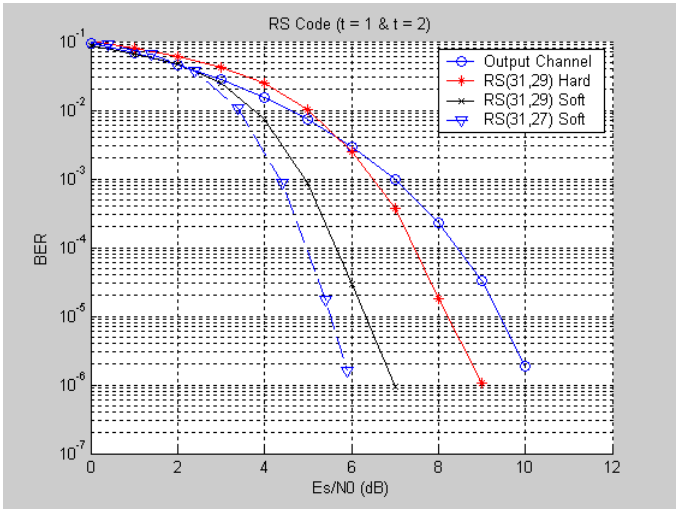

Figure 7. Reed Solomon RS(31, 29) and RS(31,27) hard and soft decoding

D. Simulation results

Results presented are obtained by simulations in the presence of Additive White Gaussian Noise (AWGN). Fig. 6 presents performance obtained with CC coders (both for 4 and 16 states). It clearly appears that the use of a differential coding decreases performance in doubling the bit error rate. We take the BER at the channel output as a reference for the 2 options, with Differential Coding (DD) and without DD (SD). At 10^{-5}, we have a loss of 2.5 dB when using DD both for hard and soft decoding. Let us recall that in the case of phase ambiguity, the decoding process may not work correctly. It also appears that we get better performance with the 16-state coder/decoder, but that 16-state decoding is more expensive in terms of computational load. All the configurations using the soft option

make it possible to lower the BER from 10^{-2} to 10^{-4}. In the case of RS coding/decoding (Fig. 7), the soft option does not allow us to reach a BER of 10^{-4}. The use of RS-BTC (31, 29) (Fig. 8) lowers the BER values from 10^{-2} down to 10^{-4} after three iterations. RS-BTC provides a better code rate (0.83) but a strong real-time constraint and a long transmitted frame.

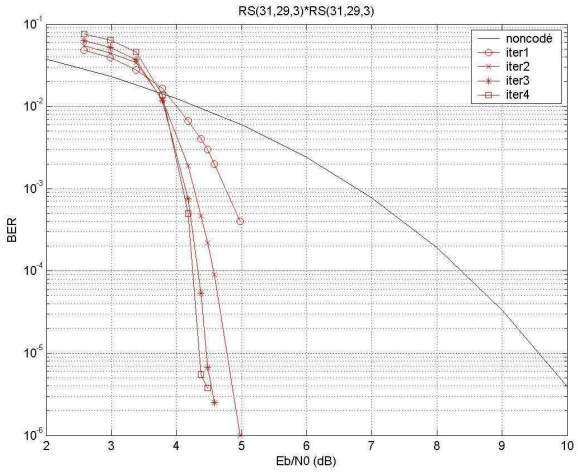

Figure 8. Reed Solomon Block Turbo Code (31, 29) soft decoding

III. SEA TRIAL RESULTS

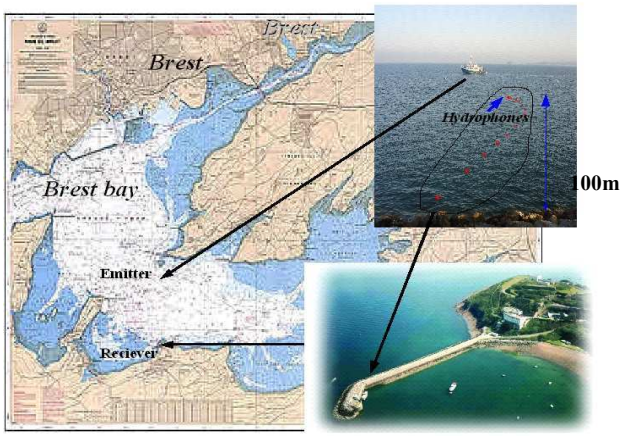

Figure 9. Sea trial site, Brest Bay

In order to test CC and RS channel coding, sea trials were carried out in the Bay of Brest in October 2007 (Fig. 9). This bay is a shallow underwater acoustic channel (10-50m depth). Objectives were to check both receiver and emitter operating in moving and realistic conditions. The emitter was on board a boat while the receiver was positioned in a laboratory van on the quay side. At reception, acoustic signals were received on four sensors. Hydrophone interspaces were almost 20cm (around five wavelengths). The first hydrophone was deployed 100m from the quay and at 5m of depth. During the sea trials, 71 sequences of three minutes each were emitted, representing 3 hours and 33 minutes of recorded signals. QPSK modulation with two carrier frequencies (11.2 kHz or 17.5 kHz) was used. Demodulation, timing and carrier recovery and equalization were computed in real time in the receiver. Channel and source decoding were then performed to evaluate the transmission quality.

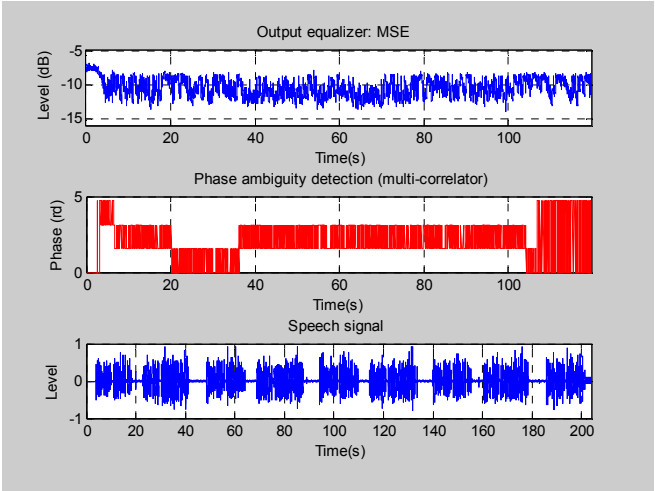

Figure 10. MSE, phase ambiguity, detection and Speech signal

One of the results concerns a speech signal transmission lasting 3 minutes. The carrier frequency is fixed at 17.5 kHz and the bit rate is 5.8 kbps. The distance between the emitter and the receiver is 2500m. We can observe in Fig. 10 a large variation of the MSE at the output equalizer, due to UWA channel perturbation. These variations generate phase ambiguities, corrected by the phase detector. The speech signal is correctly decoded.

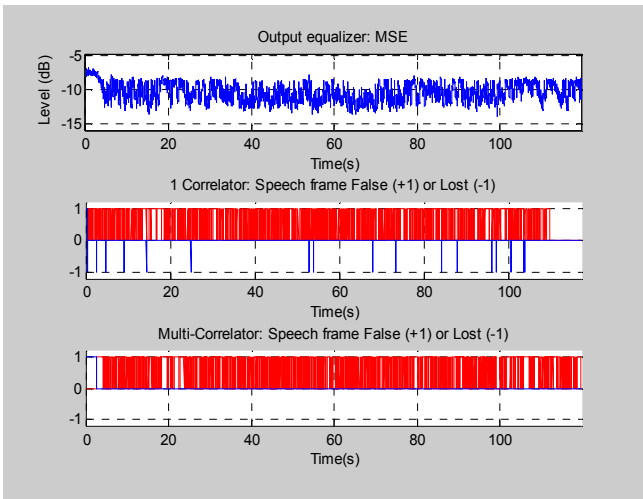

Figure 11. Frame false or lost with the use of one or five correlators

The information frame detected with the use of one or five correlators is shown in Fig. 11. The frame indicator equals +1 when the speech frames are false and -1 when the speech frames are lost. With one correlator, 125 frames are lost during the transmission, corresponding to 5.6 s of speech signal. With a multi-correlator, we do not lose any frames. After phase

ambiguity correction and frame synchronization, the bit error rate fell from 4.09 10^{-2} (BER_{in} decoder input) to 3.6 10^{-2} (BER_{out}, output) in the case of hard decoding and 3.14 10^{-2} in the case of soft decoding.

Other sea trials for testing RS-BTC channel coding took place in Brest Bay in March 2010. Two boats were used for these sea trials (Fig. 12). The transmitter was on board the "Aventurière II". The transducer was at a depth of 4 m. The receiver was on board the boat "Idaco". The four hydrophones were towed behind the boat, 3m below the keel. These trials were carried out in rough sea conditions. During the trials, five and a half hours of transmitted signal were recorded, representing 162 two-minute sequences. Both emitter and receiver were moving (less than 4 knots), with a range from 300m up to 3000m. The position of the two boats during each sequence transmission (named AIT) for tests conducted on March 24 was recorded (Fig. 13). During these trials, three carrier frequencies and four bit rates for each carrier frequency were used to transmit the information frames.

Figure 12. Sea trial configuration

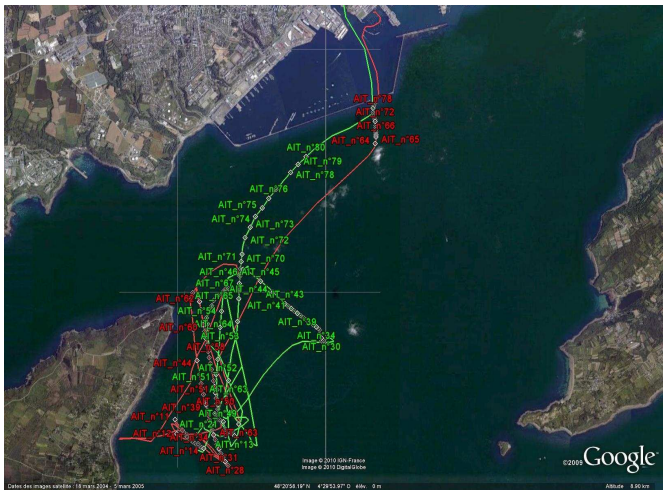

Figure 13. Brest Bay sea trials: recording position (March 24th)

The result marked AIT24 shows the behavior of the receiver for image transmission with a 17.5 kHz carrier frequency and a bit rate fixed at 11.6 kbps. Transmitter and receiver speeds are around 1 knot. The distance between the transmitter and the receiver was 1000m. In Fig. 14, the first plot shows the Mean Square Error (MSE). The success of the equalization process should be noted.

This sequence showed very good overall performance. It clearly appears that the transmission was processed without any kind of difficulty. This sequence was emitted without differential coding. After decoder synchronization, 8 iterations were processed for the channel decoding. The BER at the decoder input (BER_{in}) was 5.4 10^{-5} and 0.0 at the decoder output. For 238 frames transmitted, not a single frame was lost (second plot, Fig. 14), 6 (2.5%) were detected false (one or more errors) at the channel decoder input (third plot, Fig. 14), and 0 (0%) were detected false at the decoder output (fourth plot, Fig. 14). During the convergence stage, frames may be lost (only one incomplete frame during this trial). The seven images transmitted were correctly decoded.

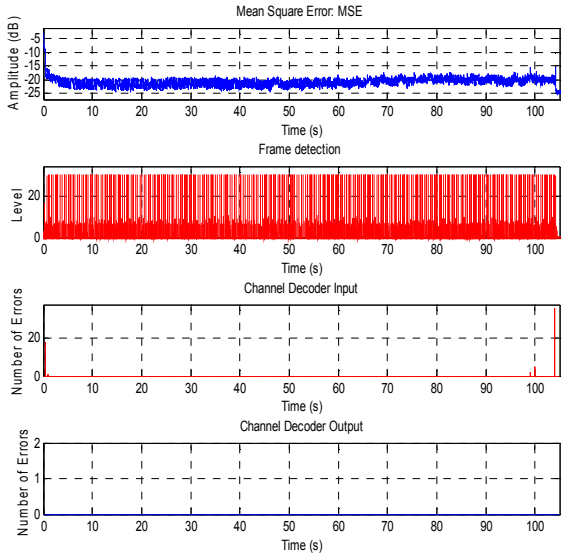

Figure 14. MSE, correlator output, decoder input and decoder output (AIT24)

The result noted AIT30 concerns a speech signal transmission. For this trial, the carrier frequency was 17.5 kHz and the bit rate was set at 7.0 kbps, with 2.4 kbps used for the speech signal. The distance between the transmitter and the receiver was 2500m. The MSE (first plot, Fig. 15) also shows how successful equalization was. After both phase ambiguity correction and decoder synchronization, the BER at the decoder input (BER_{in}) was 2.4 10^{-3} and the BER_{out} was 0.0 at the decoder output. For 144 frames transmitted, no frames were lost. 144 frames (100%) were detected false at the decoder input, with 0 (0.0%) false detections at the decoder output. Eight iterations were processed for the channel decoding. The speech signal was correctly decoded (Fig. 16).

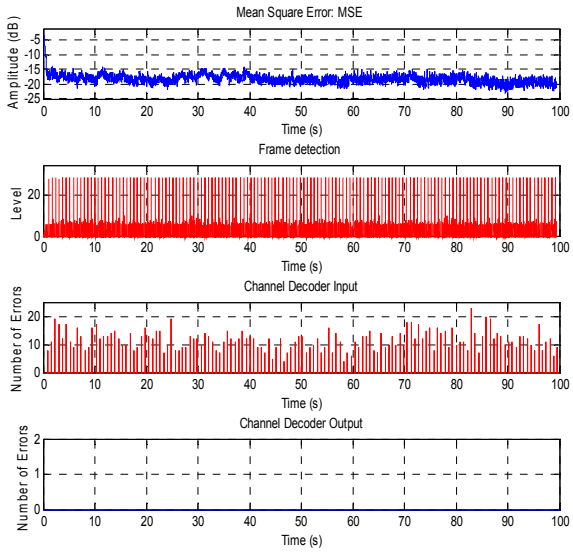

Figure 15. MSE, correlator output, decoder input and decoder output (AIT30)

The result indicated by AIT151 concerns image transmission. The distance between the transmitter and the receiver was 1000m. For this trial, the carrier frequency was 11.2 kHz and the bit rate was fixed at 3.7 kbps. In this trial, the sequence was emitted without differential coding, so a phase jump appearing at the end of the transmission was not detected. The MSE (first plot, Fig. 17) also shows the equalization success, only disturbed during the phase jump. For 72 frames transmitted, 62 were detected, no frames were lost and 26 (2.5%) were detected false at the decoder input, before the jump. The BER_{in} at the decoder input was 1.7 10^{-4} and the BER_{out} was 0.0 at the decoder output. 10 frames (12 s) were lost after the phase jump. Eight iterations were processed for channel decoding. The images were correctly decoded before the phase jump. A quarter of an image was lost during this trial.

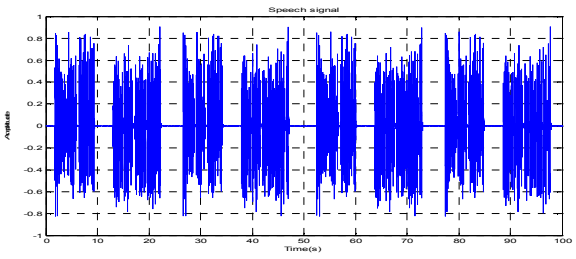

Figure 16. Speech signal (AIT30)

More than 5 hours of transmitted signal were recorded. A large number of sequences were successfully decoded at different distances, namely 300, 1000 and 2500m in moving conditions, using three carrier frequencies and different bit rates ranging from 3.7 to 11.6 kbps. These sequences show that channel coding/decoding perform well when synchronization and equalization work correctly.

IV. CONCLUSION AND PERSPECTIVES

This paper presents the extension of the TRIDENT system, developed by GESMA in collaboration with TELECOM Bretagne. This underwater acoustic link is designed to transmit different kinds of data as text, images and speech signal. A blind spatio-temporal equalizer is used to reduce different shallow underwater acoustic perturbations. The first tests in an operational context show that real-time transmission of information (image, speech, text) is feasible even with harsh channels, such as the underwater acoustic channel, and in the presence of multiple interferers. In this context, the contribution of channel coding can improve the transmission robustness and protect the data transmitted from remaining errors. The aim is to lower the BER from 10^{-2} to 10^{-4}. First, CC and RS channel coding were tested in real conditions. These two channel coding types do not provide an adequate level of correction. To improve underwater acoustic link performance, RS-BTCs were introduced and tested in real conditions. The use of RS-BTC allows us to reach a lower BER. CC and RS use a short frame length, whereas RS-BTC works on longer frames. Differential coding has been used to solve the phase ambiguities with the RS-BTC option in the case of phase jump and possible frame loss. RS-BTC requires a higher computational load but this is not a disadvantage for underwater acoustic communications due to the bit rate. CC and RS seem more suitable for speech signal transmission and RS-BTC for image transmission.

If the Doppler effect is not compensated for before any processing on the received signal, it is very difficult to extract information. Future work will be carried out to improve both Doppler-shift compensation and timing recovery. Due to impulsive noise, others interleavers have to be checked, especially the bits interleaver, in the case of RS-BTC.

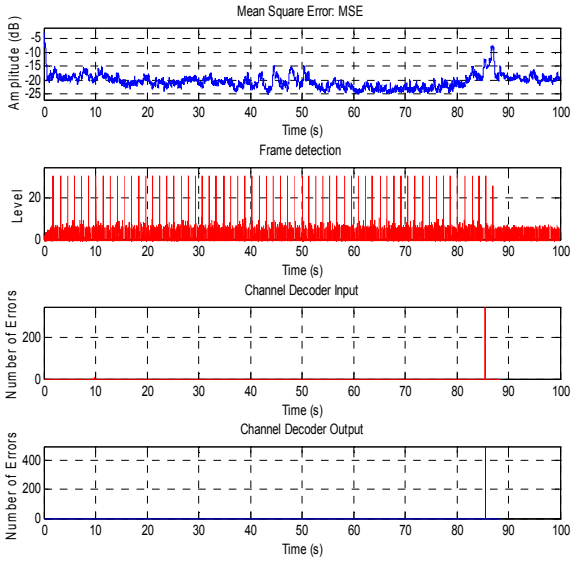

Figure 17. MSE, correlator output, decoder input and decoder output (AIT151) (undetected phase jump in the sequence)

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