Improved Error Correction for Stanag 4539 appendix H proposal: HF XL

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***Abstract*— A new appendix [1] for STANAG 4539 [2] is currently under review by the NATO BLOS CaT experts. This proposal introduces a wideband non-contiguous waveform that offers more reliability thanks to the introduction of frequency diversity and also is able to reach throughputs in excess of 150kb/s. This waveform, called "HF XL" proposes to use Turbo codes instead of traditional convolutional codes as forward error correction (FEC) coding scheme. This paper explains the rationale behind that choice and presents simulation results proving the interest of Turbo codes over wideband HF channels.**

***Index Terms*— High Frequency (HF), Error correction codes, Turbo codes, frequency-selective fading channels.**

I. Introduction

High Frequency (HF) radio communications have been used for almost a century to provide communications from short to long range with minimal infrastructure. For many decades, this media was used only for voice and very low data rate (e.g. using Morse code), which led to the definition of particularly robust yet simple waveforms. At the turn of the century, studies led to the definition of more efficient waveforms, with more complex modulation schemes, ultimately leading to the definition of STANAG 4539 [2] with a capability of 9600 b/s in a 3 kHz channel.

Dedicated to data transmission, this new high data rate solution requires very low bit error rate (BER: typically 10^{-5} when voice requires only 10^{-3}). As Berrou and Glavieux proposed at the same time the Turbo codes [3], a new and particularly efficient forward error correction scheme, the HF engineers naturally considered the possibility to use turbo codes for their waveforms. First studies were not really conclusive: some such as [4] for 2400 b/s single carrier modems exhibited only very limited gain while other such as OFDM parallel modem [5] showed promising gains. Interestingly, further analysis and studies showed that the gain was particularly interesting when diversity (for instance modulation diversity [6]) is introduced in the waveform. Ultimately, it was shown that at system level a parallel modem with turbo coding could provide better performances, through better bit and packet error rates [7].

In the 2010's, new design efforts have been made to answer to ever evolving customer requests, namely to have 1/ a better resilience (HF being still very much seen as a non-reliable medium), and 2/ higher throughput, ultimately allowing for IP usage over HF. The HF community has come up with solutions relying on increased transmission bands when compared to the classical 3 kHz narrow band channelization. Interestingly, as shown by Vogler & Hoffmeyer [8], HF channels coherence band is generally lower than 12 kHz, which corresponds to the fact that wideband HF channels exhibit frequency diversity. This diversity consequently should allow an efficient use of turbo codes.

This paper is organized as follows. In Section II is presented the HF non-contiguous multiple tone wideband approach [1][9] proposed for standardization as a new STANAG 4539 appendix, and details in particular the proposed Turbo Code. In section III, simulations results are presented that compare performance obtained with turbo code and performance with a traditional convolutional code. Finally, in Section IV, conclusions are drawn.

II. Multi narrow-band modem with a turbo code scheme

The STANAG 4539 appendix H proposal [1] describes an HF data modem over multiple discrete channels, using an elementary serial waveform derived from Annex B of the same STANAG [2]. It addresses NATO non-EPM multi-application requirements up to 200 kbits/s in an integrated HF communication system named HF XL.

HF XL solution addresses the concerns that have arisen on the practical feasibility of disposing in real conditions of bands up to 24 kHz on the field. Relying only on narrow band (3 kHz) non-contiguous channels bonding, HF XL allows to increase the band of the transmission, while selecting only channels authorized and where the expected signal to noise ratio is good enough to permit a good transmission. Interestingly, the increased PAPR (Peak to Average Power Ratio) introduced by multi-carriers modulations can be limited (typically to 8dB) through Crest Factor Reduction techniques that allow to limit the degradation when compared to single carrier high order modulations, whose PAPR can reach 5 dB.

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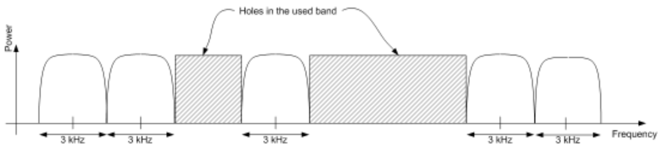

Fig. 1. Multiple discrete HF channels serial waveform ("HF XL", proposed as app. H for STANAG 4539): illustration of the channel arrangement.

As illustrated by Fig. 1, the physical layer is based on a multiple subcarrier modulation process (for a number of n=1 .. 16 channels) and a wideband radio (typically 200 kHz). This allows matching traditional 3 kHz Single Side Band (SSB) frequency allocations inside the 200 kHz radio band.

The system is based on multichannel modulation patterns called superframes. The number of channel used, the position of the channels in the radio band, the elementary channel power level, the type of modulation used on each channel, as well as the overall error correcting code and interleaver are variable from one superframe to another. This allows the transmitting radio to optimize the throughput of the global system or latency, based on local operational needs, and quality information and/or spectral occupancy monitoring from the other radios that participate to the link.

The block diagram of the transmitter is shown in Fig. 2. The block diagram of the receiver is shown in Fig. 3. Operational constraint time data (CTD) and non-constraint time data (NCTD) flows can be combined, encoded, interleaved and sent to n individual modulators having different data rates, each attached to a single channel. These modems are combined in a frequency division multiplex and this composite signal modulates the HF radio.

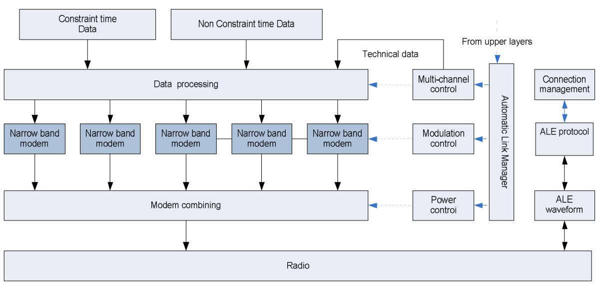

Fig. 2. Transmitter block diagram.

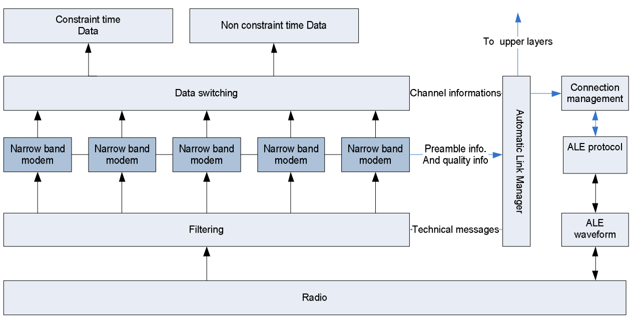

Fig. 3. Receiver block diagram.

Each block of input data is encoded using a block encoding technique with a code block size equal to the size of the block interleaver. Thus, the input data bits are sent as successive blocks of bits that span the duration of the interleaver length selected, allowing to take advantage of the time diversity provided by the interleaver.

As shown in TABLE I, various modulation and coding schemes are available. The considered convolutional code is identical to STANAG 4539 Annex B SSB waveform, but offers either rate=½ (non-punctured) or rate=¾ (usual punctured version). The Turbo code is the one proposed in the 3GPP TS 36.212 Release 11 Standard [10]. It provides a coding a scheme with a mother Turbo code of rate 1/3 followed by a Rate-Matching block.

TABLE I
MODULATION AND CODING SCHEMES

	Proposed schemes
Modulation	BPSK; QPSK; 8-PSK; 16-QAM; 32-QAM; 64-QAM
Error Correction codes	Rate ½ convolutionnal code – unpunctured, constraint length 7; Rate ½ convolutionnal code –punctured to rate = 3/4, constraint length 7; Turbo Code with mother TC rate 1/3 followed by a Rate-Matching block

III. SIMULATION RESULTS

The modem described in the previous section has been simulated in order to validate the interest of using Turbo coding with respect to the traditional convolutional code.

A. Simulation settings

The simulations were done with an HF ionospheric Watterson model. Two channel parameter sets were considered: Gaussian (AWGN) and CCIR Poor (with two paths, a delay spread of 2 ms and a Doppler spread of 1 Hz on the two paths). Two interleaver sizes were considered: short (S: 1.08 s) and very long (VL: 8.61 s). Two values of channel configurations have been considered: n=1, which is equivalent to narrow band STANAG 4539, and n=16, which is the widest version of HF XL. When n>1 multi-carriers are considered, said channels are taken independent.

The Turbo code rate is fixed to ¾ (labeled TC7000) and the input packet size (before encoding) is taken equal to K = 432 bytes. The decoding process number of iterations is fixed and equal to 8. The two convolutional code rates have been simulated. Rate=¾ (labeled CONV_34) can immediately be compared to the Turbo code, and rate=½ (labeled CONV_12) will be used for comparison, but it should be kept in mind that it offers a reduced useful throughput.

Finally, for the different simulations, the SNR (signal to noise ratio) values are given with respect to 3 kHz bandwidth transmission.

B. *Performance for n=1 channel*

Fig. 4, Fig. 5 present the results obtained with a very long interleaver over Gaussian channel and CCIR poor channel respectively. Fig. 6 provides results for short interleaver over CCIR poor channel. In those three figures, only one 3 kHz channel has been considered, and one sees that when enough diversity is present, as in the case of the Gaussian channel or with very long interleaver, the Turbo code scheme noticeably gains over the convolutional code at the same coding rate. When comparing the Turbo code of rate=¾ with the convolutional code of rate=½, one sees that the diversity offered by the very long interleaver is not sufficient to permit the Turbo code to offer better performance, even at very high signal SNR.

These results are coherent with the observations made in Section I, but still lead to recommend using a Turbo coding scheme, which will always perform either as well or better than convolutional code.

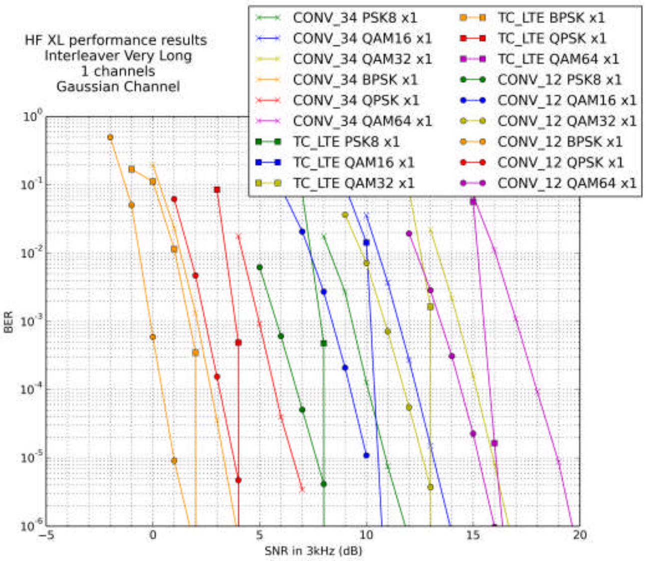

Fig. 4. Comparison of performance between Turbo code (R=3/4) and Convolutional code (R=3/4 and R=1/2) with n=1 channel for ST4539 app. H proposal for very long interleaving (VL) over Gaussian channel.

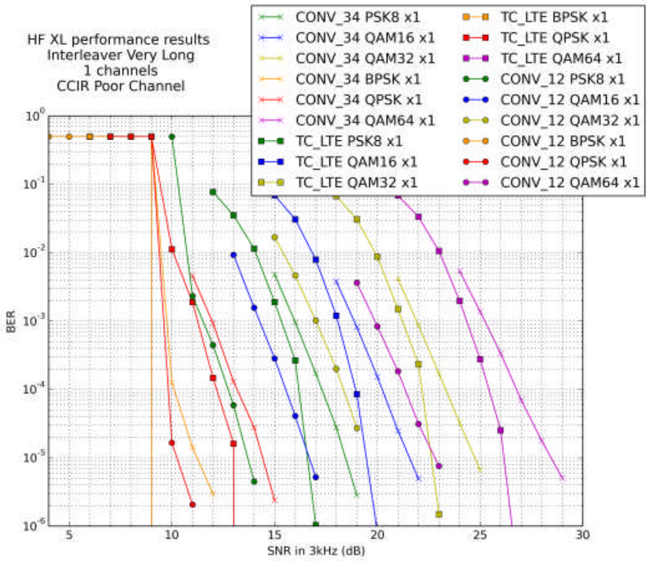

Fig. 5 Comparison of performance between Turbo code (R=3/4) and Convolutional code (R=3/4 and R=1/2) with n=1 channel for ST4539 app. H proposal for very long interleaving (VL) over CCIR Poor channel.

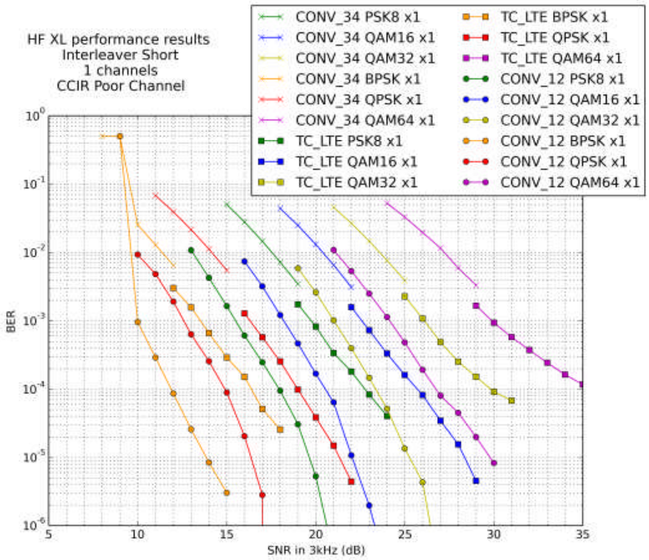

Fig. 6 Comparison of performance between Turbo code (R=3/4) and Convolutional code (R=3/4 and R=1/2) with n=1 channel for ST4539 app. H proposal for short interleaving (S) over CCIR Poor channel.

C. *Performance for 16 channels*

Fig. 7 and Fig. 8 present the results obtained with a very long interleaver over Gaussian channel and CCIR poor channel respectively.

Fig. 9 provides results for short interleaver over CCIR poor channel. In those three figures, n=16 3 kHz channels have been considered. When compared with the curves presented in Section III.C, one sees that the combination of time diversity (provided by the VL interleaver) and frequency diversity (provided by the HF XL waveform) allow the turbo coding scheme to noticeably outperform the convolutional scheme of rate=¾. The Turbo code even reaches better performance than the convolutional code of rate=½ for BER between 10^{-5} and 10^{-6} … while offering 50% more throughput!

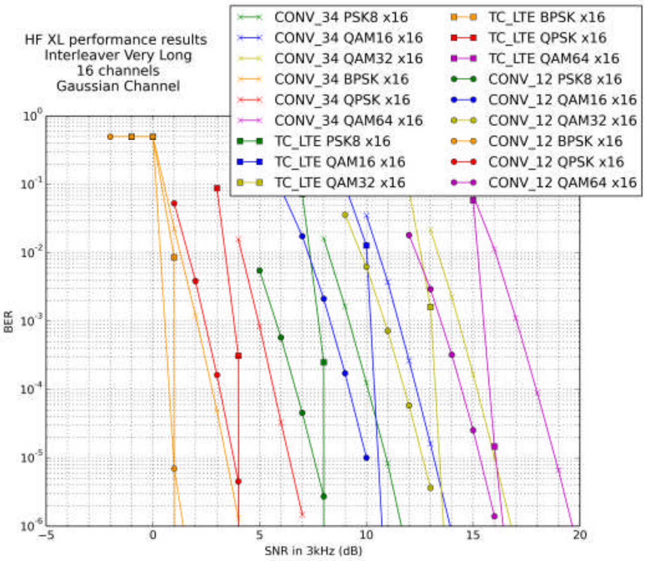

Fig. 7. Comparison of performance between Turbo code (R=3/4) and Convolutional code (R=3/4 and R=1/2) with n=16 channels for ST4539 app. H proposal for very long interleaving (VL) over Gaussian channel.

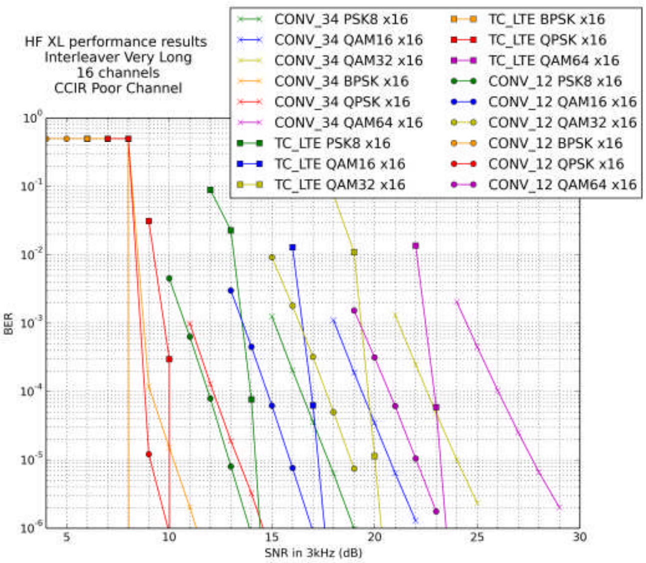

Fig. 8. Comparison of performance between Turbo code (R=3/4) and Convolutional code (R=3/4 and R=1/2) with n=16 channels for ST4539 app. H proposal for very long interleaving (VL) over CCIR Poor channel.

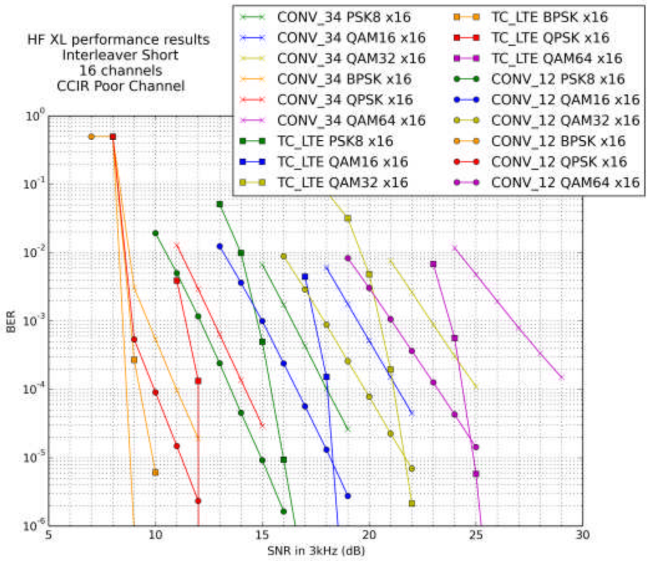

Fig. 9. Comparison of performance between Turbo code (R=3/4) and Convolutional code (R=3/4 and R=1/2) with n=16 channels for ST4539 app. H proposal for short interleaving (S) over CCIR Poor channel.

D. Performance comparison for 4, 8 and 16 channels

In order to illustrate the fact that the Turbo coding scheme does not require n=16 channels to be efficient, Fig. 10 and Fig. 11 show comparison of performance for 4, 8 and 16 channels with modulations QPSK, QAM-16 and QAM-64 for Short and Very Long interleaving configurations. It logically appears that the frequency diversity gain is more important when there is no time diversity (Short interleaver), but the most interesting fact is that more than 2/3 of the gain is observed already with n=4 channels.

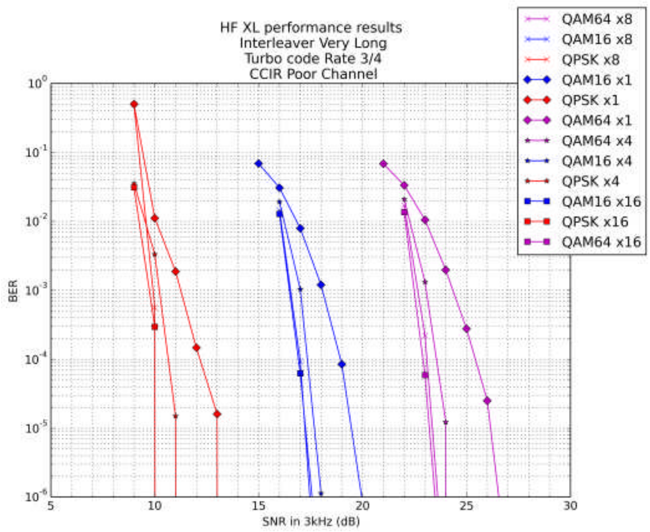

Fig. 10. Comparison of performance for n=1, 4, 8 and 16 channels with Turbo code (R=3/4) of ST4539 app. H proposal for very long interleaving (VL) over CCIR Poor channel.

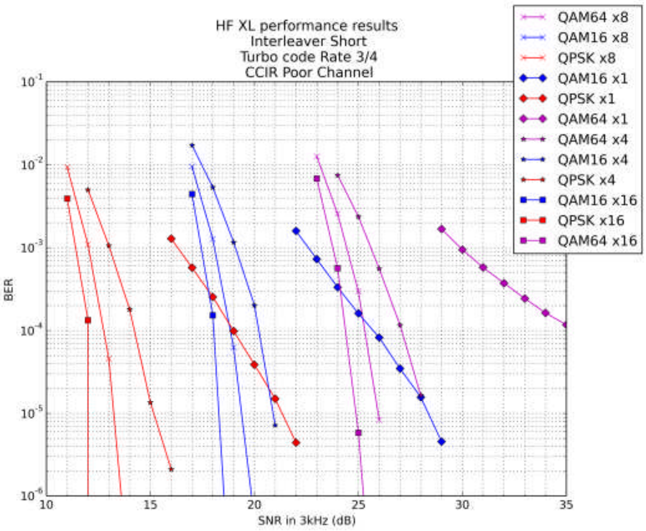

Fig. 11. Comparison of performance for n=1, 4, 8 and 16 channels with Turbo code (R=3/4) of ST4539 app. H proposal for short interleaving (S) over CCIR Poor channel.

E. Analysis

TABLE II presents examples of gains offered by the Turbo code when compared to the convolutional code of same coding rate=¾ for several configurations simulated in previous sections. As already stated, it is shown that the Turbo coding scheme outperforms the convolutional code.

It should nevertheless be observed that the use of the short interleaver reduces the gain, in particular if there is only one channel. This led us to further work on the validity of the frequency diversity hypothesis, in order to make sure that the n=16 channels simulations are not too optimistic.

Firstly, simulations have been made to compare results with n=1, 4, 8 or 16 channels.

TABLE III presents the gains for several channels when compared to a single one; that proves that a diversity of 16 is not necessary to obtain the Turbo coding gain.

TABLE II
PERFORMANCE GAIN (DB) BETWEEN CONVOLUTIONAL CODE AND TURBO CODE FOR SEVERAL CONFIGURATIONS (VERY LONG OR SHORT INTERLEAVER)

Modulation	Gaussian channel	CCIR Poor channel
VL, QPSK, 1 channel, BER=10^{-3}	+1	+0.5
VL, QPSK, 1 channel, BER=10^{-5}	+2.4	+1.5
VL, QPSK, 16 channels, BER=10^{-3}	+1	+1.2
VL, QPSK, 16 channels, BER=10^{-5}	+2.4	+3.4
VL, QAM-64, 1 channels, BER=10^{-3}	+1.5	+1.1
VL, QAM-64, 1 channels, BER=10^{-3}	+2.8	+2.2
S, QAM-64, 1 channels, BER=10^{-3}	+1.6	+1
S, QAM-64, 1 channels, BER=10^{-5}	+2.8	
VL, QAM-64, 16 channels, BER=10^{-3}	+1.5	+2.2
VL, QAM-64, 16 channels, BER=10^{-3}	+2.8	+4.5
S, QAM-64, 16 channels, BER=10^{-3}	+1.5	+3
S, QAM-64, 16 channels, BER=10^{-5}	+2.8	>5

TABLE III
PERFORMANCE GAIN (DB) FOR N=4, 8 AND 16 CHANNELS WHEN COMPARED TO N=1 CONFIGURATION FOR TURBO CODE WITH VARIOUS MODEM AND INTERLEAVER CONFIGURATIONS OVER CCIR POOR CHANNEL

Modulation	n=4	n=8	n=16
VL, QPSK, BER=10^{-5}	+1.0	+1.3	+1.5
VL, QAM-16, BER=10^{-5}	+1.1	+1.5	+1.6
VL, QAM-64, BER=10^{-5}	+1.3	+1.7	+1.9
S, QPSK, BER=10^{-5}	+3.3	+4.3	+4.9
S, QAM-16, BER=10^{-5}	+3.5	+4.5	+5.2
S, QAM-64, BER=10^{-5}	+4.3	+5.5	+6.1

Secondly, results [11] from field trials performed in March 2014, in France, in NVIS (near vertical incidence skywave) propagation conditions have been analyzed. Fig. 12 illustrates the frequency diversity that is observed between the different 16 channels used, by plotting the SNRe (SNR estimated thanks to the demodulation error) for each channel for a transmission with n=16 channels and VL interleaver over four successive frames. Evolutions of SNRe in time can be greater than 10 dB, which clearly exceeds the limited noise floor evolutions in less than 200 kHz, and is shown not very correlated, justifying the simulation hypothesis.

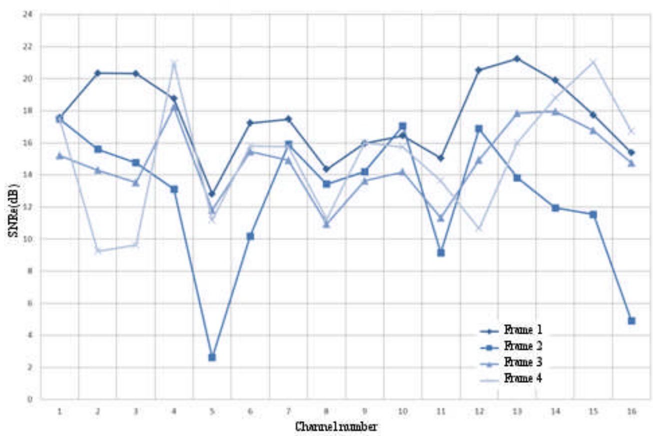

Fig. 12. Illustration of frequency diversity observed in the field (field trials realized in March 2014 in France, source: [11]).

IV. CONCLUSIONS

A non-contiguous multi-carrier waveform with embedded turbo coding scheme has been proposed for HF reliable and high data rate transmissions. It is shown that with sufficient diversity, provided by time diversity, frequency diversity or both, the proposed Turbo coding scheme offers efficient performance and noticeably outperforms traditional convolutional codes. This is corroborated by first field results, and shall be further confirmed by comprehensive field testing and use of a channel simulator based on Vogler & Hoffmeyer work [8] once the HF XL waveform “SALAMANDRE” demonstrator currently being developed for French DGA is finalized.

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