HF XL: ADAPTIVE WIDEBAND HF TRANSMISSIONS

Catherine Lamy-Bergot*, Jean-Baptiste Chantelouve*, Jean-Yves Bernier‡, Hélène Diakhaté* and Jean-Luc Rogier*
(*) THALES Communications & Security
4 avenue des Louvresses, F-92622 Gennevilliers Cedex

(‡) THALES Communications Belgium
Rue des Frères Taymans 28, B- 1480 Tubize

Abstract

This paper presents a solution to increase the throughput of an HF (High Frequency) physical (PHY) layer in particular to allow for services such as IP over HF. Additionally, this new PHY layer can improve the adaptability of the waveform to the channel variations, in particular to limit the retransmissions due to errors. Taking into consideration the existing HF spectrum occupancy and its high interference level, the proposed "HF XL" approach relies on narrow band (3 kHz) non-contiguous channels bonding.

Key words

HF transmissions, high data rate, wideband HF communications, IP over HF, adaptive waveform.

I. INTRODUCTION

During the last century, HF waveforms were designed for voice or low-rate data communications, with a focus on the waveform robustness. Besides the obvious importance of communication resilience to ensure that the link is maintained, the main reason for this focus on robustness is the extreme variability of the HF ionospheric propagation channel, which led engineers to design specific mechanisms to cope with strong fadings, other user interference …

At the turn of the century however, the need for more efficient transmissions has risen, leading to the definition of more efficient waveforms, in particular the STANAG 4539 [1] whose coded modulations allow to reach up to 9600 b/s in a 3 kHz band. The obvious issue with higher efficiency modulations is the higher signal to noise ratio (SNR) required to operate: the variability of the HF channel does not permit to guarantee such high SNR for long periods. This explains the necessity of defining procedures to regularly adapt the transmission parameters to the variations of the channel, in order to ensure a sufficiently low bit error rate for the applications to operate successfully. The will to maintain backward compatibility with existing equipment led to define the STANAG 5066 [2], a protocol suite able to manage the modems from the higher layers. This standard, as well as the more recent STANAG 4538 [3], have allowed the deployment of battleforce electronic emails, sometimes also called HF-EMAIL. The possibility to transmit emails over HF offers a standard interconnection, albeit at limited rate, with wired communication networks but also with higher throughput wireless links such as satellite or V/UHF ones.

Nevertheless, those other wireless media have themselves evolved, answering to the new needs that have since appeared, in particular with the rise of Internet Protocol (IP) and with the interconnectivity capability it offers. Two key issues have been identified: the first consists in increasing the bitrate at the physical layer, and the second in managing successfully the physical layer with respect both to the application and transport layer needs and to the potential variations of the propagation channel. On this last topic, a recent study carried out under the auspices of the European Defence Agency (EDA) showed [4] that standard applications could be used over an IP convergence layer and an adaptive data link layer. On the first topic, studies have long been carried out, since the proof of concept in 2000 [5] and more recently with different standards, whether civilian with the Digital Radio Mondiale [6] or military ones [7][8]. However, concerns have arisen on the practical feasibility of disposing of wider bands on the field. Increasing the used bandwidth in the HF spectrum may not be simple, when taking into account the existing systems in use, existing allocations worldwide… This led to questions on the feasibility of the MIL STD 188-110C appendix D [8] standard on the field. Another proposal was consequently recently made, with the so-called "HF XL" approach. HF XL relies on narrow band (3 kHz) non-contiguous channels bonding, in order to increase the band of the transmission, while selecting only channels where the expected signal to noise ratio is good enough to permit a good transmission.

This article presents the rationale beyond the HF XL approach. In Section II is given a short analysis of the HF spectrum occupancy, coupled with circuit establishment probability, that demonstrate the validity of a multiple non-contiguous channel approach for high data rate transmissions. Secondly, in Section III the modem waveform, operating over n channels, is defined and described. Finally, Section IV presents an adaptive usage of said modem, based on channel quality evaluation, together with first field results and Section V draws some conclusions.

II. SPECTRUM OCCUPANCY ISSUE

Following the introduction of the MIL STD 188-110C in 2011, questions have risen on the possibility to obtain sufficient band allocations to ensure efficient use of this new waveform. The studies made in Canada [9] present an analysis of the availability of bands of 3, 12 and 24 kHz in August and November 2011, independently of actual frequency allocations. This paper shows, as illustrated by its Table 2, that :

- free 3 kHz bands are easily found all day long, despite a minimum during the night due to a spectrum congestion peak,

- free 12 kHz bands and 24 kHz bands are noticeably less available, in particular for the lower part of the HF spectrum, except for a few hours each day.

A similar study was carried out in Sweden [10]. Here again is highlighted an almost unavailability for good quality 24 kHz channels, and a limited availability for 12 kHz channels in the lower part of the HF band ([3-12] MHz), which is of primary interest for short and medium range links.

Finally, another study was made in France [11], leading to the same conclusions. Furthermore, this last study also proposed an analysis on the availability of noncontiguous 12 kHz or 24 kHz worth of HF spectrum. It shows that 16 non contiguous channels of 3 kHz distributed in a 200 kHz band have an availability similar to the availability of one 12 kHz channel, leading to conclude to a clear advantage of considering noncontiguous channels. Furthermore, the study points out the need to take into account the different back-off constraints on the amplifier when comparing contiguous and non-contiguous configurations. Such a comparison combining the spectrum availability measured with simulated circuit availability on an example link of ~350km is presented in [11]. Two conclusions are drawn in this study:

- first, as illustrated by Figure 1, the back-off due to the HF XL multi-carrier approach can be entirely compensated by the possibility in the non-contiguous case to consider wider bands, if they are available.

- second, that throughputs of 76,8 kb/s can be obtained during the day with a better probability with the noncontiguous configurations than the contiguous ones.

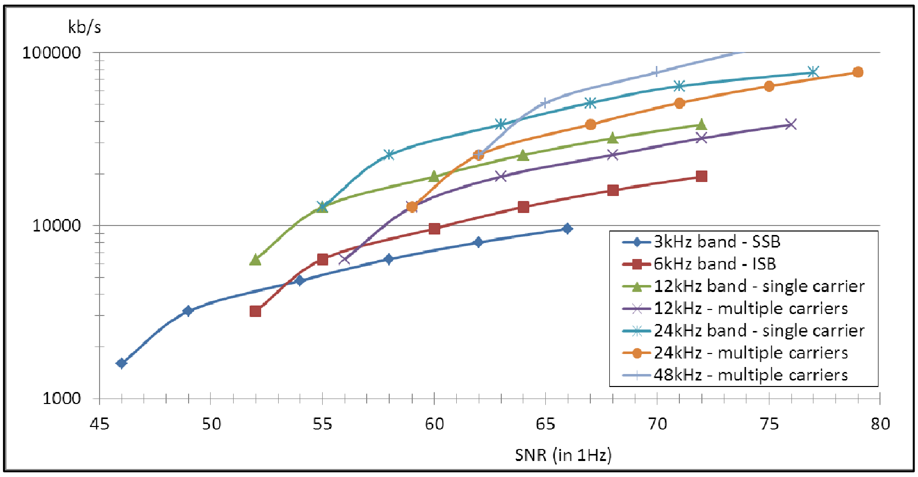

Figure 1 – Comparing the required SNR for different contiguous and noncontiguous configurations.

These different studies allow concluding on the obvious interest of considering a waveform able to operate over non-contiguous portions of the spectrum. Such a modem proposal is detailed in Section III.

III. A MULTI-NARROW BAND MODEM

Following the trend introduced in MIL STD 188-110 B appendix F, and its straightforward extension proposed by Jorgenson et al. in 2000 [5], we have considered a multiple subcarrier modulation process and a wideband radio (200 kHz). As illustrated by Figure 2, each carrier supports a 3 kHz serial waveform, in such a way to match traditional 3 kHz Single Side Band (SSB) frequency allocations inside the 200 kHz radio band. The unused channels are not selected either because they are not authorized for the considered link or because they are perturbed by interferers.

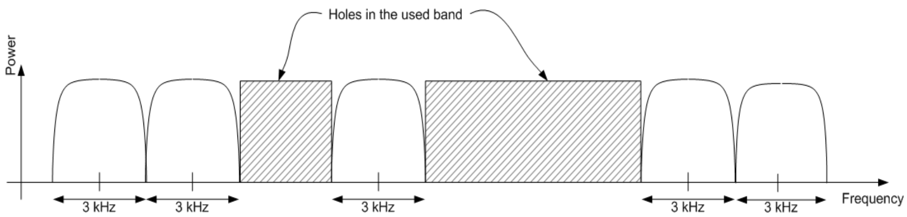

Figure 2 – HF XL multiple carrier principle.

The system is based on multichannel modulation patterns called superframes, whose structure is presented in Figure 5. The number of channel used, the position of the channels in the radio band, the elementary channel power level and the type of modulation used on each channel, are variable from one superframe to another. This allows the transmitting radio to optimize throughput of the global system or latency, based on local operational needs, and quality information and/or spectral occupancy monitoring from the other radio(s) that participate to the link. The block diagram of the transmitter is shown in Figure 3. The block diagram of the receiver is shown in Figure 4. Operational constraint time data (CTD) and non-constraint time data (NCTD) flows are combined, coded, interleaved and sent to different 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.

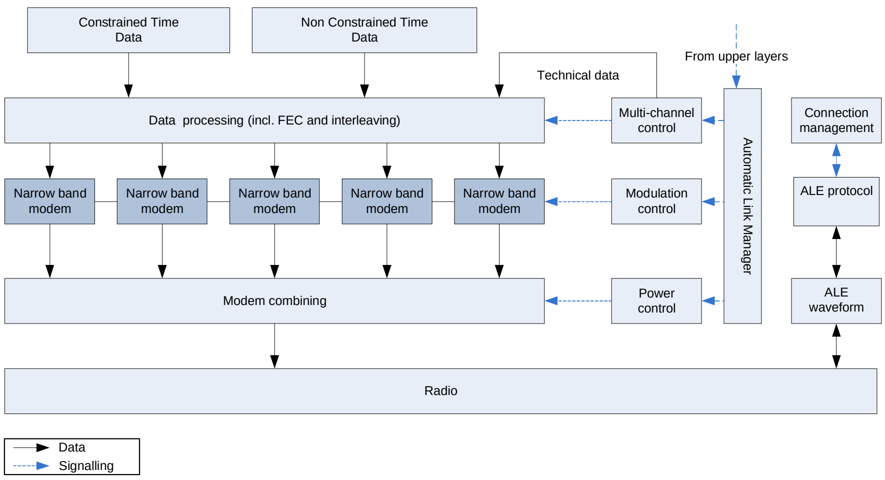

Figure 3 – HF XL transmitter block diagram.

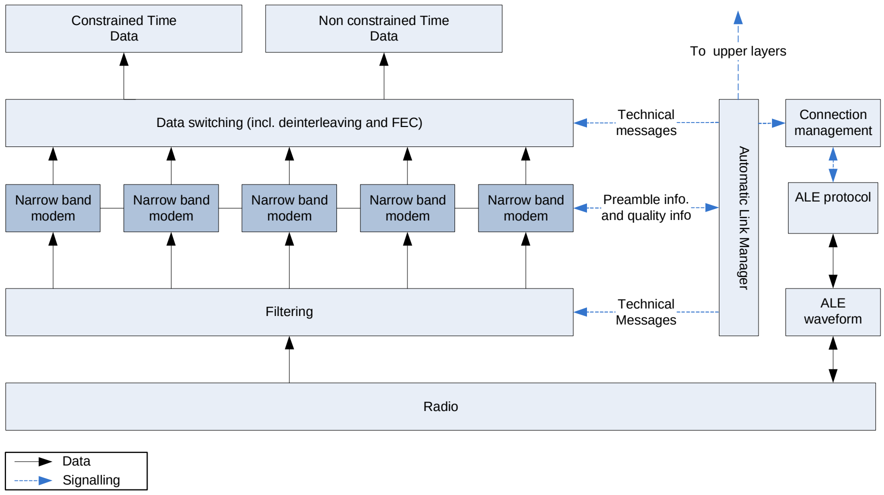

Figure 4 – HF XL receiver block diagram.

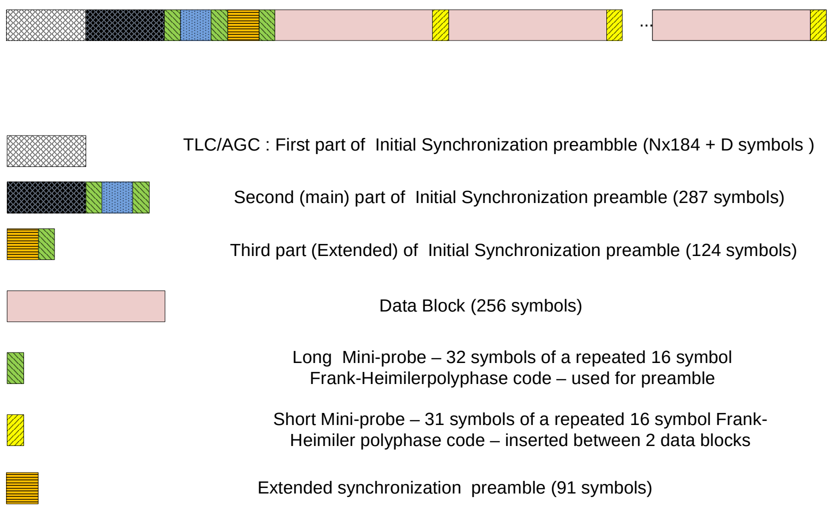

Figure 5 – HF XL frame structure.

As illustrated by Figure 5, the superframe format has been defined for compatibility with STANAG 4539 [1] and MIL STD 188-110C appendix F "ISB"[8]. It consists of an initial synchronization preamble, followed by 72 frames of alternating data and known symbols. Each data frame consists of a data block consisting of 256 data symbols, followed by a mini-probe consisting of 31 symbols of known data. The preamble consists of three parts:

- a Transmitter Level Control / Automatic Gain Control (TLC/AGC) sequence, including an optional D symbols sequence to provide offset between channels.
- the main synchronization preamble, compatible with STANAG 4539 preamble,
- an extended synchronization preamble, specific to HF XL. This last part, not included when operating according to 4539 or ISB modes, is combined with the main preamble to carry all information necessary to the HF XL waveform, in particular information on modulation choice for each channel. Furthermore, a specific redundancy capability is introduced, that ensures resilience to the loss of a channel as long as the number of channels is greater or equal to 3.

In total, as illustrated by Figure 6, the preamble conveys 14 additional bits defined as follows:

- a 4 bits modulation "M" $M_0M_1M_2M_3$ identifying the modulation used on the channel,
- a 4 bits code "K" ($K_0K_1K_2K_3$) identifying the number of the channel (from 1 to n),
- a 4 bits code "X" ($X_0X_1X_2X_3$) that provides, depending on the value of K modulo 3, the forward error correction code used, the employed interleaver and the total number of channel considered.
- a duplicate of M code (M'3, M'2, M'1, M'0) of the adjacent m+1 modulo n channel, for the redundancy capability,
- a 14th bit 'R' set to 0 when the number of channels is equal or greater than 3.

For compatibility reasons, the two first parts of the preamble are identifical to the STANAG 4539 preamble, except for the two tribits defining the modulation and interleaver types. As inspired by the "ISB" approach, the three bits carrying the data rate information are fixed to '111', while the three bits carrying the interleaver settings are used to convey information bits M_3,M_2,M_1 defined above.

	Preamble 2nd part			Preamble 3rd part						
	D0	*D1*	*D3*	D_3	D_4	D_5	D_6	D_7	D_8	D_9
MSB	*1*	*1*	*1*	R=0	K_0	K_2	X_0	X_2	M'_0	M'_2
LSB	M_0	M_1	M_2	M_3	K_1	K_3	X_1	X_3	M'_1	M'_3

Figure 6 – HF XL autobaud fields.

Beside the inherent redundancy introduced in the preamble to ensure that one or few channel loss does not result in the loss of the whole superframe, the HF XL multiple carrier signal presents an added robustness when compared to single side band solutions. This is due to the common forward error correction and interleaving process among the n channels, which takes advantage of the frequency diversity, considering both the jamming environment, and the propagation in wideband HF channels as shown by Vogler & Hoffmeyer model [12].

IV. BITRATE ADAPTATION WITH RESPECT TO THE CHANNELS QUALITIES

A. PROPOSED PROTOCOL

As said before, the HF propagation channel is an error prone, varying channel, experiencing time and frequency selective fading. In order to reach a high throughput, the different propagation channels are closely and individually monitored. This process optimizes the transmission parameters, to ensure the highest data rate for a minimal bit error rate. This is the role of the Dynamic Rate Control (DRC) protocol.

Traditionally, the DRC mechanism is driven by the automatic repeat request (ARQ) function, which does not take advantage of the fine channel characterization, available at the modem level, such as modulation error ratio or channel estimation. Furthermore, this approach is oriented by the single carrier approach employed by existing waveforms, including the recent MIL STD 188-110C appendix D [8]. In the case of the HF XL waveform, the DRC protocol must define the most efficient combination of channels to use, with for each channel the best adapted modulation and the signal power level. This combination is defined by the set of $x_{i,j}$ values ($x_{i,j}$ = 1 when j[th] channel uses modulation bit rate d_i among the $[d_i]_{i=1..m}$ existing modulation bit rates, ordered forward, and $x_{i,j}$ null otherwise). Denoting P_{tot} the total power available for the composite signal, and $P = [P_i^j]_{i=1..m}^{j=1..n}$ the matrix of necessary power level for each of the j[th] observed propagation channels to allow correct transmission using the i[th] modulation type, the DRC algorithm must solve the following maximization problem:

$$\max \sum_{j=1}^{n}\sum_{i=1}^{m} x_{i,j} d_i$$

under constraints C_0 of integrity and C_1 of total power

$$(C0): x_{i,j} \in \{0;1\}, \sum_{i=1}^{n} x_{i,j} = 1\ \forall j,\ (C1): \sum_{j=1}^{n}\sum_{i=1}^{m} x_{i,j} P_i^j \le P_{tot}$$

$$\textit{with } P_i^j \le P_i^{j+1} \textit{ and } d_i > d_{i+1}\ \forall i$$

Taking into consideration the information already present in the HF XL preamble fields, the DRC mechanism only needs to inform the receiver in case of new channel addition to the composite signal, to ensure that the receiver processes the corresponding added channels. This information is transmitted through a technical message, embedded in the data stream, for application in an ulterior superframe.

Additionally, filtering mechanisms can be considered, either to present hysteresis between configurations or to filter rapid channel variations.

B. NUMERICAL RESULTS

Using the test-bench described in [13], trials have been made with a first implementation of the protocol proposed in Section IV-A. During the trials, configuration update choices were constrained to a maximal bitrate increase of a factor 4.

Figure 7 presents a capture of the reception interface of the test-bed in five different instances of an automatic adaptation test. The following steps are automatically selected by the algorithm to converge at a bitrate of 92 kb/s:

- step 1: launch of the system with four pre-selected frequencies agreed upon by emitter and receiver. All four channels use QPSK modulation,

- step 2: after channel evaluation over several frames, the RX side has informed the transmitter of the quality of other channels authorized in the 200 kHz band. Four of those channels have been selected and integrated in the multiple carriers signal using QPSK modulation,

- step 3: after again evaluation over several frames, six new channels are added to the multiple carriers signal and two channels are attributed a higher data rate modulation: 16-QAM,

- step 4: a last channel is added, several channel modulations are modified, leading to a multiple carrier signal of 15 channels with 64-QAM, 32-QAM and 8-PSK modulations.

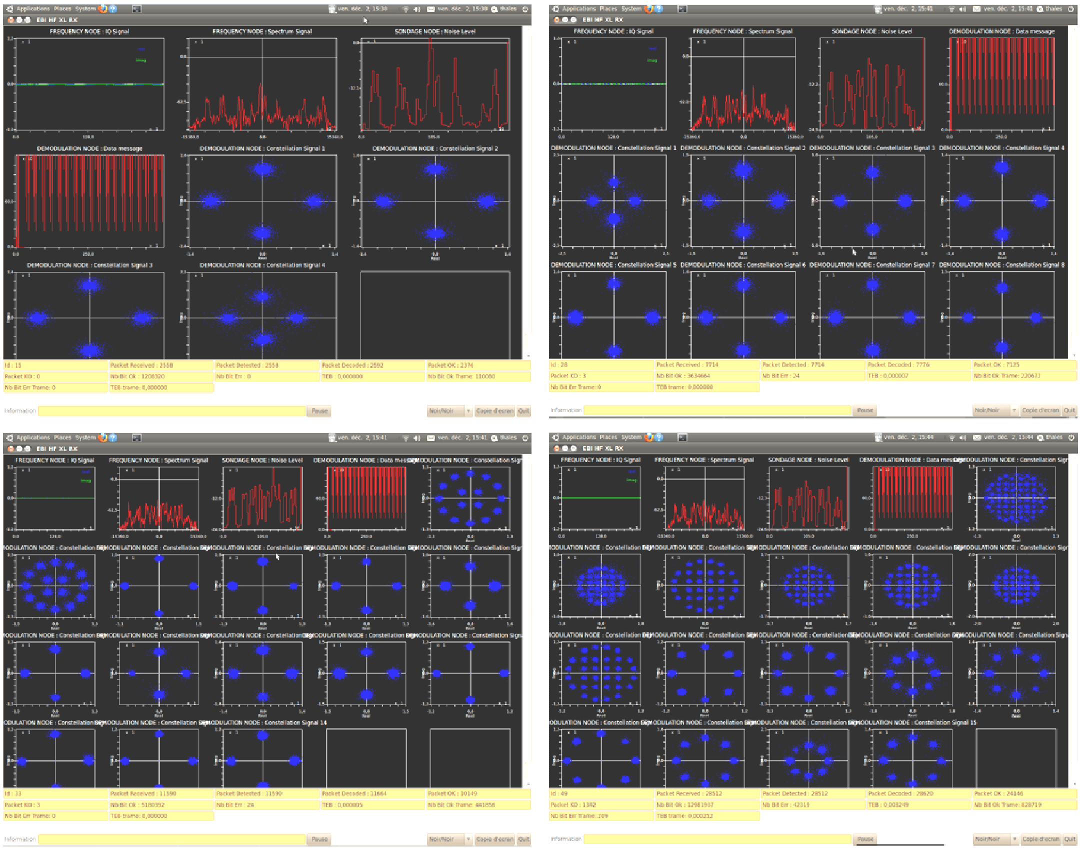

Figure 7 – Automatic adaptation for the HF XL waveform: illustration of 4 different steps converging to a 92 kb/s link.

V. CONCLUSIONS

A new wideband high data rate HF waveform is proposed in this article. Employing multiple non-contiguous channels evaluated for their quality, and tailoring the power levels and modulations used on each carrier to the actual propagation conditions, the HF XL waveform allows reaching throughputs higher than 100 kb/s, while respecting the existing HF spectrum allocations. Furthermore, the HF XL waveform can be easily adapted to the presence of interferers and is intrinsically resilient to errors. First field trials on the adaptation mechanisms have been presented, based on the test-bed prototype presented in [13].

Future works will focus on further defining the adaptation procedure, and its integration with the automatic link establishment procedure, as well as further validating this procedure in field trials.

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