# Time-division Approach in HF Wideband: Surfing the Wave to Offer a Better Performance

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*Abstract*—**HF ionospherical channels are very challenging due to their time and frequency selective, and highly varying natures. Furthermore, they offer only limited data rates, which led generations of engineers to limit the signalization information and to reduce the number of turnarounds to preserve a maximum throughput for useful data. However, new wideband modems[1][2] have recently been proposed, that achieve much higher data rates and a much better resilience on the HF link, leading to re-assess such traditional strategies. This paper presents a protocol relying on a time division approach, which can follow very closely the channel variations between two stations for only a limited signaling overhead, and as such allows to optimize the transmissions. Experimental results are given, that demonstrate the interest of such an approach over various ionospherical HF channels.**

*Index Terms*—**Adaptive systems, Communications system, Fading channels, Ham radios, High Frequency (HF), Military communication, Time division multiple access.**

## I. INTRODUCTION

High Frequency (HF) radio communications have slowly being replaced in civilian usages (broadcasting, wireless telegraphy…) over the last decades by satellite, land lines and cellular networks, but they are still a playing a very important role in military communications, especially in mobility and emergency situations as they allow to provide communications with minimal to none infrastructure from short to very long distance.

Historically operated on 3 kHz channels, HF transmissions were totally human driven up to the introduction of the so-called Second Generation (2G) of HF means. 2G relies on an Automatic Link Establishment (ALE) [5] procedure that links distant stations by automatically testing a set of frequency and selecting a good one (possibly adapting said frequency when the channel conditions vary). Once the link is established, communications can begin, typically voice communications in push-to-talk (PTT) mode, or other data services, relying on STANAG 5066 [6], which defines standard interfaces for applications, proposes a reliable retransmission protocol (also called ARQ for Automatic Repeat reQuest), and management of the HF modem. But performance offered by this 2G approach [7] could be improved, especially in harsh environment, which led to the introduction with STANAG 4538 [8] of a so-called Third Generation (3G). 3G protocols still consider 3 kHz narrow band modem, but define a more efficient ALE procedure [9], and a better performing data service approach, especially at low signal to noise ratios [10]. Full STANAG 4538 solutions are however seldom deployed due to lack of clear security interoperable definition.

Still, even 3G solutions were not able to offer sufficient performance, in terms of resilience, throughput or latency, to allow the HF communications standards to enter the digital world and answer to today's customer needs for efficient and resilient link adapted to modern applications (*e.g.* chat, web access, messaging, large file transmission…). This has led recently to the emergence of new solutions relying on wider useful bandwidth (up to 16 times 3 kHz), either non contiguous [1] or contiguous [2] (this latter being an extension of [3]). The corresponding standard on the radio is also being discussed [4], but the protocol part with link establishment, link maintenance, channel access definition and modem management, is still only in its infancy. Concerning ALE, several proposals exist, that consider either an evolution of 3G ALE [11], an evolution of the new contiguous waveform modes with principles similar to current ALE [12][13]... or a more radical change relying on a very wideband front-end, with the capacity to listen to several channels at the same time [14], or even to the whole HF band [15] ! Concerning reliable data transmission, most studies focus on evolution of the 2G ARQ, the main issues to be assessed being the possible evolution of link towards possibly a time division duplex scheme [16][17], the evolution of modem management with Data Rate Change (DRC) piloting a new dimension with the bandwidth size, and the introduction of a Cognitive Engine (CE) managing the band choices and ALE frequency uses, by combining embedded prevision algorithms and real-time measurements.

This paper is organized as follows. Facts on HF propagation channels are recalled in Section II. Section III presents the HF XL strategy, with the protocol with time division access strategy proposed over STANAG 4539-H [1] physical layer, to follow the channel variations. Field trials results are given in Section IV. Finally, in Section V, conclusions are drawn on the interest of the time division approach.

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## II. HF CHANNEL CONDITIONS

Traditional HF channel models such as Watterson model [18] (most used), but also its wide band evolution proposed by Vogler et al. [19], consider that the channel is stationary over the length of the transmission, which means that the statistics of the channel do not vary with time over said transmission. This hypothesis does not mean that no variability is taken into account–typically the Doppler parameter in Watterson model allows to take into account the mobility effect coming from the ionosphere drift velocities–but that long term non stationarities are not taken into account. While such an assumption may have been valid at a time where only short (voice) transmissions were considered, this is in practice no longer true today when longer IP-based communications (*e.g.* for transmissions of large data sets) are desired. A recent work [20], based on a large measurement campaign has allowed to show the difference between such models and the reality, in the context of Near Vertically Incident Skywave (NVIS) channel models. We found similar results with the experimentations that we have been carrying out with HF XL wideband demonstrator. This is illustrated in Fig. 1, where the evolution of instantaneous received power (green curve) as well as mean and 25% percentile values after sliding averaging process over 2 minutes are presented. It is clear that with variations as big as 10dB in 5 minutes, one is far from the flat evolution that is obtained with a traditional Watterson model with reference ITU profiles!

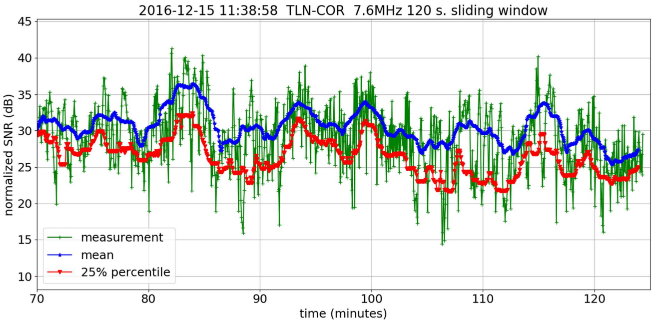

Fig. 1. Illustration of non stationarity of HF channel (Field trials, location: France, Dec. 2016, link 2 as defined in Section IV).

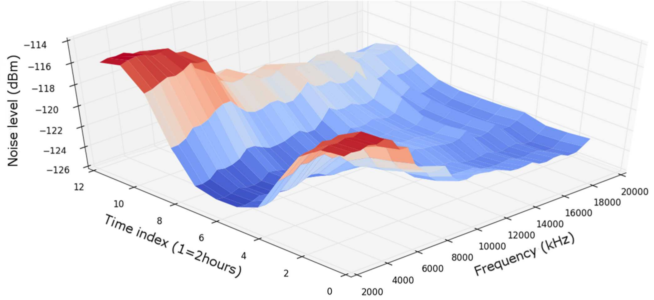

Fig. 2. Illustration of noise floor variation, location: France, year: 2011.

This non-stationarity leads to questioning the traditional approach relying on favoring long transmission times, with very long interleavers and limited turnarounds. Again, that approach had clearly sense with older amplifiers with very low rise time, in particular when using them for very long distance transmissions at data rates as low as 75 b/s in such cases, the cost of turnaround was prohibitive. However, modern and agile radios and modems allow another choices, namely to follow the channel variations, and adapt to it, as will be further described later.

Still, the noise floor level remains quite stationary over several minutes, as can be seen in Fig. 2. Even when in presence of impulsive noise, this stability is verified as using median noise value allows avoiding bias due to noise bursts. This stability is coherent with reference ITU model, that is used to derive the noise floor in prediction models such as SATIS [21] or VOACAP [22]. However, we have found in our analysis that despite being globally consistent with this ITU model, the noise floor seasonal variations were often overestimated, especially in winter, as illustrated in Fig. 3 from measurements collected over a whole year (2011) in France. It is then advantageous to re-estimate regularly the noise floor, and use this real value for budget link evaluations rather than the theoretical value. This approach has further advantages: it allows to take into account the influence of the antenna type, as well as possible local perturbations (such as cosite emissions) which are not taken into account in simulators relying on a general noise model for given areas.

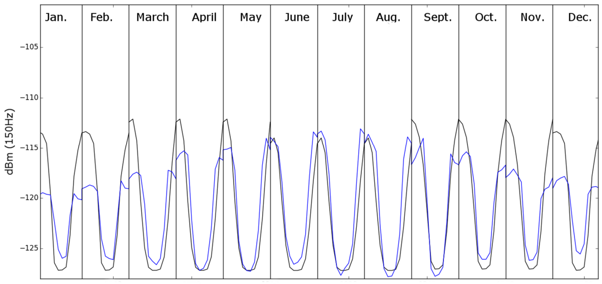

Fig. 3. Illustration of average “mean day” noise floor variation measured (blue curve) vs. UIT model (black curve), F=5 MHz, location: France, year: 2011.

A second interesting input from channel conditions monitoring is the more usual evaluation of short term noise level in the transmission band, especially when using very wideband receivers such as the ones proposed in [23]. This allows to measure for each channel being used a total signal strength that is the sum of useful signal S, jamming J, noise N, and for authorized but non-used channels a signal strength corresponding to J+N only. Fig. 4 illustrates this capacity to dispose simultaneously of different measures for both used and non-used channels, which enables the translation of the quality observed on a used channel to the expected quality of an unused channel.

As a summary, we use as inputs to our CE and DRC procedures to decide on the best transmission parameters:

1- An estimation of the noise floor, obtained in the frequency domain. The spectral density of the current 200 kHz band is estimated with 500 Hz resolution periodogram (64 FFT averaging) for each slot. With such a resolution, the 10% lowest frequency bins are used for the estimation. This noise floor estimation can be regularly exchanged between different users, since it depends significantly of the station environment. This noise floor is used by the CE to select the preferred subbands.

2- An estimation of the total noise and jamming level, measured in each possible transmission channel. These values are used by the DRC to select the channels to be used and their modulations.
3- Modem estimations of signal to noise ratios.
4- Signal receive level.

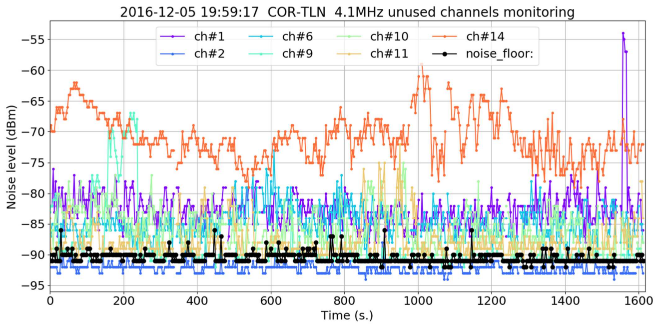

Fig. 4. Illustration of evaluation of narrow band channel occupancy through wideband channel measurements.

## III. WAVEFORM PRINCIPLES

As detailed in [24], the STANAG 4539-H current draft [1] defines an HF data modem operating over multiple discrete channels, using an elementary serial waveform derived from Annex B of the same STANAG, to achieve up to 153 kb/s in an integrated HF communication system named HF XL. This solution has been proposed to overcome the non-availability of contiguous frequencies up to 48 kHz (resp. 24 kHz) such as needed for STANAG 5069 proposal [2] (resp. MIL STD 188-110C-D [3]), but also to allow for insertion of technical messages, in order to exchange, as illustrated by Fig. 5, between stations the channel quality information described in Section II: noise floor level, respective channel qualities, but also other useful information such as possibly evolution of transmission bands or transmission channel that can be decided by the Cognitive Engine. Those technical messages are interleaved with the data flow and protected by a Cyclic Redundancy Check (CRC).

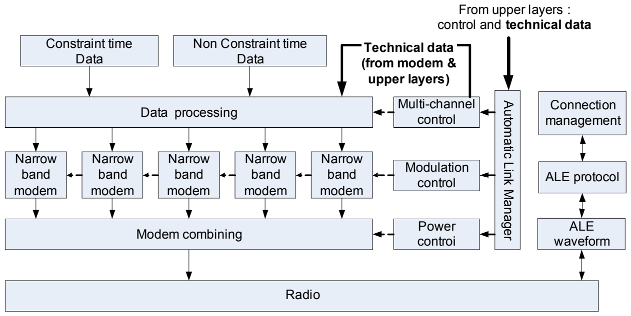

Fig. 5. Illustration of Transmitter block diagram, with highlighting of the technical data message insertion in the data flow.

At data link level, the main evolution introduced by the HF XL approach waveform when compared to previous narrow band ones, as well as contiguous ones, is the use of a time division duplex (TDD) scheduling, with eventually different slot sizes. While common in V/UHF bands, such a scheme has been rarely considered for HF, except for Link 22, due to the limited throughput that could be obtained, as shown for instance by Jorgenson et al. [17]… issue that is, again, overcome by the wideband HF evolution. Conversely, Time Division schemes offer:

- easy access to the channel in short times to any user, which was not the case with mechanisms such as End of Transmission (EOT) or Token Ring piloted by the transmitted node defined by STANAG 5066 [6],
- simple exchange of channel conditions information and evolution of transmission parameters desired by the protocol. The DRC mechanism decides of these parameters, dealing with an added dimension (bandwidth) in wideband HF. It shall decide of the number of channels used, their positions in the band, the modulation used for each channel, … as long as a minimal performance level can be reached. Below such a level (i.e. when the link risks to be lost, or below performance level acceptable for the application used), the Cognitive Engine suggests a new band to consider to reach the required performance,
- capacity to overcome momentary synchronization losses due to a deep fading, as can occur in traditional HF schemes (ex: when PTT is not received).

Obviously, it is important to have several slot patterns to be considered, in order to accommodate for both strong latency constraints (*eg.* with voice) and large throughput requirements (*eg.* for large files). As such, in the current prototype built to demonstrate STANAG 4539-H waveform, several slots sizes have been considered: 1.5s and 9s, as well as their hybrid combination. TABLE I gives the projected results of our on-going optimization for maximal throughput that can be obtained with those three TDD schemes, as well as an estimation of the overhead cost for technical messages, and time duration for the adaptation cycle. The adaptation cycle is defined as the time needed to operate a DRC change, that is the total period comprising a transmission slot, measurement of its quality, transmission of said quality in technical message, decoding of the message and use by the DRC, and application of the new DRC parameters. In the current prototype, this cycle is equal to 3 (tx, rx) phases, to be reduced to 2 cycles with the aforementioned optimization, corresponding depending on the selected TDD scheme to 5.7 to 35.8s of time. In practice, some filtering is applied to prevent hysteresis in the adaptation, which may increase slightly the cycle duration.

TABLE I
OVERHEAD AND THROUGHPUTS FOR EACH TDD SCHEME

| | 1.5s / 1.5s | 1.5s / 9s | 9s / 9s |
|---|---|---|---|
| Max throughput A=>B (kb/s) | 58 | 15.9 | 74 |
| Max throughput B=>A (kb/s) | 58 | 127.8 | 74 |
| Total throughput A<=>B (kb/s) | 116 | 143.7 | 148 |
| Overhead cost for technical messages | 0.35 % | 0.35% (A=>B) | 0.09 % |
| Adaption cycle time duration | 5.7 s | 20.8 s | 35.8 s |

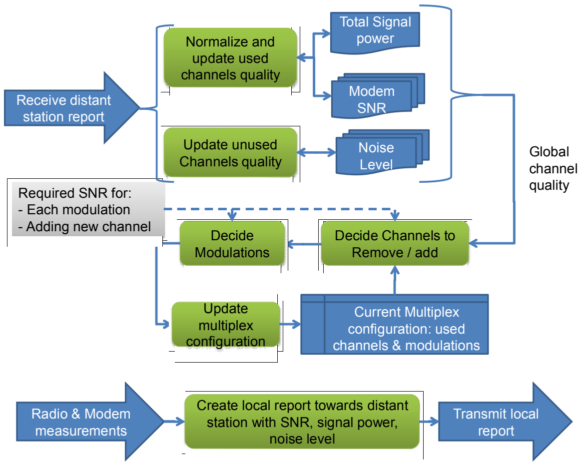

Fig. 6. Flowchart of HF XL DRC algorithm.

Fig. 6 summarizes the different steps of the proposed DRC algorithm. Contrarily to the STANAG 5066 standard, DRC is operating at modem level, in the black side, and has access to all modem and radio measurements: noise level for unused channels, signal level, and SNR as estimated at modem level for used channels. The role of the DRC mechanism is to exploit all the degrees of freedom of the frequency multiplex to optimize a given criterion, typically the maximum data rate under a limited error rate constraint. If many channels are available, the DRC will allocate as many as possible for it increases reliability, whereas if low throughput is required, it may not select high efficiency modulation as low efficiency ones are more robust and will allow to offer the service. Finally, the DRC protocol maintains memory on the available channels quality, to be able to resist also to intermittent jammers. Ultimately, it could change the slot duration, the maximal number of channels to use…, or increase the interleaver size when detecting longer fading on the channel. As a summary, its role is to present a "channel" possibly varying in throughput but as stable as possible in terms of error rate to the higher layers, which operates on data units (or PDU for Protocol Data Unit).

## IV. TRANSMISSIONS RESULTS

Two different experimentations set-ups have been considered in our various campaigns. They are referred in the following as Link 1 and Link 2:

- Link 1 corresponds to medium range with ~310km ionospherical propagation between two French cities (Cormeilles, Cholet), with trials done in Sept-Oct 2016;
- Link 2 corresponds to higher range with ~730km ionospherical propagation between two French cities (Cormeilles, Toulon), with measurements made in Nov-Dec 2016.

The stations are deployed in a tactical cabinet of 12 U, linked to a tactical power amplifier of 400 W, and on-the-halt antennas (no infrastructure antenna, almost no directivity). Results given hereafter have been done with the 1.5s/1.5s mode, the most adaptive one, as in most cases applications such as web browsing requiring low latency have been used.

As a reference, Fig. 7 provides the statistical prediction obtained with SATIS [21] for both links for 400W and isotropic 0dBi antennas in rural conditions, which can be compared to the required SNR needed in 1Hz for narrow band modems over CCIR Poor channel: 53dB to reach 3200 b/s, and 72dB for 9600 b/s. These curves show that the challenge to use tactical equipment (antenna and power amplifier) is important, for with both links narrow band equipment would allow around 8000 to 9600 b/s.

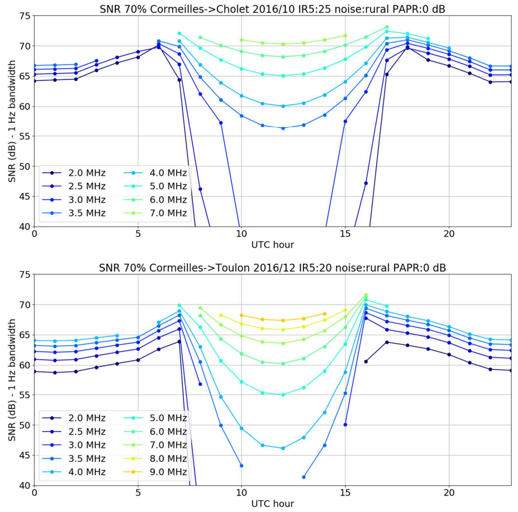

Fig. 7. Statistical prediction for SNR (in 1Hz) for link 1 in October 2016 and link 2 in December 2016 [21].

The SATIS prevision tool is used in the demonstrator initially to estimate the throughput that can be obtained on the link, and its previsions are refined with taking into account measurements as soon as they are available: first local conditions (noise floor estimation, conditions on the traffic available channels, …) and distant conditions once the link is established. To obtain good performance in real conditions, the key issues are:

- to have a good ALE algorithm allowing to select a subband with enough usable frequencies. We used a wideband evolution of 2G ALE [14] in our trials,
- to have a correct DRC algorithm able to operate over a non-stationary channel, and adapt constantly in order to offer the best of the channel, as described in Section III,
- to strengthen the link as much as possible, by both using retransmissions, in our demonstrator done with an adaptation of STANAG 5066 ARQ to higher data rates and to the new DRC mechanism, but also by taking advantage of frequency diversity thanks to the use of up to 200 kHz wideband transmission (typically according to our field trials, channels need to be separated by more than 30 kHz to face independent fadings, see hereafter).

Frequency diversity allows to improve performance when compared to narrow band performance, and is able to compensate the added back-off of multi-tone modulations when compared to single tone ones. Fig. 8 illustrates this time diversity, by showing the equivalent Signal to Noise Ratio (SNR) that would be obtained for a single narrow band transmission in four channels of the same subband, one being the reference and the three other being respectively at 12 kHz, 52.7 kHz and 63.2 kHz of the first one. The diversity gain is absent for 12 kHz but obvious when frequency separation is greater than 50 kHz, allowing to obtain a better average SNR (measured over the multi-tone modem) with also a lower standard deviation, which will allow to reduce the margin needed to have the ARQ mechanism perform correctly.

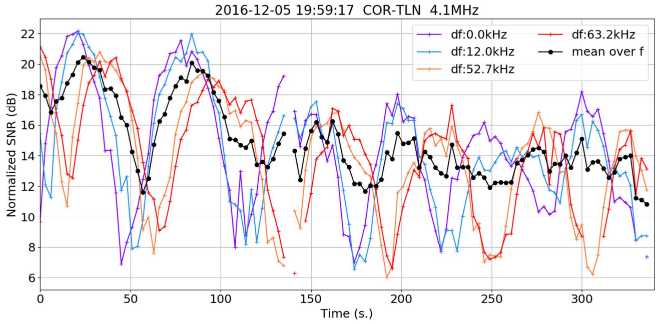

Fig. 8. Illustration of frequency diversity, offering an added resilience via an improvement of average signal to noise ratio. Link 2, Dec. 2016.

Field experimentations allowed to demonstrate the capability to realize dissymmetric adaptations, as illustrated in Fig. 9 where different noise floors are observed (average 5dB difference), leading to very different evolutions of the useful band decided over the two different directions for Link 2. The channel variations are followed by our system which "surfs the channel wave" as illustrated in Fig. 10 and Fig. 11. One sees that the modem data rate (red, y-left axis) follows the evolution of the average received power (green, y-right axis), with a latency of about 30s-1min, in coherence with the cycle duration introduced previously.

Details on throughputs (only error free slots are considered for throughput statistics) observed for both links are given in TABLE II. For Link 2, with a tactical 400W amplifier and antenna over 730km, i.e. with a few watts for each 3 kHz channel, peak througputs (defined as the 95% percentile of the modem throughput) of 32 kb/s in Toulon (resp. 48 kb/s in Cormeilles) were observed, with mean throughputs of 12 kb/s (resp. 21 kb/s). Limited throughputs were observed, reducing the mean value, and found due to autobaud definition [1] that is being corrected for the next draft version. Nevertheless, the link performance allowed to operate ACP127, HF-Email, chat, image transfer and web browsing. Over the shorter Link 1, higher throughputs, average 35 kb/s, and up to 75 kb/s were obtained, with the same services used. In all cases, the Slot Error Rate (SER) was derived thanks to the CRC on technical messages (see Section III) to estimate the slot good reception.

Another lesson from the field experimentation has been the very good capability of the DRC to maintain the link and adapt over long periods on the channel variations: contrary to habits in narrow band, it was found possible to maintain the link in the same subband over several hours, without having to change the ALE subband, except at the frequency transition times. Fig. 12 illustrates this capability, with first two ALE performed at the beginning of the sequence to accommodate changes of ionospheric conditions, followed by more than 5 hours of continuous link availability.

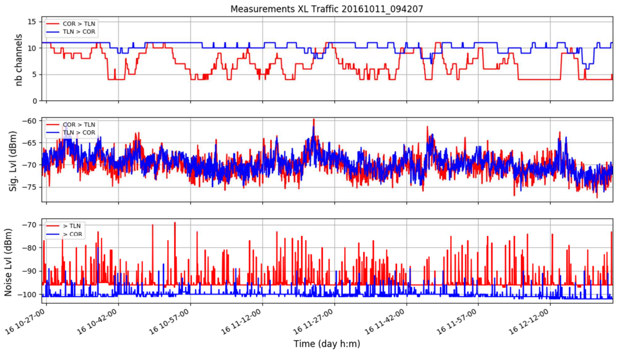

Fig. 9. Adaptation of the communication in both directions over link 2 with respective (a) number of channels used, (b) signal strength variations and (c) noise floors, with very strong impulsive noise in Toulon site, Nov. 2016.

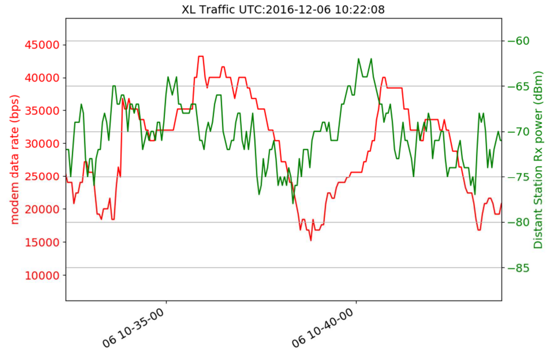

Fig. 10. Following the channel variation with our adaptive protocol: illustration over link 2, Dec. 2016.

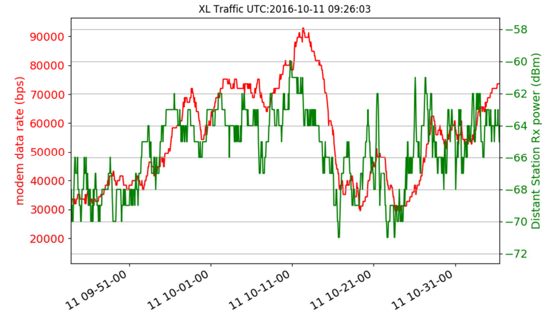

Fig. 11. Following the channel variation with our adaptive protocol: illustration over link 1, Oct.2016.

TABLE II

THROUGHPUTS OBSERVED DURING THE DIFFERENT TRIAL DAYS

| Throughputs (A -> B / B -> A) | Link 1, Sept. 2016 | Link 2, Dec. 2016 |
|---|---|---|
| Best throughput observed (kb/s) | 75.2 / 75.2 | 32.0 / 48.0 |
| Average throughput obtained (kb/s) | 34.4 / 37 | 11.9 / 21.1 |
| Slot Error Rate (%) | 2.5 / 2.8 | 11.0 / 4.7 |
| Total traffic duration (hours) | 23 | 24 |

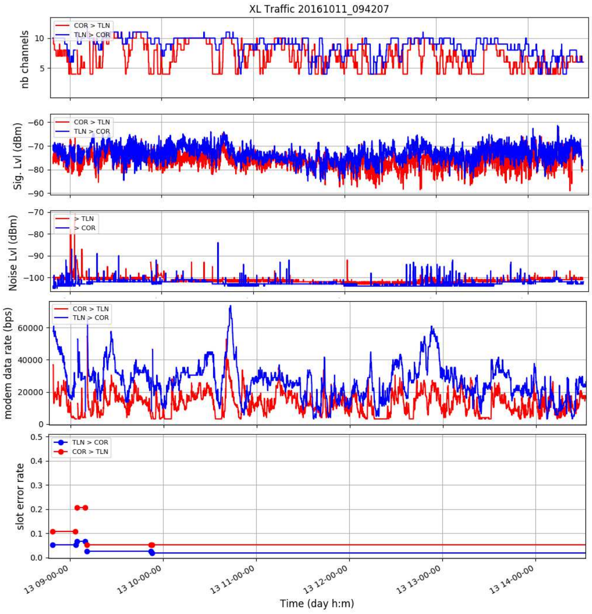

Fig. 12. Illustration of link maintenance over several hours, link 2, Dec. 2016.

## V. CONCLUSIONS

The non-contiguous wideband HF modem proposed for STANAG 4539-H has been combined with a time-division access scheme whose aim is to dynamically adapt with the channel thanks to both propagation prevision and channel measurements.

Field experimentations have allowed to prove that wideband non-contiguous approaches can offer further resilience thanks to the use of frequency diversity, of synchronization maintenance natively offered by the time-division scheme, and also by the low latency DRC mechanism that automatically adapts all the transmission parameters to the non-stationary channel in a few tens of seconds. This capability to "surf the channel waves" allows the modem to optimize finely to the varying channels without needing to take large margins or without loosing a lot to retransmission mechanisms. The capability to maintain the link over hours without needing to relaunch ALE, and to operate even over 300 to 700 km with land tactical equipment at data rates up to 80 kb/s and offer modern (IP) digital applications have been demonstrated, showing the operational interest of wideband HF.

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