Empowering HF systems with cognitive wideband radio capabilities

Dr Catherine Lamy-Bergot
THALES Communications & Security
Dr Hicham Khalifé
THALES Communications & Security
Jean-Baptiste Chantelouve
THALES Communications & Security
Hélène Diakhaté
THALES Communications & Security
Jean-Luc Rogier
THALES Communications & Security
FRANCE
{catherine.lamy-bergot , hicham.khalife , jean-baptiste-chantelouve , helene.diakhate , jean-luc.rogier}@thalesgroup.com

ABSTRACT

Automatic Link Establishment (ALE) in HF radios allows channel selection between a sender and a receiver without human intervention. In the absence of a priori knowledge or control information exchange, the ALE procedure enables the source and the destination to select the best channel for communication. In practice, the main challenge of ALE resides in finding the best available channel for communication and as quickly as possible. In this paper, we propose a new generation of ALE mechanism capable of exploiting the new wideband capabilities being introduced for the different next generation HF radio proposals, in order to improve automatic link establishment in terms of likelihood and speed for finding a good quality channel for the transmission.

1.0 INTRODUCTION

HF radio communications have been used during the last century to provide mostly voice or low-rate data communications with none or minimal infrastructure over short to very long (up to 10000km) distance. The initial main focus was and remained for a long time on the communication waveform and its robustness, to overcome the extreme variability of the HF ionospheric propagation channel. However, due to the often poor knowledge of the channel conditions, as well as the varying requirements depending on the different services (typically voice vs. data), the establishment of HF links was for a long time dependent on the high skilled radio operators who selected manually the best frequencies to be used. This led unfortunately to the impression that HF communications were both often unreliable and less efficient than they should when no such skilled operator could be present. The previously cited observations motivated to the development of automatic link establishment techniques in the 80's, with further refinement since, all targeting *i)*to ensure that HF could remain a reliable medium of communication, *ii)*to reduce the need for skilled radio operators, and *iii)*possibly perform even better thanks to quicker automatic procedures.

Currently, two generations of ALE mechanisms do coexist in the field, that both try to answer these demands. Several comparisons between these two standards exist today in the literature [1][2]. The main differences can be highlighted as follow:

- the first standard, traditionally denoted as ALE 2G is the MIL-STD-188-141 [3]. The ALE 2G standard is completely asynchronous. In order to establish a communication with a destination on a particular channel, the source transmits for a long duration. This transmission time is computed in a way to enable the destination to scan all the available channels during the emitter transmission. Previous studies have pointed out the fact that 2G performs poorly due to its simplistic modulation scheme (8-FSK). Nevertheless, when signal to noise ratio is high this limitation has low impact on the observed performance.

- the second standard, traditionally referred to as ALE 3G is the STANAG 4538 [4]. The ALE 3G introduces synchronization between different ALE stations. Because all stations are synchronized to listen at the same time to the same channel, an emitting station knows at time *t* over which channel it can reach its receiver. This procedure yields a faster ALE than the second generation. More practically, such features make the ALE 3G more suitable for small messages exchange and for highly loaded networks (close to saturation limit).

The emergence of new solutions for high data rate transmissions [5][6] is leading the HF community to reconsider those existing mechanisms in order to take into account 1) the ever-existing requirement for improving link establishment and 2) the fact that wideband channels cannot be selected by the existing narrow band procedures. In particular, concerning the improvement of the link establishment procedure, the increasing variety of modulations, from analog to high efficiency digital ones, lead to the necessity of better estimating the channel propagation conditions, in order to correctly estimate the performance the different waveforms can offer.

In this paper, we propose a new generation of ALE mechanism capable of exploiting the new wideband capabilities being introduced for the different next generation HF radio proposals, and that exploits wideband listening and transmitting capacities. In that aspect, the proposed ALE goes beyond proposal made in [7] which is only capable of 24 kHz contiguous analysis, and which does not offer an acceleration capability with respect to existing 3G ALE procedure. Thanks to the wideband capability, it becomes possible to make use of particular potential usually exploited in the cognitive radio domain, such as adapting the transmission and the reception band dynamically as well as sensing different channels in order to characterize their availability. Our solution is not only promised to offer better performance in terms of delays and throughput but also ensures backward compatibility with today’s 2G or 3G standards.

2.0 WIDEBAND ALE MECHANISM

2.1 Rationale behind the ALE 4G mechanism

Lots of work has been done since the 80’s and the first version of ALE 2G mechanism to improve automatic link set-up, whether at the modulation level, with the introduction of new modulations, both more robust and easier to be detected with less false alarm rate, or at the protocol level, with both the synchronous mechanism used in ALE 3G to improve the set-up time and the Link Quality Assessment (LQA) usage to increase the probability to select quickly good channels. Yet, the end-users regularly indicate their wish to have a better ALE process capable to integrate in a standardized manner (meaning interoperable) the most recent evolutions or suggestions presented by the scientists.

In particular, the following requirements appear desirable in a future 4G ALE protocol:

- (C1) a better estimation of the ionosphere conditions, allowing to perform more efficient short term prediction based not only on monthly averaged values. These refined estimations will allow to forecast the operational Maximal Usable Frequency (MUF) and consequently to define the best frequencies, typically through total electron content (TEC) estimation sensors relying on GPS transmissions [8]-annex 2[8],

- (C2) a capability to listen to several channels in parallel, in order to overcome the main drawbacks in the STANAG 4538 3GALE system, namely the potentially long link establishment time and the risk of calling collisions in a network with heavy traffic load [9],

- (C3) an evolution of the Automatic Link Maintenance (ALM) mechanism coupled to the ALE one in order to anticipate the failure of a link before it actually fails [10], and consequently to avoid needing to redo the full ALE process in the middle of a transmission when said transmission was long/varying enough to see an evolution of the channel propagation conditions,

- (C4) a better quality of service management in order to consider the increasing differences between the different services offered over the HF link, from low latency to high latency ones, and from very low BER (e.g. data) to robust to errors services (e.g. voice),

- (C5) obtaining as an output not only a frequency to be used, but a set of frequencies, whether contiguous for usage with a waveform such as the so-called WBHF (MIL STD 188-110C-D), or non-contiguous for usage with a waveform such as the so-called HFXL (under proposal for evolution of STANAG 4539).

Obviously, it is also desirable that such a new ALE mechanism operates for a maximum of existing waveforms and in particular the new wideband communications solutions arising [5][6], namely for waveforms operating up to 24 kHz and 200 kHz of band. In particular, it appears of interest to ensure the cohabitation of narrow band users with wideband ones, and as to investigate the feasibility of a mechanism that could be at least compatible with legacy (3 kHz/6 kHz only) equipment.

2.2 Description of the ALE 4G mechanism steps

In the following, in conformance with the objective (C5) given in section 2.1 of proposing an algorithm compatible with the different new wideband solutions (>6 kHz) currently under discussions within the HF community, we define wideband as going beyond the traditional 3 kHz bands in the listening phase. Indeed, with a larger listening band, it becomes possible to analyse several channels simultaneously, and thus to establish a faster and more efficient ALE mechanism. In the sending phase, our ALE proposal adapts/exploits capabilities from the cognitive radio domain to bond multiple possibly disjoint 3 kHz bands based on the quality estimation obtained during the ALE handshake.

The overall procedure can be described in the following 3 phases, and is synthetized in the flow chart presented in Figure 1:

1- Offline channel estimation. Based on the destination, each station determines the channel that is most likely to have the best quality.

The capability to predict on demand a list of best channels per destination already exist in some product implementations. This list can be established based on predefined knowledge (such as atmosphere and propagation properties) as well as history information and previous communications with other stations (incl. LQA). This should also be reinforced by using any information available on the propagation channel. In particular, knowing that the best quality frequencies in terms of signal to noise ratio (SNR) are generally the higher frequencies available (below the MUF), we will consider the promising technique of estimating MUF through estimation of the critical frequency (foF2) taking into account quasi real-time ionosphere characteristics via TEC measurements [11] (constraint (C1)).

2- Backward compatibility phase: link initiation.

As already mentioned, the proposed approach guarantees backward compatibility with a legacy ALE procedure. For this reason the first part of the handshake will be conducted in narrowband similarly to 2G and 3G link establishment. It is to be noted that as both ALE 2G and ALE 3G procedures are not interoperable, a choice has to be done. In the following (see section 2.3), we present the possible results when going either with asynchronous ALE 2G or synchronous ALE 3G. Within this phase, it is foreseen to have 4G capable station to indicate so, via specific messages, for instance with ALE “CMD” messages in ALE 2G. Thanks to this message, the transmitting station will be able to determine whether or not the called station is capable/willing to pursue in 4G. If not, the emitter will decide either to continue with the traditional procedure or to simply abort (e.g. if the service desired is not achievable with low data-rate). Interestingly, as will be detailed in Section 2.3, this backward compatible phase can also be enhanced thanks to wideband capabilities as wideband receivers and emitters can operate on several frequencies at the same time.

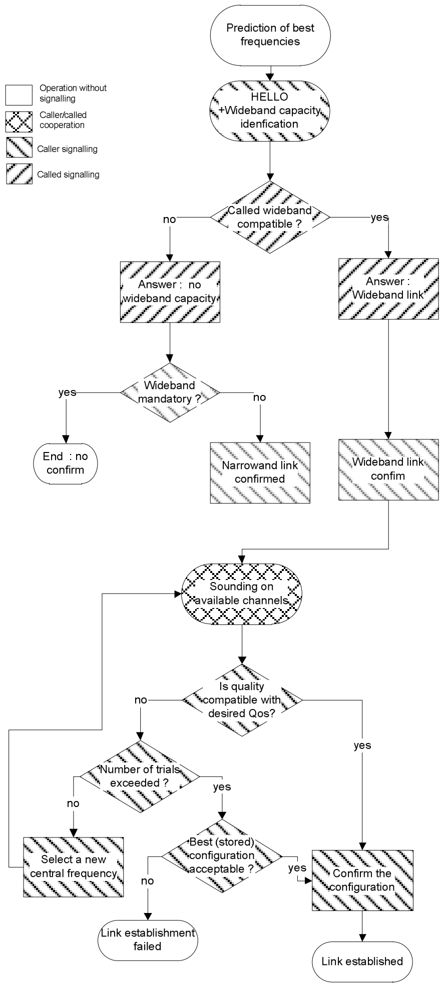

Figure 1 – Flow diagram for wideband ALE process.

3- Channel selection and capacity estimation: decision on frequencies to use.

During this third phase, whose output will be a set of frequencies following the requirement expressed in the previous section, the transmitting and receiving stations communicate in wideband over a dedicated band (typically of 200 kHz). The choice of this band results from the two previous phases: prediction and information shared during the narrow band compatible handshake, as well as the quality of service expected for the services desired, in accordance to constraint (C4). In order to determine the channels to exploit in this band (which and the total number), source and destination characterize the quality of each of them with a particular challenge. This challenge will allow the emitting station to select a set of channels within the band in order to meet the demand in terms of QoS.

Note that if the procedure fails over the selected wide band (the QoS requirements are not met), another 200 kHz band is negotiated and phase 3 is started again.

Furthermore, since the process resulting in the selection of a plurality of frequencies, in particular in the non-contiguous frequencies case, it will be possible to combine it with the link management procedure. This can be done in order to detect before the quality of service requirements are not met anymore the degradation of one or several frequencies sufficiently in time to re-launch only a part of the ALE process, answering then to constraint (C3).

2.3 Illustration of the interest of wideband radio capabilities and ALE 4G procedure

The procedure proposed in previous section is oriented to ensure that one obtains the desired set of frequencies to be used with a wideband modulation, and as such requires from both caller and called stations a wideband capability. Interestingly, it must be noted that by configuration one can envisage to make it work whether for wideband contiguous or not contiguous waveforms, as well as with asynchronous or synchronous phase 2. This is illustrated in the following (sections 2.3.1 and 2.3.2).

It is also worth noting that even during the narrowband phase, the wideband capability can be used in order to accelerate the process, both in synchronous and asynchronous modes, as illustrated also hereafter.

2.3.1 With asynchronous mode

Figure 2 and Figure 3 illustrate (with 200kHz front end) respectively the interest of being able to transmit and receive respectively over several channels at the same time. Obviously, this capability allows to answer to constraint (C2) and to increase the probability to detect quickly a free frequency.

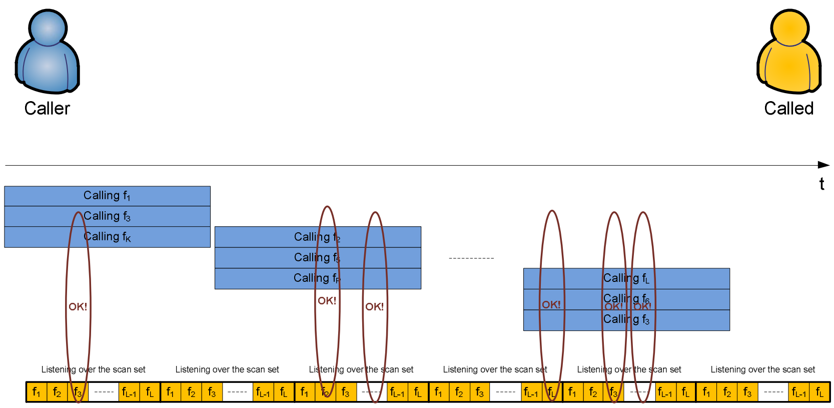

Figure 2: Illustration of the possible improvement of wideband ALE phase 2 with parallel wideband emission (asynchronous mode).

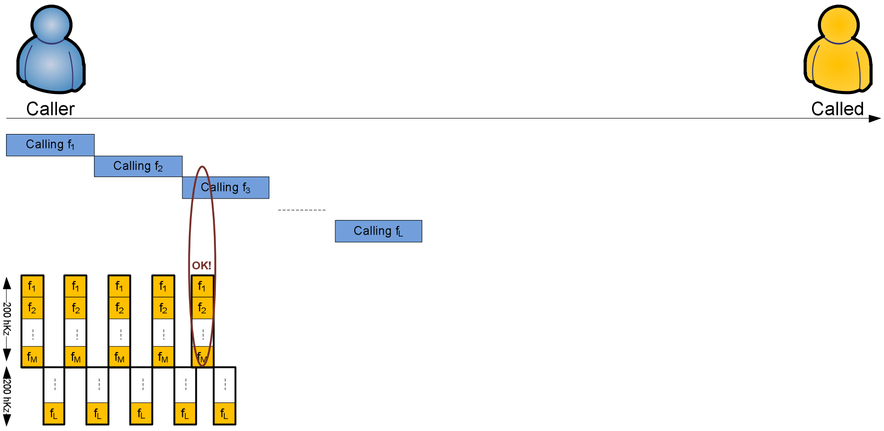

Figure 3: Illustration of the wideband ALE phase 2, with backward compatibility with an existing asynchronous ALE (asynchronous mode).

The combination of both capabilities, corresponding to having actually both a wideband caller and called station is presented in Figure 4. It is shown that despite receiving in wideband, the receiver is a priori obliged to scan different bands, as it cannot predict advance on which sub-band of 200 kHz it will be called. Such a receiver will consequently be able to pass the total scan set quicker (due to the fact that it should be able to listen to several frequencies at the same time), but not instantaneously. Interestingly enough however, and in line with the spirit of constraint (C2), further gain can be expected if one is able to listen over an even wider band. This is what we will call very wideband reception, and which is expected to work over up to 1 or 2 MHz. In several configurations, in particular in tactical configurations where the usable frequencies are mostly within such a range, the system will then be able to work while remaining on the same band, increasing greatly the response time, as illustrated in Figure 5.

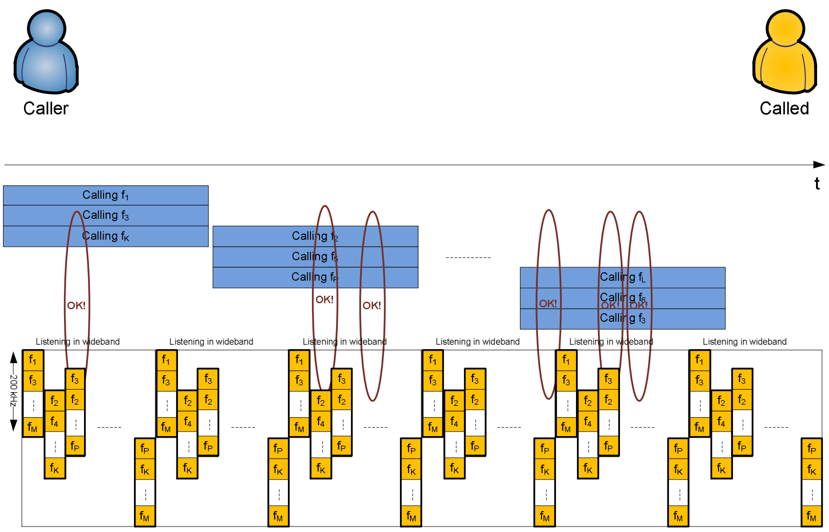

Figure 4: Illustration of the wideband ALE phase 2 including the wideband emission acceleration, with backward compatibility with an existing asynchronous ALE (asynchronous mode).

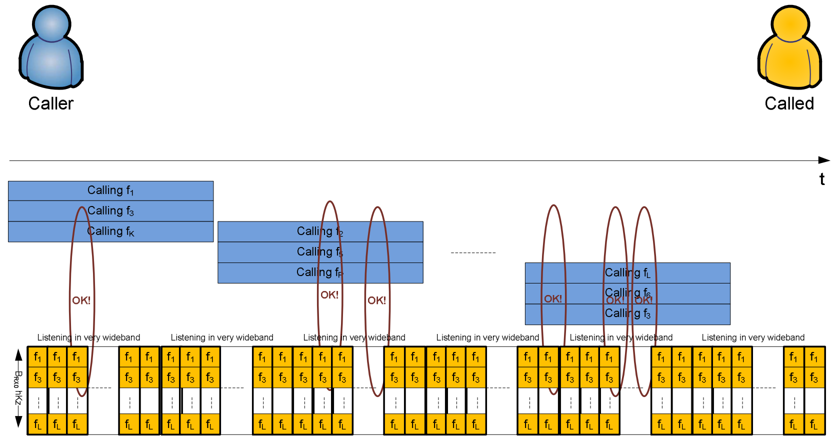

Figure 5: Illustration of the wideband ALE phase 2 including the wideband emission acceleration, with backward compatibility with an existing asynchronous ALE in the case of a very wideband receiver (asynchronous mode).

2.3.2 With synchronous mode

In the case of synchronous ALE such as ALE 3G, the gain that can be obtained with wideband strategies is slightly different. As a matter of fact, considering that one wants to keep interoperability with existing legacy radios, the scan pattern must be respected, otherwise a legacy receiver would not be able to operate. Still, supposing that the called station is wideband, it becomes possible to improve the performance by calling over several frequencies at the same time, including the “current” one (meaning the one as required by the scan pattern). Interestingly, in the case where the current frequency is already occupied and consequently not usable, one could also decide to call on another frequency even if the caller station is only narrow band capable, as illustrated in Figure 6.

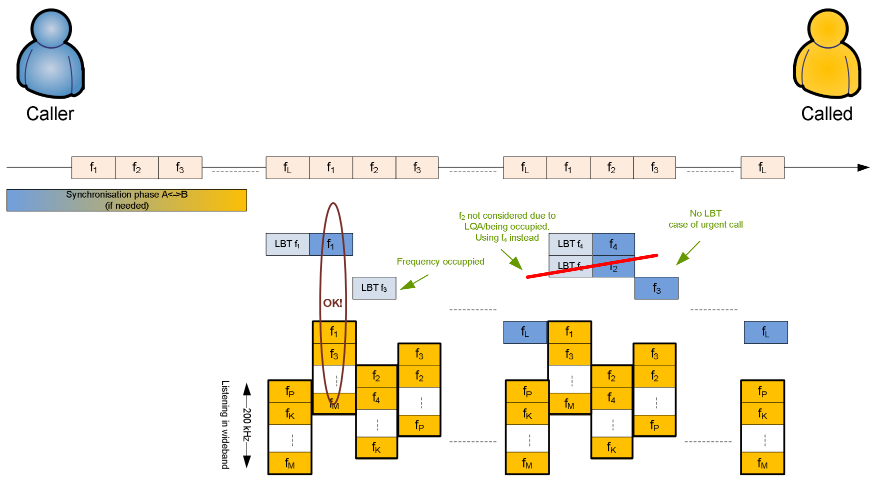

Figure 6: Illustration of the wideband ALE phase 2, with backward compatibility with an existing asynchronous ALE (synchronous mode).

Finally, as also considered in the asynchronous case, the mechanism can be more powerful if the caller is wideband capable and the receiver is very wideband capable, as illustrated in Figure 7.

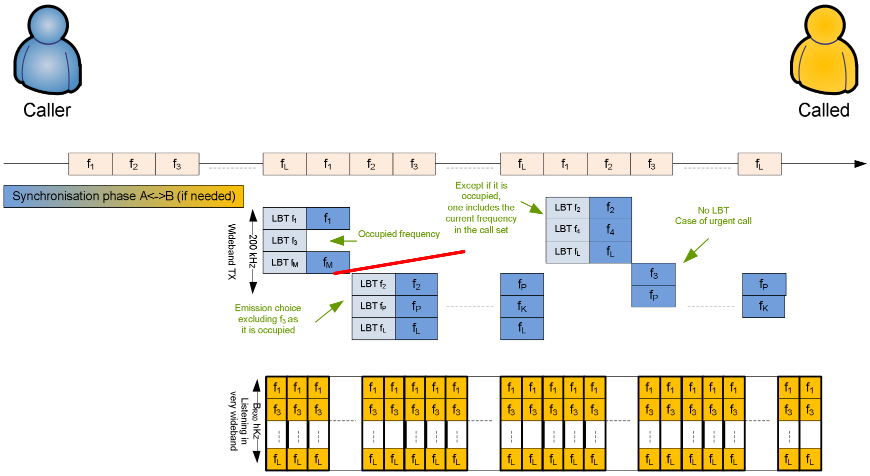

Figure 7: Illustration of the wideband ALE phase 2 including the wideband emission acceleration, with backward compatibility with an existing asynchronous ALE in the case of a very wideband receiver (synchronous mode).

2.4 Feasibility of such a wideband ALE

The procedure presented in this section 2 meets the different design constraints introduced in section 2.1. However, it is important to underline that it is very innovative and demanding both in terms of RF and digital capabilities: the equipment shall have a wideband (or even a very wideband) front-end going much further than the standard existing ones that are mainly 3 or 6 kHz wide, and must embark sufficient digital CPU to allow performing parallel treatments over several channels.

As stated in [9], a multitude of SDR units exist now on the market that have such capabilities, and it was already proven by [12] that wideband 200 kHz emissions and reception over a plurality (n=15) of channels was feasible with HFXL prototype. Nevertheless, we propose to further detail in section 3 the evolutions made to the HFXL prototype to prove that such wideband and very wideband designs are realistic.

3.0 FIRST RESULTS AND DISCUSSION

3.1 Test bench settings

As stated in section 2.4, the objective of the test bench is to prove the feasibily first of a multiple parallel reception and second of wideband and very wideband strategies. It will also help illustrate the capability to compare different channels and estimate their quality in order to meet the desired QoS, as per requirement (C4).

To reach this goal, we propose to demonstrate the capacity to listen to a plurality of channels disseminated over several 100 kHz simultaneously. For practical reasons, as we need to demonstrate a reception capacity wider than the emission capacity, we will be using two different emitters to transmit different set of carriers sufficiently separated from each other. As illustrated in Figure 8, we consider a reception band $\Delta f \geq 200kHz$ centered around central frequency fc, and the two emitter, each respectively centered around central frequency f1 and f2, and emitting over an emission band $\Delta f1 = \Delta f2 = 200kHz$. The receiver both in wideband (200kHz) and very wideband (>200kHz) modes consist of the HFXL prototype including the RFNUMXL card, and the double emitter is composed of two Universal Software Radio Peripheral (USRP N210) from Ettus Research US as shown in Figure 8.

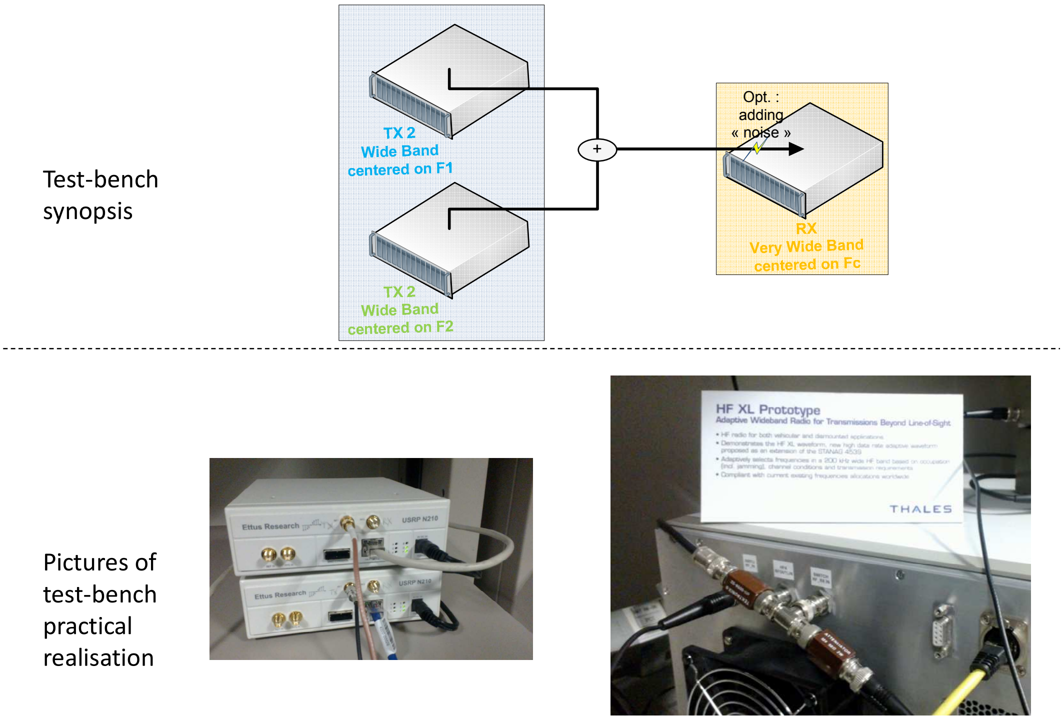

Figure 8: Practical implementation with HF XL test bench.

The test-bench has been used in several configurations, in particular we have been testing the transmission of 10 different carriers spread over the Δf band centered at fc=6.9MHz at the same time. Those carriers are divided into two sets of 5 carriers, each spread over their 200 kHz transmission band and consisted of HFXL waveform superframes which are an extension of STANAG 4539 definition (see [6]). The different carriers are sent with various delay to represent random access to channel in an asynchronous mode: each frequency in a set is delayed of 1 sec with respect to the other ones in its set f1i,i=1..5 (resp. f2i,i=1..5) and the two sets are not synchronized. Furthermore, an additional perturbation has been added at the reception side, resulting from previous spectrum sensing measurement campaign (noise acquisition also centered around 6.9 MHz), and each time at least one of the emitted frequency has been purposedly placed in a very noisy part of the spectrum, to verify that one would not receive it (or very degraded). Beside allowing to improve the representativity of the test-bend experiment, the presence of this variable real noise allows to obtain different channel qualities for the different carriers, and as such to demonstrate the channel quality estimation and comparison part of the process.

3.2 Preliminary results

In the following we will present two different experimentations, the first, or experimentation A, with Δf = 500kHz (f1 and f2 being separated by 300 kHz) and the second, or experimentation B, with Δf = 800kHz (f1 and f2 being separated by 600 kHz). In both cases, the signal to noise ratio is measured for each of the frequencies in the scan set, and the ALE candidate selected for phase 2 is the one with best SNR.

Figure 9 illustrates the result of noise addition process performed in the test-bench.

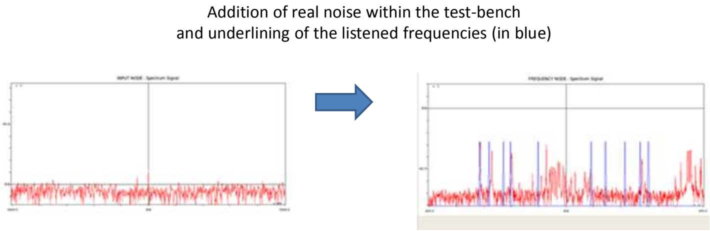

Figure 9: Illustration of the noise addition process (experimentation A).

3.2.1 Parallel reception

The parallel reception of multiple channels, that is a wished capability (constraint (C2)) as indicated in [9] is easily achieved with an HF XL system, which in practice realizes non synchronous multi-carriers demodulations. The wideband parallel reception needed for ALE is a bit different due to the possible random delays on the different channels representing the asynchronous mechanism. For both experimentations A and B, the 10 carriers are demodulated and decoded in parallel, as illustrated by Figure 10. One sees on the interface that nine modulations were recovered, with different constellations obtained, more or less noisy. This, as well as the lost channel, is due to the real channel addition detailed in the test-bench description.

In practice, the system can easily go beyond 10 parallel carriers estimation. As a matter of fact, the system is even able to demodulate more than 16 channels as when used in communication mode (see [6]).

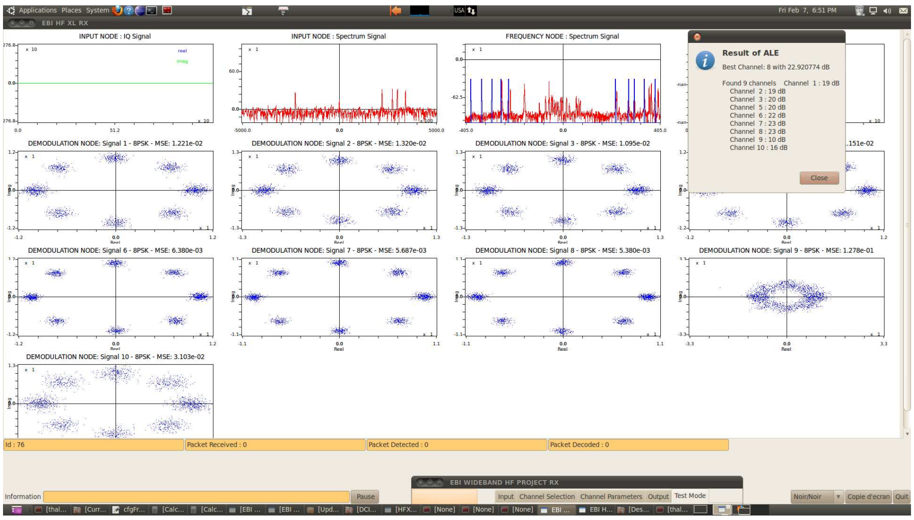

Figure 10: Illustration of parallel reception process (experimentation B).

3.2.2 Very wideband reception

The very wideband reception principle, i.e. the capability to go beyond a reception of 200 kHz, is demonstrated in Figure 11. This shows the different frequency shifts between each of the 10 reception frequencies and the central frequency fc in the case of implementation A. One sees that the two extreme frequencies are located at -252kHz and +243kHz, yielding a frequency span of 495kHz (for a Δf = 500kHz)!

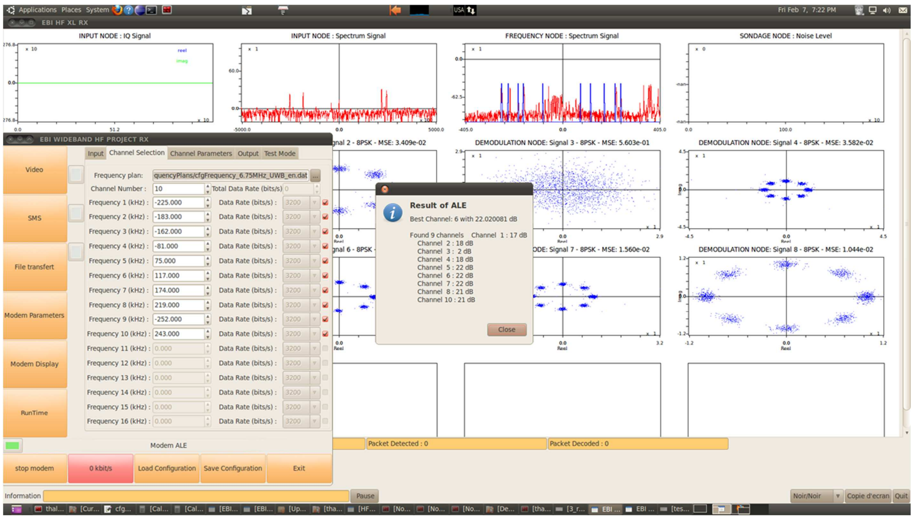

Figure 11: Illustration of the different reception channel frequency difference wrt. central frequency (experimentation A).

3.2.3 Channel quality estimation

Based on the demodulation of each carrier, a signal to noise ratio can be estimated and a corresponding quality can be attributed to the frequency, as long as the message carried allowed to confirm that the challenge (CALL) was indeed transmitted towards the reception station. As illustrated in Figure 11 for experimentation A and in Figure 12 for experimentation B, the ALE phase 2 ranking process allows to select the best channel from the different detected ones.

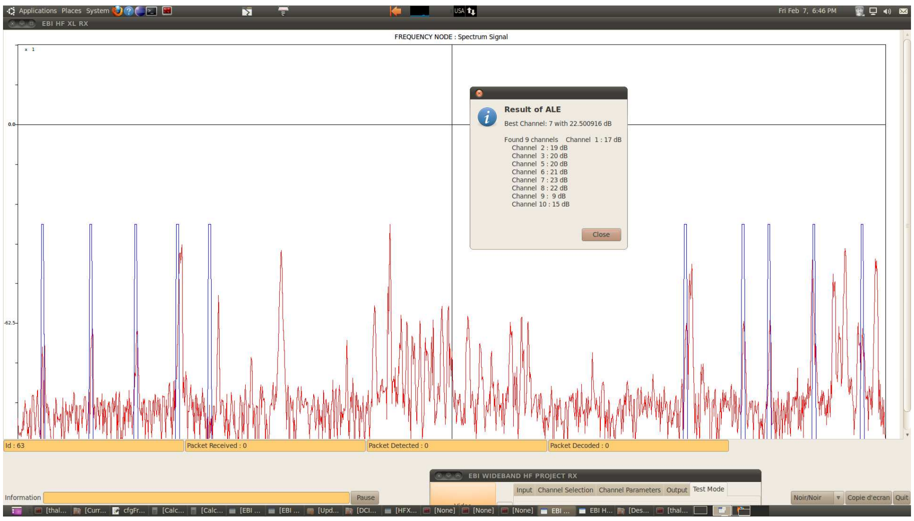

Figure 12: Channel quality measurement and ranking (experimentation B).

4.0 CONCLUSIONS

A new wideband efficient automatic link establishment (ALE) procedure is proposed in this article. Structured in three phases, it first employs an off-line prediction based on all type of external information available (geographical positions and long-term predictions, sensing measurements, previous scanning and link qualities …) similar to those explored in cognitive radios; second it performs a backward compatible narrow band link establishment procedure, aiming at helping the cohabitation between narrow band and wideband equipment; and third it realizes a wideband link quality sensing and evaluation, to define the best configuration addressing the service and QoS desired either for contiguous or non-contiguous waveforms.

This new procedure is expected, based on its cognitive radio capabilities, to simplify greatly the link setup process that is one of the weaknesses for HF communications hindering its easy use by non-specialist end-users. It is expected that the evolution of processing powers and corresponding new capabilities for wideband radios will allow to implement those techniques from infrastructure settings down to portable radios, allowing HF to keep its important role in military communications.

Future works will focus on further defining the parameters of the ALE procedure, in particular through the simulation of the complete procedure and its comparison with existing ALE 2G or ALE 3G protocols.

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