Wideband HF transmissions: operating in a crowded spectrum

Catherine Lamy-Bergot[*], Arnaud Kermorgant[*], Frédéric Gourgue[*], Jean-Yves Bernier[‡], Hélène Diakhaté[*] and Jean-Luc Rogier[*]

(*) THALES Communications & Security

4 avenue des Louvresses, F-92622 Gennevilliers Cedex

(‡) THALES Belgium

Rue des Frères Taymans 28, B- 1480 Tubize

SUMMARY

The HF community has been working on defining and developing new standards enabling both a higher throughput and an improved reliability of data links established over HF channels. Two branches have emerged in that purpose: the first one, relying on an enlarged 24kHz RF carrier uses a single tone PSK/QAM modulation and is described in MIL STD 188-110C appendix D, while the second consists in multiple 3kHz PSK/QAM modulated carriers, contiguous or not, distributed over a 200kHz bandwidth. This paper presents an analysis comparing the respective efficiency of the two schemes to access a crowded spectrum, as a function of the contiguous or non-contiguous frequency allocation constraint. An analytical model is described, expressing the probability of accessing to a wideband channel as a function of the narrow band 3kHz channel availability. It is then applied to discuss the applicability of contiguous and non-contiguous approaches.

KEY WORDS

Wideband HF communications, channel availability, statistical analysis.

1   INTRODUCTION

The HF band [3;30] MHz offers since the beginning of the twentieth century the possibility to establish links beyond line-of-sight (BLOS) thanks to the reflection of HF waves on the ionosphere. Originally the only trans-horizon wireless communication mean, HF transmissions have since been first challenged, and even now often replaced by satellite communications in many cases. This preeminence of satellite communications (satcom) is due mainly to two reasons:

  - firstly, the recognized difficulty to operate HF equipment to accommodate the complexity and the variability of the HF medium, characterized by its deep variations susceptible to randomly affect the quality of the link, and the need to maintain a specific expertise that follows- the HF radio operators being viewed as a 'breed apart' [1];

- secondly the emergence this last decade of civil and military satcom solutions in X/Ku/Ka bands, that offer much higher throughput communications (e.g. in Ku/Ka bands) as they can benefit from several dozens or even hundreds of MHz of bandwidths, at the cost however of having a heavy infrastructure to put in place, maintain in operational condition and having to manage the spatial segment.

The HF communication are definitely not addressing the same objectives as the spatial segment: their main purpose is offering multiple communication applications that offer "daily-live" service while leveraging on limited data-rates: voice communications, HF-emails, flash messages or specific file transfers can be efficiently performed through HF thanks to either legacy (e.g. [2]) or most recent (e.g. [3][4]) standards. Added values of HF communications are its capability to bring those services in the absence of an intermediate relay and leveraging on a limited spectrum: less than 30MHz. As such, the real key improvements that HF communication means must address are to be easy-to-use, resilient and consequently always "really available".

In the military domain in particular, this notion of availability is of paramount importance, as users must be confident they can get the service during an emergency or a crisis. This explains why most systems are designed to guaranty an availability greater than 90%, even sometimes 99%, taking into account possible ionospheric perturbations. Following this system point of view, we propose in this article to derive an analytical formula to compute the availability of a wideband frequency allocation, comparing the performances of the wideband contiguous and non-contiguous standards [3][4].

The article is organized as follows. In Section 2, the two wideband contiguous and non-contiguous modem principles are reminded. In Section 3, our analytical model is given and justified. In Section 4, corresponding numerical results are derived for both wideband approaches, and those numerical results are analyzed in line with real narrowband spectrum occupation measurements. Finally, conclusions are drawn in Section 5.

2   WIDEBAND HF MODEMS

As highlighted before, the HF community has worked for the past decade on the development of new standards to answer the end-users needs for better throughputs. Two approaches have emerged, that are currently being standardized by NATO [5].

The first one, described in MIL STD 188-110C appendix D [3] relies on a single carrier approach over 3 to 24kHz of band, and can be seen as a generalization of the narrow band approach with different bandwidths, with better coding schemes, synchronization sequences and new modulations for very low throughputs. As illustrated in Figure 1, such a single carrier modem requires contiguous allocation of k x 3kHz, k=1..8 to reach 24kHz.
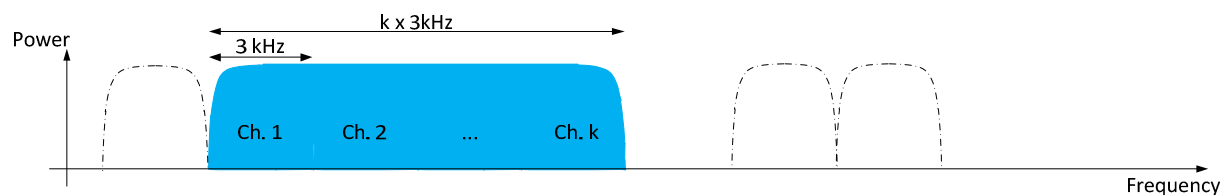

Figure 1 – Illustration of contiguous allocation used for a single carrier modem.

Several field experiments proved the concept when the spectrum is available, but several concerns were raised about the effective availability in real operational conditions of contiguous channels above 6kHz and up to 24kHz[6][7]. Such concerns have partially been worked upon through the establishment of an *ad hoc* working group on availability measurements within the HFIA (HF Industry Association) since 2014 [8]. However, the results of this adhoc working group remain as of yet inconclusive, due to the large discrepancies between the considered survey sites, in particular between the US and Europe.

The alternative approach, described in STANAG 4539 appendix H proposal [4], relies on multiple 3kHz sub-carriers that are not mandated to be contiguous, and consists in the combination of several narrow band 3kHz carriers sharing the same error correcting code with an embedded frequency diversity capability and an improved coding scheme. As illustrated in Figure 2, such a multiple carrier modem can work either with contiguous or non-contiguous allocation of k x 3kHz, and its capability to establish high-rate data link has also already been proven by field experiments [9]. A key question linked to the multi-tone characteristic was its capability to maintain the level of spurious emissions at an acceptable level[10]: it has been addressed via the definition of the admissible spectrum mask for non-contiguous modems in STANAG 4203 app. E [5].
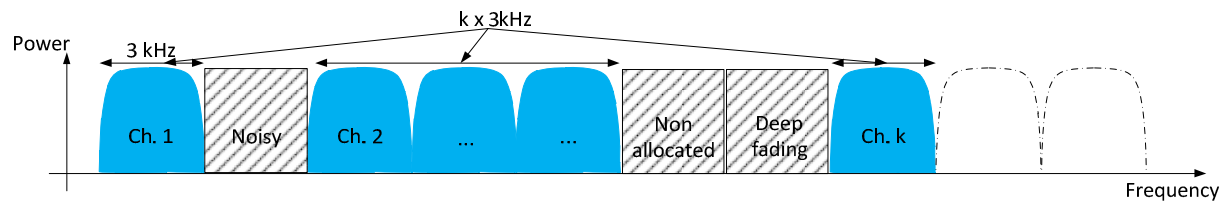

Figure 2 – Illustration of possible non-contiguous allocation used with a multiple carrier modem.

3   ANALYTICAL MODEL ON ONE WIDEBAND CHANNEL AVAILABILITY

3.1   NOTATIONS AND HYPOTHESIS

In order to compare the respective capability to access to wide bandwidths (k x 3kHz) in busy spectrums representative of usual operation conditions for the two wideband modems described in the previous section, let us consider a sub-band of interest of size N x 3kHz over which we will derive the probability $P(N,k)$ to have at least one k x 3 kHz contiguous or non-contiguous available channels.

We base our analysis on a modeling of the target bandwidth - consisting in a channel with a bandwidth of N x 3kHz as illustrated in Figure 1 and Figure 2 – into sub-channels of 3 kHz. This allows conducting analytical formula and deriving numerical data through a statistical approach.

The model is as follows:

- the N elementary sub-channels are considered as independent

- with an individual probability ρ to be available ($0 \leq \rho \leq 1$).

- As an example, we can take a sub-band of bandwidth 200 kHz resulting in N=66 channels of 3 kHz.

The hypothesis that the elementary channels are independent and have the same probability law (depending only of the sub-band) is a strong one, but the approach is sustained by the following facts: a/ today's usages are almost only such 3kHz allocations, which are independent due to their independent users, b/ the channel coherence bandwidth is greatly inferior to the 200kHz considered sub-band [11] and c/ that for a sub-band inferior to a few 100 kHz [12], the mean propagation conditions vary sufficiently slowly when one is not too close to the Maximal Usable Frequency (MUF).

3.2   FORMULA DERIVATION

Let us now derive $P(N,k)$ for both of the cases where the sub-channels are mandated or not to be contiguous.

3.2.1   Non-contiguous-case

The non-contiguous case is the easiest one. As a matter of fact, due to the independence of the elementary 3 kHz channels, and the fact that the channels need not be ordered, the probability to have <u>exactly</u> n bands available among the total of N is given by the binomial law: $C_N^n \rho^n (1-\rho)^{N-n}$.

This allows us to express as follows the probability $P(N,k)$ when contiguity of sub-channels is not imposed:

$$P(N,k) = \sum_{n=k}^{N} C_N^n \rho^n (1-\rho)^{N-n} \qquad \text{Eq. (1)}$$

3.2.2   Contiguous-case

In the case where the channels are imposed to be contiguous, the derivation is more complex because one need to avoid counting several times the same bands. Let us order those bands from 1 to N.

Let us denote $E(N,n)$ the set of realisations among the 2^N possible ones for which exactly n elementary sub-bands are available. $E(N,n)$ contains C_N^n independent elements of the same probability $\rho^n (1-\rho)^{N-n}$. Let finally $C(N,n,k)$ be the set of realisations in $E(N,n)$ that contains at least k contiguous available elementary bands. $C(N,n,k)$ contains $f(N,n,k)$ realisations that all have the same $\rho^n (1-\rho)^{N-n}$ probability.

We will derive $f(N,n,k)$ recursively, taking into account that if N=n, $f(N,n,n) = 1$.

For N>n, meaning that at least one elementary band is not available, let i be the index of the first[1] non-available band (i is unique in [1; N-n+1]).

---

[1] Lowest in frequency

If i>k, $C_{>k}(N,n,k)$ is the set of all realisations beginning with k available bands, followed by N-k bands among which n-k are available, without constraints on contiguity (the contiguous requirement being already achieved), hence $C_{i>k}(N,n,k)$ contains $f_{i>k}(N,n,k) = C_{N-k}^{n-k}$ realisations.

If i≤k, $C_i(N,n,k)$ is the set of elements beginning by i-1 available elementary bands, then an unavailable one, and N-i elementary bands among which exactly n-i+1 one are available with at least k ones contiguous. As a consequence, $C_{i\leq k}(N,n,k)$ contains $f_{i\leq k}(N,n,k) = f(N-i, n-i+1, k)$ realisations.

As the first non-available band is unique, the k+1 number of realisations are all separated, and can consequently be summed to express $f(N,n,k)$ recursively:

$$f(N,n,k) = C_{N-k}^{n-k} + \sum_{i=1}^{k} f\left(N-i, n-i+1), k\right)$$

This allows us to express as follows $P(N,n,k)$ the probability to have exactly n bands available among the N of the sub-band:

$$P(N,n,k) = \left[C_{N-k}^{n-k} + \sum_{i=1}^{k} f\left(N-i, n-i+1), k\right) \right] \rho^n (1-\rho)^{N-n}$$

It is then easy to derive $P(N,k)$ for the contiguous case, by summing $P(N,n,k)$ for n between k and N:

$$P(N,k) = \sum_{n=k}^{N} \left[C_{N-k}^{n-k} + \sum_{i=1}^{k} f\left(N-i, n-i+1), k\right) \right] \rho^n (1-\rho)^{N-n} \qquad \text{Eq. (2)}$$

4   NUMERICAL RESULTS

4.1   NUMERICAL APPLICATION OF OBTAINED FORMULAS

The numerical application of equations 1 and 2 obtained in Section 3.2 is straightforward and allows to draw curves providing the availability of a wideband "channel" (whether contiguous or not, corresponding to the probability of availability for k x 3 kHz individual channels considered in a 200 kHz sub-band).

Figure 3 and Figure 4 show the probability of availability of a channel of 12 kHz (k=4) and of 18 kHz (k=6) as a function of the spectrum occupancy reflected by the individual probability ρ of the 3kHz sub-channels. It appears that the capability to reach the objective of 95% availability for the wideband channel, i.e. to ensure that the user can get the desired bandwidth, is very much sensitive to the individual probability ρ. For 12 kHz (resp. 18 kHz) useful band, a ρ of 12% (resp. 15%) only is needed for the non-contiguous approach, whereas a ρ of at least 55% (resp. 70%) is needed when contiguous channels are imposed.

Figure 5 is drawn to compare availability of 24 kHz channels, and one sees that a ρ of 20% only is needed for non-contiguous, whereas the contiguous approach requires a ρ of at least 80% … the gap is even more pronounced at 48kHz.

Finally, Figure 6 and Figure 7 show comparison between a non-contiguous 48 kHz channel and a 12 kHz and 9 kHz contiguous versions. It can be observed that the non-contiguous 48kHz channel is always easier to obtain than a 12 kHz contiguous one, and even that a 9 kHz contiguous one, when one wishes wideband availability greater than 50% !
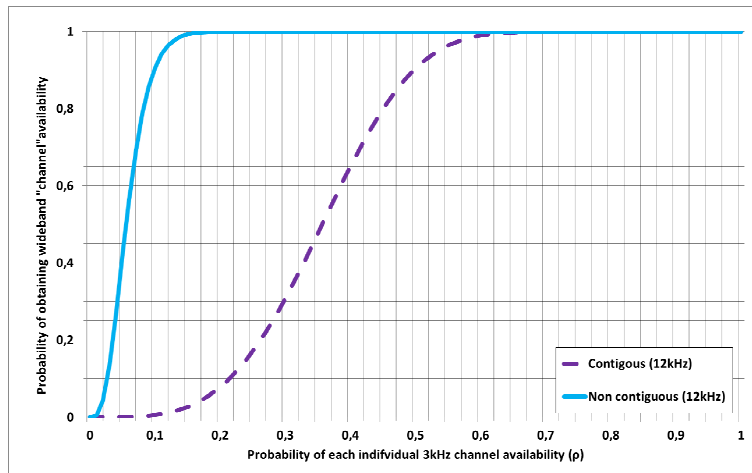

Figure 3 – Analytical probability for obtaining (a) a wideband contiguous of 4*3=12kHz versus (b) a non-contiguous channel of 4*3=12kHz.

Figure 4 – Analytical probability for obtaining (a) a wideband contiguous of 6*3=18kHz versus (b) a non-contiguous channel of 6*3=18kHz.

Figure 5 – Analytical probability for obtaining (a) a wideband contiguous of 8*3=24kHz versus (b) a non-contiguous channel of 8*3=18kHz or of 16*3=48kHz.

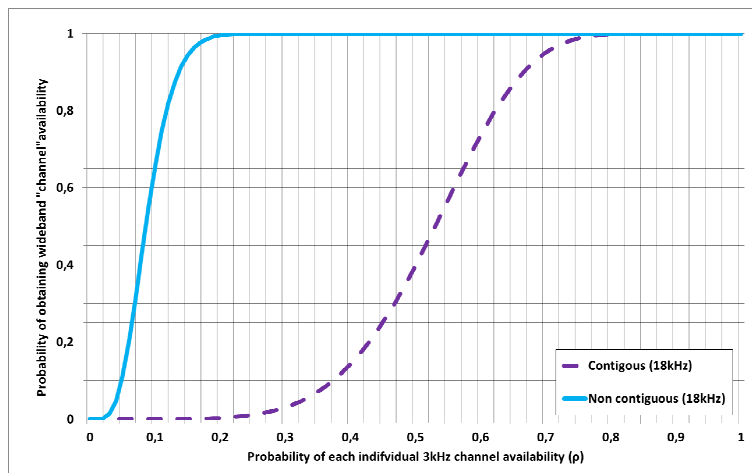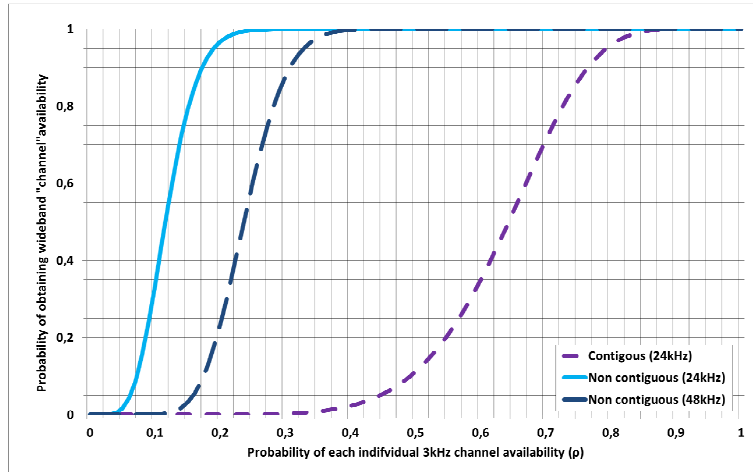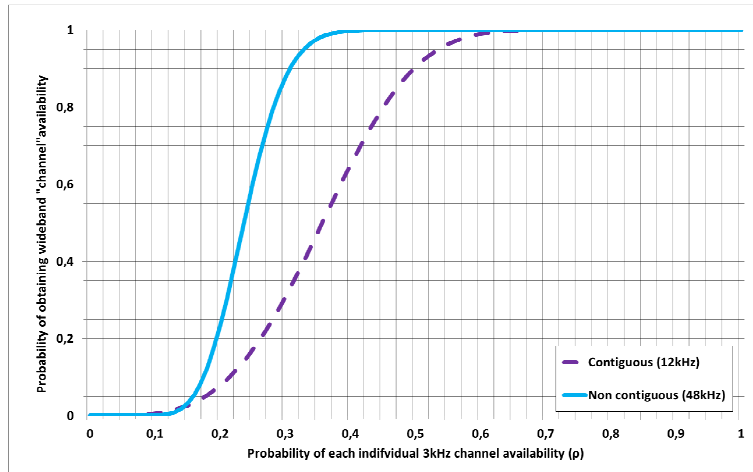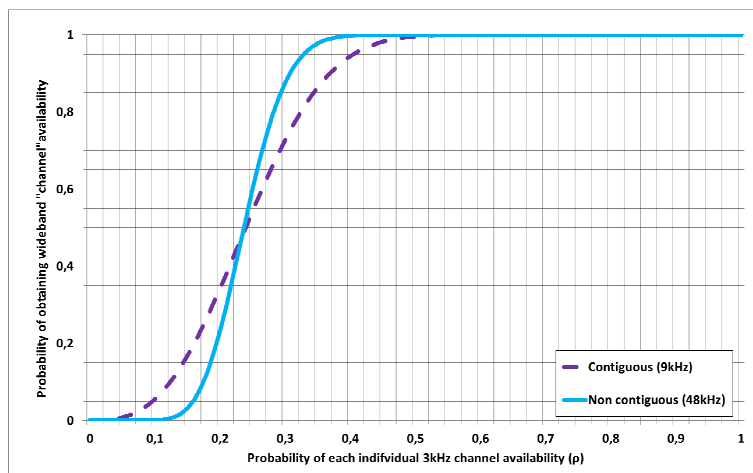**Figure 6 – Analytical probability for obtaining (a) a wideband contiguous of 4*3=12kHz versus (b) a non-contiguous channel of 16*3=48kHz.**

Figure 7 – Analytical probability for obtaining (a) a wideband contiguous of 3*3=9kHz versus (b) a non-contiguous channel of 16*3=48kHz.

4.2   ANALYSIS ON THE WIDEBAND CHANNEL AVAILABILITY

In order to better evaluate the practical implications of the results obtained in previous section, we propose to use preliminary results obtained within the HFIA ad hoc group on wideband channel availability [8]. A common measure protocol is being defined within this group, in order to estimate the HF band usage and conversely frequency availability for both contiguous and non-contiguous approaches. Even though the measurement protocol is still under discussion for wideband measurements, we propose to already consider the results obtained for 3kHz narrow band availability, that corresponds to our definition of ρ. As explained in [13], two measurement methods are currently under discussion, which lead to two different availability values. Figure 8 illustrates the obtained values of ρ, with in x-axis the frequency, by step of 1MHz, and in y-axis the time of day, by step of 1hour. It can be seen that with both methods, for this measurement example done in Belgium on Feb. 1st, 2016 (similar values having being obtained on same location also in Dec. 2015), the value of ρ for channels most likely to be in LUF-MUF for NVIS (Near Vertical Incidence Skywave) transmissions (below 12MHz and passing frequencies) are almost systematically above 30% and below 70 to 80%.

When comparing these values with the curves obtained in Section 3.1, we can then further emphasize the fact that contiguous 24kHz channel availability will be very unlikely, whereas non-contiguous 24 kHz or even 48 kHz will be easily obtained. Obviously, it will be interesting to confirm the occupancy model definition, and then to realize field measurements in other locations in order to confirm this preliminary analysis.

	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29
0	0.77	0.77	0.78	0.81	0.79	0.79	0.92	0.77	0.99	0.97	1.00	1.00	0.98	1.00	0.99	0.99	0.97	0.98	1.00	1.00	0.98	0.99	1.00	1.00	1.00	1.00	1.00	1.00
1	0.77	0.77	0.76	0.81	0.79	0.76	0.92	0.73	0.98	0.94	0.99	1.00	0.98	1.00	0.99	0.99	0.97	0.98	1.00	1.00	0.97	0.98	0.99	1.00	1.00	1.00	1.00	1.00
2	0.76	0.78	0.76	0.80	0.79	0.78	0.93	0.80	0.98	0.92	0.98	0.99	0.98	1.00	0.99	0.99	0.96	0.98	1.00	1.00	0.97	0.98	0.99	1.00	1.00	1.00	1.00	1.00
3	0.79	0.81	0.78	0.81	0.80	0.78	0.94	0.81	0.96	0.93	0.99	0.99	0.98	1.00	0.99	0.99	0.97	0.98	1.00	0.98	0.99	0.99	1.00	1.00	1.00	1.00	1.00	1.00
4	0.78	0.77	0.80	0.82	0.80	0.79	0.94	0.81	0.97	0.95	1.00	0.99	0.98	1.00	0.99	0.99	0.96	0.98	1.00	1.00	0.97	0.98	0.99	1.00	1.00	1.00	1.00	1.00
5	0.76	0.74	0.81	0.82	0.82	0.79	0.95	0.82	0.98	0.92	0.97	0.97	0.98	0.99	0.99	0.99	0.97	0.98	1.00	1.00	0.97	0.98	0.99	1.00	1.00	1.00	1.00	1.00
6	0.76	0.75	0.78	0.81	0.81	0.79	0.93	0.84	0.99	0.96	0.96	0.95	0.97	0.95	0.99	0.98	0.96	0.98	1.00	1.00	0.97	0.98	1.00	1.00	1.00	1.00	1.00	1.00
7	0.79	0.77	0.80	0.81	0.82	0.79	0.89	0.83	0.95	0.91	0.94	0.95	0.94	0.83	0.98	0.89	0.95	0.97	0.98	0.99	0.98	0.99	1.00	1.00	1.00	1.00	1.00	1.00
8	0.83	0.82	0.83	0.84	0.82	0.82	0.88	0.87	0.94	0.86	0.90	0.94	0.91	0.80	0.96	0.81	0.97	0.96	0.96	0.98	0.98	0.98	1.00	1.00	1.00	1.00	1.00	1.00
9	0.94	0.87	0.85	0.87	0.83	0.84	0.87	0.89	0.93	0.85	0.92	0.94	0.90	0.80	0.94	0.83	0.95	0.95	0.96	0.96	0.98	0.97	0.98	1.00	1.00	1.00	1.00	1.00
10	0.95	0.90	0.89	0.90	0.80	0.80	0.85	0.82	0.90	0.81	0.87	0.89	0.86	0.75	0.92	0.83	0.93	0.93	0.96	0.91	0.95	0.97	0.98	1.00	1.00	0.99	1.00	1.00
11	0.97	0.92	0.92	0.92	0.82	0.82	0.85	0.83	0.89	0.82	0.88	0.88	0.88	0.77	0.93	0.83	0.93	0.94	0.94	0.87	0.93	0.98	1.00	1.00	0.99	0.99	1.00	1.00
12	0.97	0.93	0.93	0.94	0.83	0.82	0.85	0.83	0.90	0.80	0.84	0.84	0.88	0.77	0.93	0.82	0.94	0.94	0.94	0.89	0.94	0.97	0.98	1.00	1.00	0.99	1.00	1.00
13	0.96	0.94	0.93	0.93	0.84	0.80	0.84	0.77	0.88	0.78	0.81	0.82	0.81	0.74	0.91	0.80	0.93	0.95	0.84	0.87	0.94	0.97	0.97	0.99	0.99	0.98	1.00	1.00
14	0.97	0.95	0.94	0.95	0.83	0.81	0.85	0.73	0.89	0.77	0.81	0.82	0.85	0.75	0.93	0.86	0.92	0.97	0.97	0.90	0.96	0.98	0.98	1.00	0.99	0.97	1.00	1.00
15	0.94	0.94	0.93	0.93	0.79	0.76	0.84	0.70	0.87	0.77	0.80	0.84	0.84	0.76	0.94	0.86	0.94	0.96	0.95	0.86	0.97	0.97	0.99	0.99	0.99	1.00	1.00	1.00
16	0.91	0.87	0.87	0.84	0.73	0.75	0.81	0.68	0.87	0.78	0.83	0.87	0.85	0.74	0.94	0.86	0.92	0.96	0.97	0.91	0.97	0.98	0.98	1.00	0.99	0.98	1.00	1.00
17	0.87	0.81	0.78	0.80	0.74	0.72	0.77	0.69	0.91	0.78	0.82	0.87	0.88	0.76	0.96	0.89	0.94	0.96	0.98	0.93	0.98	0.98	0.98	1.00	0.99	0.96	1.00	1.00
18	0.82	0.79	0.76	0.78	0.76	0.71	0.81	0.74	0.92	0.80	0.91	0.92	0.94	0.86	0.98	0.90	0.97	0.99	0.99	1.00	0.99	0.99	1.00	1.00	1.00	0.99	1.00	1.00
19	0.81	0.80	0.79	0.80	0.75	0.72	0.87	0.77	0.95	0.82	0.92	0.96	0.97	0.93	0.99	1.00	0.99	1.00	1.00	1.00	0.99	0.99	1.00	1.00	1.00	1.00	1.00	1.00
20	0.79	0.79	0.79	0.81	0.76	0.74	0.88	0.76	0.96	0.88	0.95	0.99	0.99	0.93	1.00	0.99	0.99	1.00	1.00	1.00	0.99	0.99	0.99	1.00	1.00	1.00	1.00	1.00
21	0.77	0.78	0.78	0.82	0.75	0.74	0.88	0.75	0.96	0.90	0.95	0.99	0.99	0.97	1.00	0.99	0.99	1.00	1.00	0.98	0.99	0.99	0.99	1.00	1.00	1.00	1.00	1.00
22	0.78	0.75	0.77	0.80	0.73	0.73	0.88	0.76	0.96	0.85	0.96	0.99	0.99	0.99	0.99	1.00	0.99	0.99	1.00	1.00	0.99	0.99	0.99	1.00	1.00	1.00	1.00	1.00
23	0.75	0.73	0.75	0.81	0.75	0.75	0.86	0.76	0.95	0.86	0.97	0.98	0.98	0.99	0.99	1.00	0.98	0.98	1.00	1.00	0.99	0.99	0.99	1.00	1.00	1.00	1.00	1.00

	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29
0	0.68	0.44	0.49	0.63	0.56	0.48	0.78	0.47	0.92	0.88	0.91	0.84	0.91	0.98	0.96	0.98	0.95	0.96	0.99	0.99	0.96	0.98	0.97	1.00	1.00	1.00	1.00	1.00
1	0.67	0.49	0.49	0.65	0.61	0.52	0.82	0.55	0.92	0.86	0.91	0.84	0.89	0.97	0.95	0.96	0.99	0.99	0.96	0.98	0.97	1.00	1.00	1.00	1.00	0.00	1.00	1.00
2	0.66	0.57	0.56	0.72	0.68	0.53	0.85	0.60	0.91	0.88	0.92	0.74	0.86	0.97	0.95	0.97	0.95	0.96	0.98	0.97	0.97	1.00	1.00	1.00	1.00	1.00	1.00	1.00
3	0.68	0.48	0.54	0.70	0.64	0.50	0.83	0.65	0.00	0.91	0.91	0.71	0.86	0.96	0.95	0.97	0.95	0.99	0.99	0.96	0.98	0.97	1.00	1.00	1.00	1.00	1.00	1.00
4	0.63	0.39	0.55	0.68	0.67	0.46	0.84	0.55	0.91	0.90	0.91	0.69	0.87	0.93	0.95	0.97	0.95	0.95	0.99	0.96	0.98	0.97	1.00	1.00	1.00	0.98	1.00	1.00
5	0.64	0.39	0.53	0.64	0.64	0.43	0.83	0.65	0.93	0.93	0.90	0.72	0.86	0.88	0.96	0.95	0.91	0.95	0.99	0.99	0.96	0.98	0.97	1.00	0.99	1.00	1.00	1.00
6	0.71	0.47	0.57	0.62	0.59	0.44	0.78	0.67	0.83	0.82	0.78	0.57	0.69	0.62	0.93	0.75	0.91	0.91	0.93	0.95	0.97	0.97	1.00	1.00	0.99	0.98	1.00	1.00
7	0.65	0.48	0.57	0.64	0.59	0.53	0.72	0.77	0.86	0.74	0.84	0.85	0.78	0.65	0.92	0.66	0.94	0.95	0.97	0.94	0.96	0.97	0.97	1.00	1.00	1.00	1.00	1.00
8	0.69	0.50	0.67	0.75	0.62	0.50	0.74	0.76	0.84	0.72	0.85	0.85	0.65	0.67	0.84	0.70	0.89	0.90	0.94	0.90	0.95	0.93	0.94	1.00	1.00	1.00	0.99	0.99
9	0.76	0.81	0.73	0.80	0.69	0.53	0.72	0.64	0.79	0.67	0.80	0.68	0.62	0.56	0.86	0.73	0.95	0.85	0.82	0.90	0.96	0.95	0.99	0.99	0.97	1.00	1.00	1.00
10	0.89	0.87	0.80	0.84	0.73	0.54	0.69	0.63	0.79	0.70	0.80	0.66	0.77	0.62	0.90	0.74	0.87	0.90	0.85	0.78	0.90	0.97	1.00	0.99	0.98	0.99	1.00	1.00
11	0.92	0.88	0.79	0.88	0.74	0.58	0.71	0.55	0.83	0.62	0.77	0.67	0.70	0.62	0.85	0.71	0.83	0.87	0.90	0.80	0.89	0.94	0.93	0.96	1.00	0.98	1.00	1.00
12	0.70	0.79	0.81	0.86	0.75	0.51	0.69	0.42	0.79	0.56	0.64	0.57	0.64	0.62	0.82	0.71	0.83	0.87	0.90	0.80	0.89	0.94	0.93	0.96	0.92	0.99	1.00	1.00
13	0.93	0.91	0.81	0.88	0.71	0.53	0.72	0.38	0.81	0.50	0.68	0.64	0.69	0.59	0.88	0.80	0.89	0.93	0.97	0.84	0.95	0.97	0.94	1.00	1.00	0.96	0.99	1.00
14	0.85	0.28	0.80	0.78	0.61	0.34	0.65	0.35	0.81	0.50	0.59	0.59	0.71	0.59	0.88	0.90	0.90	0.75	0.91	0.95	0.94	0.97	0.98	0.95	1.00	1.00	1.00	1.00
15	0.82	0.75	0.66	0.59	0.43	0.34	0.65	0.24	0.76	0.55	0.70	0.70	0.70	0.59	0.87	0.83	0.88	0.93	0.95	0.82	0.96	0.97	0.95	1.00	1.00	0.98	0.92	1.00
16	0.78	0.46	0.41	0.56	0.44	0.30	0.59	0.34	0.83	0.57	0.64	0.59	0.72	0.60	0.86	0.80	0.85	0.87	0.95	0.86	0.95	0.98	0.97	0.99	0.97	0.93	1.00	1.00
17	0.74	0.39	0.52	0.54	0.51	0.36	0.65	0.43	0.89	0.38	0.74	0.78	0.86	0.77	0.93	0.88	0.91	0.98	0.99	0.97	0.97	0.98	0.96	0.99	1.00	1.00	1.00	1.00
18	0.67	0.32	0.60	0.65	0.50	0.37	0.66	0.52	0.90	0.68	0.88	0.93	0.94	0.88	0.98	1.00	0.99	1.00	1.00	0.97	0.98	1.00	0.99	0.99	1.00	1.00	1.00	1.00
19	0.67	0.38	0.60	0.66	0.55	0.42	0.71	0.49	0.90	0.76	0.91	0.97	0.96	0.89	0.98	0.98	0.97	1.00	1.00	0.94	0.98	0.97	1.00	0.99	1.00	1.00	1.00	1.00
20	0.58	0.32	0.56	0.65	0.53	0.44	0.74	0.47	0.90	0.65	0.90	0.98	0.95	0.95	0.97	0.99	0.98	0.98	1.00	0.98	0.96	0.98	1.00	1.00	1.00	1.00	1.00	1.00
21	0.70	0.43	0.60	0.67	0.56	0.50	0.74	0.63	0.97	0.95	0.96	0.92	0.96	0.99	0.97	0.98	0.95	0.97	0.99	0.99	0.96	0.98	0.98	1.00	1.00	1.00	1.00	1.00
22	0.65	0.43	0.59	0.70	0.56	0.54	0.80	0.61	0.96	0.93	0.95	0.84	0.92	0.97	0.98	0.98	0.95	0.96	1.00	0.99	0.96	0.98	0.97	1.00	1.00	1.00	1.00	1.00
23	0.69	0.38	0.56	0.65	0.57	0.50	0.82	0.58	0.95	0.95	0.95	0.84	0.89	0.98	0.95	0.97	0.95	0.96	0.99	0.99	0.96	0.98	0.97	1.00	1.00	1.00	1.00	1.00

Figure 8 – Field measurement of 3kHz channels availability in the HF band, done for Feb. 1st 2016, in Belgium (above: method with averaging over 1s measures, below: method with averaging over 60s measures).

5   CONCLUSIONS

The analytical model introduced to compare the contiguous and non-contiguous modems allows quantifying the benefit of the non-contiguous approach when willing to maximize the probability of availability of a wideband channel. This analysis on the frequency allocations needed from a system point of view to ensure that a wideband HF channel will statistically be available can be used as a tool for frequency planning authorities, to derive capacity evaluations. It should be noted that this approach is both applicable to traditional fixed allocation strategies as well as radio cognitive oriented ones, where the end users will operate on frequency pools.

In particular, the derived model proves that the non-contiguous approach "HF XL" allows to get the bandwidth required for high data-rates in much tighter radio channel conditions than contiguous solutions. Preliminary field measurements made in Belgium illustrate that for NVIS communications, probability of availability of 24kHz contiguous channels will typically not match operational requirements, while the situation will be considerably, improved with the scheme that does not impose the contiguity of the sub-channels.

REFERENCES

[1]   S.G. Farquhar, A.J. Baynham and A.E. Talbot, "BLOS communications technologies for the deep battle-a UK perspective," Proc. of MILCOM 2000 conference, vol. 1, pp. 40 - 44, 2000.

[2]   STANAG 4539 (Ed. 1), Nato Standardization Agreement: "Technical Standards for Non-hopping HF Communications Waveforms", (June 2005).

[3]   MIL-STD-188-110C, Military Standard: interoperability and performance standards for data modems, September 2011.

[4]   STANAG 4539 appendix H (draft). Technical specifications to ensure interoperability of application communication systems using multiple discrete HF channels serial waveform. V0.4, 2016.

[5]   STANAG 4203 ed. 4.0 (draft). Nato Standardization Agreement: "Technical standards for single channel HF radio equipement", 2015.

[6]   D.I. Warner, S. Bantseev and N. Serinken, "Spectral occupancy of fixed and mobile allocations within the High Frequency band"; IRST'2012 conference, York, UK, May 2012.

[7]   R. Berg, B. Johansson and P. Nagy, « Wideband measurement of HF spectral occupancy in the Baltic region », presented at the HFIA'13 meeting by Swedish Defence Agency, San Diego, USA, January 2013. URL: http://hfindustry.com/ (link visited January 2016).

[8]   http://hfindustry.com/channel_availability.htm (visited Feb. 2016).

[9]   C. Lamy-Bergot, J-B. Chantelouve, J-Y. Bernier, H.Diakhaté and J-L. Rogier, "HFXL: adaptive wideband HF transmissions," Proceedings of the Nordic HF'13 conference, Fårö island, Sweden, August 2013.

[10] E. Koski, J. Nieto, M. Thompson and J. Russell, "RF performance implications of wideband HF waveforms," Proceedings of MILCOM'14, pp. 1491-1497, 2014.

[11] L.E. Vogler and J.A. Hoffmeyer, "A model for wideband HF propagation channels," Radio Science, vol. 28, n.6, pp. 1131-1142, November-December 1993.

[12] Recommendation ITU-R P.533-13, Method for the prediction of the performance of HF circuits. July 2015.

[13] JY. Bernier, C. Lamy-Bergot, JL. Rogier, H. Diakhaté, "HFIA wideband HF channel availability, a new measurement method", Wideband HF Channel Availability Working Group, HFIA, Feb 2016, San Diego (see: http://hfindustry.com/channel_availability.htm)