On the Benefits of Random FDMA Schemes in Ultra Narrow Band Networks

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***Abstract*—Ultra narrow band transmission (UNB) systems have already been deployed and have proved to be ultra-efficient for point-to-point communications. This paper presents this technology and gives some insights on the scalability of UNB for a multi-point to point network. This configuration corresponds to an uplink scenario where multiple nodes compete to send their packets, with neither coordination nor feedback from the sink. In particular, we present and analyze two multiple access schemes based on random frequency selection: discrete random FDMA (DR-FDMA) and the new continuous random FDMA (CR-FDMA). An ideal system where the carrier frequencies are exactly obtained is first considered and extended to a more realistic case, with rough carrier frequencies. We analyze the system performance in terms of bit error rate and outage probability. The presented results clearly show that, even if in the ideal case, the DR-FDMA scheme outperforms the CR-FDMA scheme; in the realistic case, both schemes lead to similar performance. Thus, this paper highlights the fact that the use of CR-FDMA is very relevant in a realistic network as it bypasses the need of an accurate carrier frequency control, and thus permits the use of even the cheapest transmitters without loss of performance.**

I. Introduction

Wireless sensor networks (WSNs) are increasingly being used in a wide field of applications in various domains, from health-care to network control and monitoring [1] [2]. In such networks, each node has a small amount of data to transmit (e.g. in applications such as temperature monitoring, electrical metering etc.). Thus, the main issue in WSN is not the individual capacity but rather finding an optimal resource sharing approach to either reduce the energy consumption or maximize the global capacity. In the case of a very large amount of nodes which compete to transmit their data to a common sink, many research works have been devoted with multi-hop and cooperative transmissions. In this paper, we present a different approach referred to as ultra narrow band (UNB). This technique is based on a highly asymmetric system, where the transmitters used UNB individual transmissions over a relatively total large band. The central base station (BS) uses a wide-band receiver to gather and decode all UNB signals transmitted by the distributed sources.

UNB technology is not a new concept. However, to obtain a very narrow band, H.R. Walker proposed in 1997 to use Very Minimum Sideband Keying (VMSK) modulation [3] and claimed to satisfy extremely high spectral efficiency (beyond Shannon's theorem). However, it was demonstrated that the claimed performances can only be obtained for perfect components [4]. So, we do not consider VMSK, but use more realistic modulation: BPSK for UNB technology to satisfy cost-effective and bandwidth-efficiency for low-throughput network. One of the main advantages of UNB technique is the reduced occupied bandwidth that induces a reduced noise contribution. Thus, the reception power sensitivity is very low, producing a very large coverage area using a single sink or base-station (BS) (more than 50 km in open field).

With such an extended coverage, a large amount of source nodes can be served. Thus, the medium access procedure is probably the most critical issue. Usual approaches based on reservation techniques are not efficient in regard of the low quantity of information to be transferred and would lead to a waste of time for protocols or synchronization issues [5]. Therefore, random access protocols are more appealing, as they present more flexibility to manage bursty and random transmissions. Furthermore, in UNB networks, we aim at reducing the cost and the complexity of the source nodes even at the price of an increasing complexity of the receiver. Therefore, random access methods are interesting since they do not require a feedback loop to trigger the transmission.

The well-known drawback of random channel access is the collisions. Interference might take place when several nodes are transmitting at the same time in the same frequency band. Commonly used protocols consider the transmission time as the random variable [5]–[8]. In this case, the transmission frequency is fixed, and the nodes either try to send their packets at randomly chosen times and re-transmit in case of transmission failure (ALOHA based protocols) [5], or obtain information before transmitting with CSMA (Carrier Sense Multiple Access) or ISMA (Inhibit Sense Multiple Access). This approach is not viable in our setting. However, it is also possible to see the transmission frequency carrier as a random variable, which comes in complement to the transmission time. In this case, the nodes can perform their transmission at any randomly chosen time and frequency. To the best of our knowledge, only few recent works considered a random access protocol based simultaneously on both time and frequency selection [9]–[12]. However, all these works focused on a discrete set of frequencies which may be compared to our DR-FDMA approach. By extension, we could also consider [13] where the authors proposed to split a given bandwidth into sub-channels, and where users are randomly affected to each sub-band. Our contribution is thus an extension of these recent works, adapted to UNB networks, with no feedback loop and where the individual transmission bandwidth is negligible with respect to the total band. Besides in our work, the individual bandwidth is not by default constrained by the spacing between the carriers. Furthermore, the CR-FDMA has never been studied and present in the proposed context where tight frequency synchronization is hardly exactly obtained (due

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to factory constraints, jitter induced by temperature variation, the chip aging, etc. [14], [15]).

The rest of the paper is organized as follows. Section II presents the wireless network model for UNB and describes the proposed random frequency access schemes. In Section III, the system performance is studied in the ideal case in which nominal frequencies can be exactly realized. Then, in section IV, the impact of the frequency jitter on the performances of the random frequency multiple access schemes is considered. Finally, Section V gives the conclusion.

II. Transmission Model

A. Ultra Narrow Band Transmission Definition

Ultra narrow band refers to the fact that the individual bands used at the transmission sides are very narrow compared to the whole available bandwidth (typically 1:100). While digital or analog data of narrow band radio system are transmitted and received over a few kHz [2], UNB signals require around 100Hz only, which can be achieved with highly selective FIR filters. Such transmissions have several benefits: flat fading can be assumed which highly simplifies the system analysis and a higher number of users can be supported. Hence, UNB is particularly suitable for IoTs/M2M applications in which the number of transmitting nodes is important and where high data rate is not necessary.

UNB technology is currently deployed, e.g. in Sigfox's networks [16]. In these deployments, a star topology is used, where BSs centered on large cells receive the data from a huge amount of source nodes spread over. Contrary to classical deployments, such technology enables an exceptionally large-scale wireless connection thanks to the ability to successfully demodulate an extremely low received power signal (-142 dBm) and very high band selectivity. These advantages allow data transmission in highly constrained environments where former technologies cannot operate and a possibility to cover a very large area with a very small number of base stations, reducing network management and deployment fees of several orders of magnitude.

B. R-FDMA Scheme Definition

In a random access frequency network, four main problems must be considered: the asynchronicity access of node in the wireless medium, randomness both in time and frequency domain and lack of contention based protocols. To illustrate the system behavior, a toy-example is schematized in Fig.1. It represents the time and frequency use of the channel for 4 active users.

The *randomness in time domain* has an impact on the number of users that are active at the same time. This value depends on several parameters: the number of possible users in the cell, the length (in time) of the packets to transmit, and the transmission periodicity. We thus present our results as a function of the number of simultaneous active users.

Furthermore, the *asynchronicity* permits to suppress the traffic overload needed for synchronization, but leads to varying interference levels during the transmission of a given packet, as packets do not start (and stop) at the same time. In order to simplify the analysis discussed in this work, we will not evaluate the performance evolution during the whole packet transmission, but only at a given point in time. For example, in Fig.1, at $t = t_0$ only 3 users among the 4 users are transmitting.

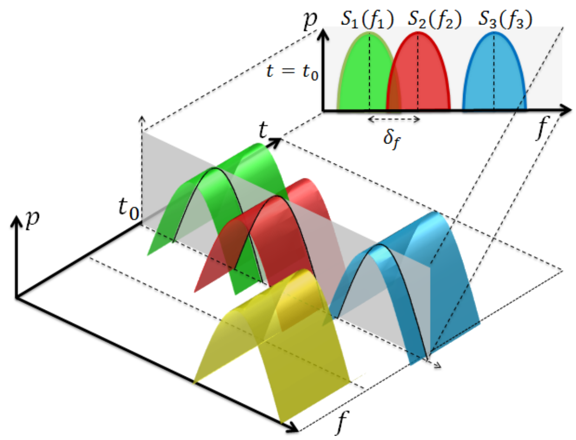

Fig. 1. Example of temporal and spectral repartition of users

The *randomness in frequency domain* has an impact on the position of each active users' carrier in the total band. Thus, it affects the interference suffered by a given user, which depends on the spacing δ_f between the user's carrier frequency and the interferers' one. In this paper, we consider either continuous or discrete frequency randomness. In the first case, i.e. CR-FDMA (Continuous Random FDMA), we consider that the carriers can be chosen at random in the continuous available total band, whereas in the second case DR-FDMA (Discrete Random FDMA), the carriers are chosen at random in a discrete and predefined subset of frequencies. From the receiver point of view (ie. on base-station side), the monitored bandwidth is filled from time to time with a set of signals of interest occupying a small amount of total spectrum and centered around unpredictable carrier frequencies. Thus, in order to handle demodulation, efficient software defined radio algorithms have been designed to analyze the total band, determine transmitter activity and retrieve data they are transmitting. These algorithms are currently deployed in SigFox's network, and do not fall in the scope of this paper.

The *lack of contention based protocols* implies that each user is transmitting without any knowledge of carrier frequencies being used in the cell. Thus, this induces interference (when at least 2 users are transmitting at the same moment and there is an overlap between the individual transmission bands). For example, in Fig.1, the green user starts transmitting even if the red one is already using the band in common.

Finally, we can note that CR-FDMA allows the use of transmitters whose time and frequency are unconstrained (except for being in the transmission total band). In practice, the randomness in frequency domain is easily done: each node has its own transmission frequency which it not controlled by the network, but defined by the node components, and may vary naturally (depending on different parameters such as temperature). It is reasonable however to assume this frequency remaining constant during the transmission of a whole packet. This assumption is very convenient from a practical point of view because it relaxes any oscillator stability factory constraint and naturally overcome the usual sensitivity of RF systems on their environment (e.g. temperature).

C. System Mathematical Model And Parameters

As described in the previous section, the main characteristic of the considered network using CR-FDMA or DR-FDMA is that each active user is transmitting at a carrier frequency randomly chosen in a given band. As a consequence, interference contribution is non-controlled and can lead to transmission errors. Consider a multiple access channel with $k+1$ active transmitters (k is thus the number of interferers at a given time in the considered cell, and $k+1$ is much smaller than the number of nodes that are actually in the cell). The total received signal at the base-station can be expressed as:

$$r(t) = \sum_{i=1}^{k+1} s_i \cdot g(f_i, t) \otimes h_i(t) + n(t) \tag{1}$$

where $s_i(t), \forall i \in [1, ..., k+1]$ is the Binary Phase Shift Keying (BPSK) symbols sent by the active user i; $g_{f_i}(t)$ the impulse response of the emission FIR filter (centered at f_i); h_i the path-loss of the corresponding link; and $n(t)$ an additive white Gaussian noise with zero mean, and whose variance is σ^2.

For the sake of simplicity in this analysis, we consider that $h_i(t) = \delta(t), \forall i \in [1, ..., k+1]$. This corresponds to the worst case where all users are at the same distance of the base station and experience the same flat channel. At the base station, the received signal is analyzed to track possible transmissions in the total band (BW), and filtered at the desired frequency. Without loss of generality, we consider in this paper that the desired user is $\#1$. The signal used for data recovery is thus:

$$\begin{aligned} r^{'}(t) &= r(t) \otimes g(f_1, t) \qquad (2) \\ &= \sum_{i=1}^{k+1} s_i \cdot g(f_i, t) \otimes g(f_1, t) + n(t) \otimes g(f_1, t) \end{aligned}$$

To evaluate the system performance, we use the signal to interference plus noise ratio (SINR) which is expressed as:

$$SINR = \frac{P_s}{P_I + N} \tag{3}$$

where P_s is the received power of the desired user, N the noise contribution, and P_I the aggregate interference. These power are estimated at a given time, and normalized with respect to P_s : $P_s = |G_{f_1}(t)|^2 = 1$, with $G_{f_1}(t) = FT\{g_{f_i}(t)\}$ the frequency response of the FIR filter. The value of P_I depends on the spacing between the carriers frequency, and its estimation will be described in the next section. We deduce the bit error rate (BER) of the BPSK transmission from the SINR as follow:

$$BER(SINR) = Q(\sqrt{SINR}) = 0.5\, erfc(\sqrt{SINR}) \tag{4}$$

We also consider the outage probability (OP) being expressed:

$$Pr(outage) = Pr(BER \geq \beta) \tag{5}$$

A data transmission is considered successful if the received BER is below the predefined threshold $\beta = 10^{-3}$, otherwise, the data are considered lost. The presented figures were obtained by applying the BER and OP theoretical formulas (4), (5) to SINR obtained by simulation.

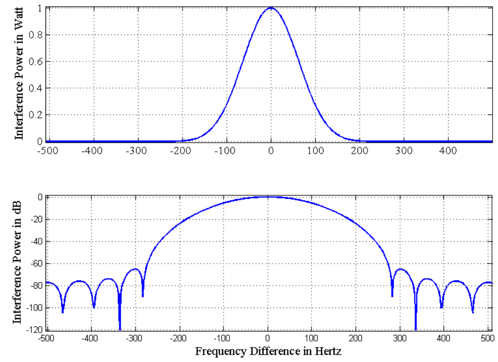

Fig. 2. Behavior of the interference according to frequency difference δ_f

III. Performance Evaluation And Results

In this section, we quantize the interference for the two different access schemes : continuous and discrete frequency distribution.

A. Continuous Frequency Distribution (CR-FDMA)

1) Single Interferer Case: For the single interferer case, we assume that there are only 2 active users using CR-FDMA (i.e. the useful signal and $k=1$ interfering signal). The interference power can be derived at a given time by multiplying the frequency responses of the useful signal and interfering signal:

$$P_I(t) = |G(f_1, t) \cdot G(f_2, t)| \tag{6}$$

At a moment, in (6), the only parameter that will influence $P_I(t)$ is the relative frequency positioning $\delta_f = |f_1 - f_2|$ between the carriers used by the active users for a frequency band particular. We thus model the interference as a function of the frequency shift between the 2 active users δ_f. In Fig.2, we can observe that the interference is lowered if the frequency difference δ_f is large enough. However, we can not neglect this interference caused for high δ_f. Indeed, in the case of a high number k of interferents, the interference will aggregate, and potentially lead to errors. On the contrary, a unique user will cause a significant amount of interference only if δ_f is very small. Indeed, the used filter is very selective. More precisely, we determined that the targeted $BER < 10^{-3}$ (i.e. $SINR = 6.8$ dB), is obtained for $\delta_f > 113$ Hz from Fig.2 and (4).

2) Multi-Interferers Case: As, in practice, the network will support a larger number of active users, we extend our study to more users.

For the sake of simplicity, we suppose that the desired user is transmitting in the middle of the total band. Besides simplicity, this case corresponds to the worst case. Indeed, at this central frequency, the desired user will suffer from statistically more interference than any other active user. This is due to the fact that, in this case, the interferers' frequency are statistically closer to the middle of the total band than any other frequency. Thus, on average, δ_f is smaller and leads to higher interference. The BER is obtained with respect to equations (4) (with a noise power 100 dB under the signal of interest). The mean BER is plotted, i.e. the BER weighted by their probability of occurrence. However, it must be noted that when the carriers are far enough, the BER is extremely small,

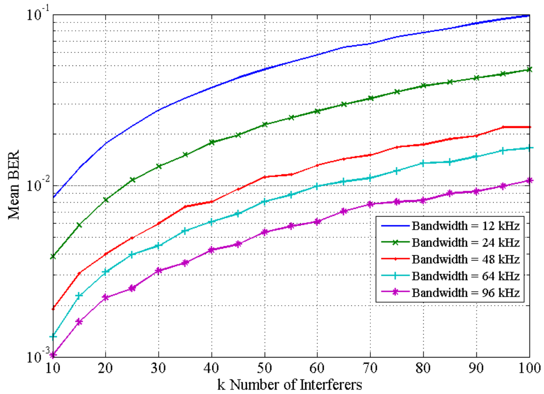

Fig. 3. CR-FDMA BER vs k, for different BW lengths

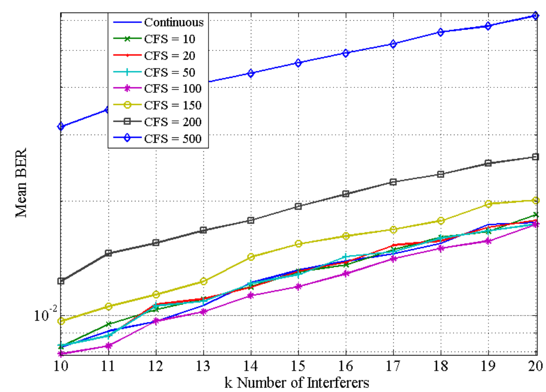

Fig. 5. CR-FDMA and DR-FDMA BER vs k, $BW = 12$ kHz

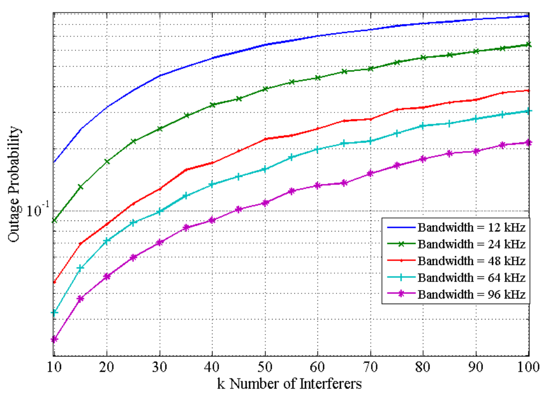

Fig. 4. CR-FDMA OP vs k, for different BW lengths

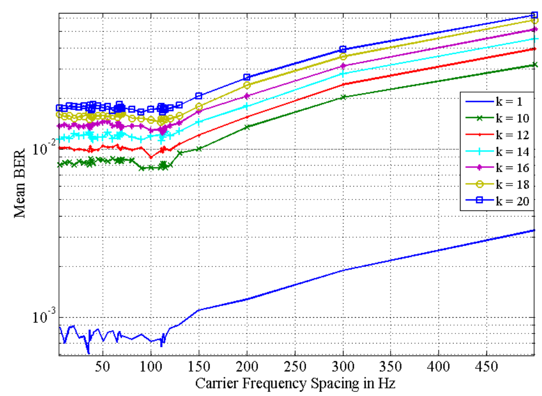

Fig. 6. DR-FDMA BER vs $\triangle_f$ for k interferers, $BW = 12$ kHz

so the mean BER is mainly impacted by low δ_f cases.

In Fig.3, we can first verify that the system performance degrades when the number of active users increases. Besides, for a given targeted BER, the system can support more active users as the total bandwidth increases. However, we can observe that k does not vary linearly with BW. E.g. for a targeted $BER = 10^{-2}$, an 8 times increase of the bandwidth from $BW = 12$ kHz to 96 kHz provides a slightly less increase of the number of interferers, from 12 to 90. This is even more apparent for outage probability (OP in Fig.4).

This is partly due to the fact that probabilities relatives to distributing u users in a B bandwidth are different than distributing $u \cdot m$ users in a $B \cdot m$ bandwidth. Besides, the aggregation of interferences amplifies the difference (as some insignificant interference contributions sum up to a significant level in case of multi-interferers).

B. Discrete Frequency Distribution

We characterize the DR-FDMA scheme by $\triangle_f$ the spacing between the possible values of carriers' frequency (CFS: carrier frequency spacing). Thus, in a given BW, the number of available carriers is $\lfloor \frac{BW}{\triangle_f} \rfloor$, and the possible δ_f values are $\delta_f = j \cdot \triangle_f$ with $j \in \left[1, ..., \frac{BW}{\triangle_f}\right]$. We can also note that CR-FDMA corresponds to DR-FDMA with an infinitely small CFS.

The behavior of the interference in the single interferer case can be readily obtained by sampling the CR-FDMA case. Thus, we directly focus on the multi-interferers case.

Fig.5 and Fig.6 represent the BER for the DR-FDMA multi-interferer case, as a function of $\triangle_f$ and the number of interferers. We can first note that, for $\triangle_f < 100$ Hz, the BER is comparable to the CR-FDMA case, whereas performances are worsened for higher values. Thus, from the BER point of view, the CR-FDMA scheme is optimal.

We now focus on the OP, and first derive its theoretical expression. First, consider the simplest case (i.e. one interferer). When $\triangle_f$ increases, the number of carrier possibilities $\lfloor \frac{BW}{\triangle_f} \rfloor$ for the interferer decreases. So the probability to choose a particular one increases. Moreover, in section III.A.1, we determined that one interferer leads to outage (i.e. $BER > 10^{-3}$) when δ_f falls into the range $[-113, 113]$ Hz. Thus, for $|\triangle_f| > 113$ Hz, there is an outage only if the interferer chooses the same carrier than the desired user, as the others possible carriers are beyond 113 Hz. Thus, in this case, the OP increases with $\triangle_f$.

On the contrary, for a given $\triangle_f < 113$ Hz, there are $1 + 2 \times \lfloor \frac{113}{\triangle_f} \rfloor$ carriers that will lead to outage. Therefore, we can derive the theoretical expression of OP:

$$OP(1) = \frac{1 + 2 \times \lfloor \frac{\delta_0}{\triangle_f} \rfloor}{\lfloor \frac{BW}{\triangle_f} \rfloor} \tag{7}$$

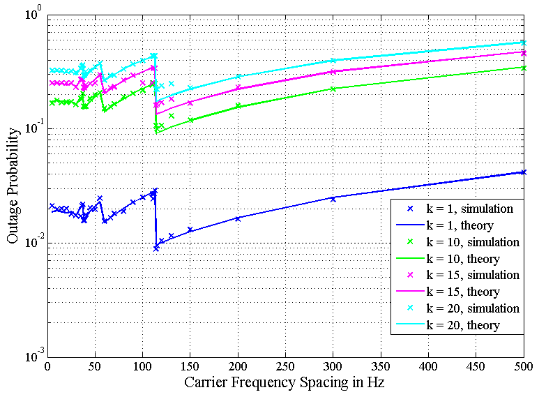

Fig. 7. DR-FDMA OP vs $\triangle_f$ for k interferers, $BW = 12$ kHz

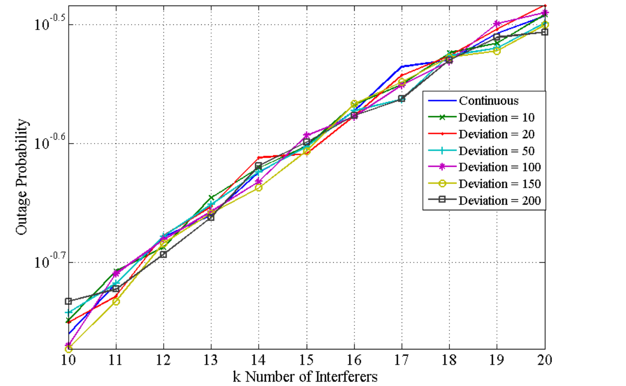

Fig. 8. CR-FDMA OP vs k interferers, with a jitter standard deviation σ, $BW = 12$ kHz

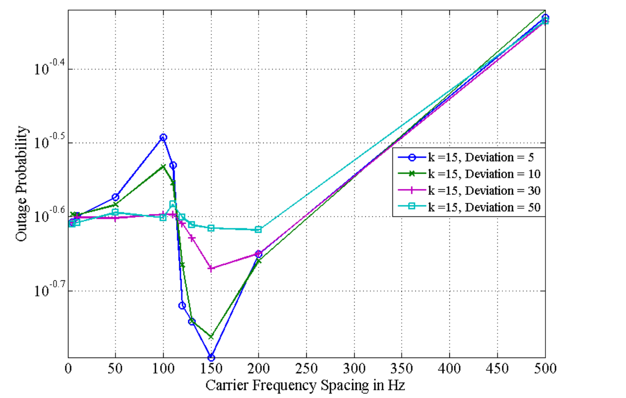

Fig. 9. DR-FDMA OP vs $\triangle_f$, with a jitter standard deviation σ, for 10 interferers, $BW = 12$ kHz

where $\delta_0 = 113$ Hz in our case. This leads to local minimums (discontinuity in the OP pattern) for $\triangle_f = \lfloor \frac{\delta_0}{i} \rfloor$ with $i \in N$.

We called the outage of single user as an event. The service probability is $(1 - OP(1))$ in case of single user $(k = 1)$ and $(1 - OP(k))$ in case of multi-users (k). Furthermore, by assuming that the outage is due to interference of individual users, and not by the interference aggregation of several users, the probability in case of none of the k events occuring is expressed as:

$$SP(k) = \left(1 - \frac{1 + 2 \times \lfloor \frac{\delta_0}{\triangle_f} \rfloor}{\lfloor \frac{BW}{\triangle_f} \rfloor}\right)^k \tag{8}$$

The outage probability in case of $k+1$ users is the probability of at least one of $k+1$ events occurring. Thus, we obtained the outage probability for the general case of $k+1$ users:

$$OP(k) = 1 - \left(1 - \frac{1 + 2 \times \lfloor \frac{\delta_0}{\triangle_f} \rfloor}{\lfloor \frac{BW}{\triangle_f} \rfloor}\right)^k \tag{9}$$

We can verify on Fig.7 that the theoretical model fits with the simulation results. However, one should note that the theoretical model is less pertinent as the number of users increases, specially for $\triangle_f$ sightly higher than 113 Hz, due to the fact that the aggregated interference was neglected. Besides, we can also observe that the OP curves as shown in Fig.7 follow a sawtooth pattern, whose local maximums and minimums do not depend on the number of active interferers, but only on $\triangle_f$, as predicted by the theoretical analysis. Besides, we can observe the DR-FDMA is optimal for $\triangle_f = 113$ Hz, and is more performant than CR-FDMA scheme.

IV. Effect Of Frequency Jitter

Results in the previous section have been obtained with the assumption that the nominal frequencies are exactly obtained. However, in practice, the actual value (linked to the integrated oscillator technology in the terminal) differs from the setpoint frequency targeted in the factory. We thus evaluate in this section, the impact of the jitter (which infers the frequency position in the total band) on the CR-FDMA and DR-FDMA schemes performances. We model this jitter by an additive random frequency variable, which follows a Gaussian distribution with zero mean and known standard deviation σ.

We can first verify on Fig.8 that the jitter has no impact on the OP for a CR-FDMA scheme. This is due to the fact that the jitter is affecting each carrier on an individual basis, but the global carrier distribution remains the same. Indeed, the outage probability obtained by simulation is the same for the different deviation σ. Therefore, the CR-FDMA scheme is not sensitive to the jitter. On the contrary, we can observe on Fig.9, that the DR-FDMA performance degrades when taking into account jitter. Indeed, the sawtooth pattern is more and more smoothed as the jitter standard deviation increases. Indeed, the statistical distribution of the interferers carrier around the targeted frequencies tends to reduce the gap between the performances of close CFS values, and especially where there was a discontinuity. Consider the example of $\triangle_f = 112$ Hz (resp. $\triangle_f = 113$ Hz). Without jitter, all the users that choose $\delta_f = 112$ Hz (resp. $\delta_f = 113$ Hz) lead (resp. do not lead) to OP. On the contrary, with jitter, in both cases, we get about half carriers under 113 Hz creating OP, while the second half does not create OP. Thus, there is no discontinuity anymore.

Furthermore, we can observe on Fig.10, that the jitter impact increases with the number of users. Indeed, for low $\triangle_f$, the curves are more smoothed. Consequently, when σ and/or k increases, the curves tend to have almost constant OP for low $\triangle_f$, and a linearly increasing OP for higher $\triangle_f$ (this second part corresponds to the well-known multiple access ALOHA).

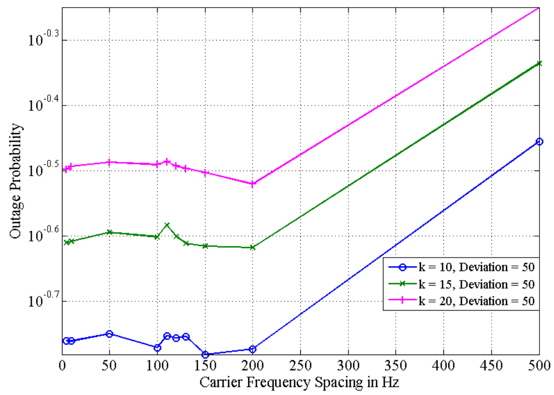

Fig. 10. DR-FDMA vs $\triangle_f$, with a jitter standard deviation $\sigma = 50$, for k interferers, $BW = 12$kHz

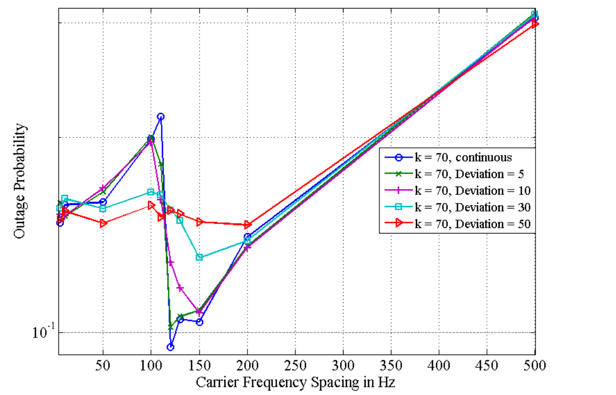

Fig. 11. DR-FDMA vs $\triangle_f$, with a jitter standard deviation σ, for 70 interferers, $BW = 96$ kHz

Thus, DR-FDMA performances are similar or worse than the CR-FDMA case. We have observed the same behavior for others bandwidth, for example $BW = 96$ kHz in Fig.11.

Finally, it must be noted that a standard deviation $\sigma = 50$ Hz corresponds to a 0.06 ppm for a 800 MHz transmission. However, devices currently on the market have standard deviation around $2 - 20$ ppm, and state of the art components reach at best 0.25 ppm [14], [15]. Thus, current devices do not permit to have the precision required such that the DR-FDMA is more performing than the CR-FDMA. In conclusion, in UNB schemes, as CR-FDMA is not sensitive to jitter, the cheapest devices can be used, with an uncontrolled access scheme, without loss of performance.

V. Conclusion

In this paper, we have introduced new multiple access schemes: CR-FDMA and DR-FDMA. We have evaluated their performances in terms of BER and OP, in the ideal case (without frequency jitter), and in the more realistic one (with jitter). We have shown that while the DR-FDMA with particular CFS is more efficient than the CR-FDMA in the ideal case, the jitter reduces the differential. Furthermore, we have estimated that the DR-FDMA scheme leads to better performance if the jitter is lower than 0.06 ppm (which is not currently possible). Meanwhile, the CR-FDMA presents the same performance for whichever jitter. Thus, CR-FDMA is more performing, and less expensive as the constraint on the frequency precision can be alleviated. To conclude, contrary to common transmission schemes, for UNB based networks, non-controlled multiple access is as efficient as controlled ones, thus alleviating the network cost.

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