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Extending the Lora modulation to add parallel channels and improve the LoRaWAN network performance

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***Abstract*—In this paper, we present a new modulation, called DLoRa, similar in principle to the conventional LoRa modulation and compatible with it in terms of bandwidth and numerology. DLoRa departs from the conventional LoRa modulation as it is using a decreasing instantaneous frequency in the chirps instead of an increasing one as for the conventional LoRa modulation. Furthermore, we describe a software environment to accurately evaluate the "isolation" of the different virtual channels created by LoRa and DLoRa when using different Spreading Factors. Our results are in agreement with the ones present in the literature for the conventional LoRa modulation. They show that it is possible to double the number of channels by simultaneously using LoRa and DLora. The higher (double) number of subchannels available is the key to improve the network level performance of LoRa based networks.**

***Index Terms*—LoRa Modulation, LoRaWAN system, Digital Modulation, Internet of Things**

I. Introduction

The Internet of Things (IoT) connectivity has seen a significant change of paradigm in recent years. The usual paradigm some years ago was that of the "Wireless Sensor Networks" (WSN,) in which the mesh topology was almost always assumed. Nowadays, the "Low Power Wide Area Networks" is the most widespread paradigm [2], [3]. This is true for the licensed frequency bands, where the NB-IoT is the technology of choice, and the unlicensed frequency bands where many different technologies are used, such as SigFox, LoRaWAN, etc.

The most popular technology for the LPWAN networks in unlicensed frequency bands is LoRaWAN, based on the LoRa modulation, a proprietary technology owned by Semtech and standardized from the protocol side by the LoRa Alliance [2].

In this paper, we focus on the LoRaWAN technology and especially on the underlying LoRa modulation. One of its main challenges is, of course, to maximize the throughput. The LoRa modulation is an adaptive modulation for which one can select a peculiar parameter, known as Spreading Factor (SF), and by using different SFs, one can create almost parallel, quasi orthogonal, channels in the same band. The amount of these almost orthogonal channels is limited and corresponds to setting the SF in the range $7, 8, \dots 12$, for a total of 6 almost orthogonal channels. To increase the throughput, increasing this number would be, of course, beneficial, but the current definition of the LoRa modulation cannot accommodate such an increase.

In this paper, as a first novel contribution, we define a new variation of the LoRa modulation, called DLoRa, which enable to create a new set of 6 almost parallel channels, indexed once again by the SF in the range $7, 8, \dots 12$, which are not only quasi–orthogonal to each other but also quasi–orthogonal to the ones using the original LoRa modulation. In total, then, by using the original LoRa modulation and DLoRa one can have a set of 12 quas–orthogonal channels, with an increase of a factor of 2 with respect to the original LoRa modulation.

The availability of a higher number of quasi orthogonal channels is, of course, beneficial for the network performance; as a matter of fact, one can think of splitting the End Nodes (EN) which in the original LoRaWAN network based on LoRa are using a certain SF in two parallel channels. This split can be done for every SF, greatly contributing to enhance the throughput since LoRaWAN uses basically (for class A devices[1], which are the vast majority) a simple Aloha access protocol.

A second novel contribution of this paper is related to the quantitative evaluation of the aforementioned quasi orthogonality. As a matter of fact, this in many papers (e.g., [1]) has been done either in a theoretical way or by numerical simulation, which the paper [5] has been proved to inaccurate. The authors in [5] resorted to a better simulation environment then and eventually to the use of hardware–based experimental evaluation. In this paper, we propose and describe an accurate simulation model for the quantitative evaluation of the quasi orthogonality between different SFs (including the ones related to the newly proposed modulation), which results are very

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[1]For the definition of Class A devices /End Nodes see [2].

similar to the simulator results of Table I of [5]. The evaluation confirms that the channels with conventional LoRa modulation and with DLoRa are all quasi-orthogonal.

The paper is organized as follows. In Section II the system model and the notation is introduced for the conventional LoRa modulation. In Section III the newly introduced DLoRa modulation and its properties are described. In Section IV, our approach to quantify the quasi–orthogonality (also called from now on "isolation") between the channels with different SF and different modulation (conventional LoRa and DLoRa) is described. The obtained results are then presented. In Section V, the conclusions of our work are drawn.

II. System model, notation and related work

In this paper, we follow the notation of [7]. For the plain LoRa M-ary modulation ($M = 2^{SF}$ where SF is the so–called Spreading Factor), in the band $[f_0-B/2, f_0+B/2]$ the complex envelope of transmitted signal in the interval $[0, T_s)$ ($T_s = MT_c$ with $T_c = 1/B$) is, for a transmitted symbol $a \in \{0, 1, \ldots M-1\}$:

$$x(t;a) = \exp\left\{\jmath 2\pi Bt\left(\frac{a}{M} - \frac{1}{2} + \frac{Bt}{2M}\right) - u\left(t - \frac{M-a}{B}\right)\right\} \quad (1)$$

where $u(t)$ is the unit step function.

Referring to *Property 3* of [7], the waveforms (1) for different values of a are orthogonal in the discrete–time domain and orthogonal with a very good approximation in the continuous–time domain (see [7] for the analytical expression in the continuous time domain).

The orthogonality conditions were analyzed in [7] assuming the same SF and they form the basis of the LoRa modulation. However, using the LoRa modulation in LoRaWAN networks entails the usage of several different SFs by several different ENs. This usage leads to the need of having (ideally) orthogonality between packets (i.e., groups of subsequent symbols)

- with different spreading factors;
- not synchronized with each other.

Unfortunately this (ideal) orthogonality, which is often assumed, does not hold and has been pointed out since the publication of one of the first papers on LoRaWAN i.e., [1]. Quoting [5]

> Current studies [...] assume that the utilization of multiple transmission channels and SFs lead to a system that can be considered as the simple superposition of independent (single channel, single SF) subsystems. This is actually a strong simplification, especially because the SFs adopted by LoRa are quasi-orthogonal

Taking into account the above mentioned quasi–orthogonality, several algorithms at network management level to assign the different SFs to the ENs have been proposed by many authors (see e.g., [4]), the latest and most promising one being [8]. In the vast majority of them, the availability of a higher number of channels (even if quasi–orthogonal) is definitely beneficial. This is remarking how valuable is to double the number of channels.

III. The DLoRa modulation

The conventional LoRa modulation is using a Chirp–like modulation where the instantaneous frequency of the chirps is always increasing. The key idea novel ideal of the DLora modulation is extending to the LoRa modulation using a decreasing instantaneous frequency. The expression 1 becomes then for a transmitted symbol $a \in \{0, 1, \ldots M-1\}$:

$$x_D(t;a) = \exp\left\{\jmath 2\pi Bt\left(\frac{a}{M} - \frac{1}{2} - \frac{Bt}{2M}\right) + u\left(t - \frac{M-a}{B}\right)\right\} \quad (2)$$

In Fig.1, a plot is shown for the DLoRa modulation compared to the LoRa conventional modulation.

It is straightforward to show that the DLoRa modulation enjoys the same properties, as far as the orthogonality of the waveforms in equation (2) is concerned, as for the conventional LoRa modulation. It is as well straightforward to see that the demodulation of the DLoRa signals can be obtained using the demodulator structure of the one for the LoRa signals, just replacing a downchirp instead of an upchirp.

IV. Isolation between Spreading Factors

In [1] we the isolation between the packets transmitted at different SFs is provided in terms of Signal to Interfence plus Noise Ration (SINR). The main problem with the values provided in [1] is that they are provided without any explanation on how they are obtained. Moreover, these values are quite different from the one values in terms of Signal to Interference (SIR) obtained in [5], where the results are first obtained through MATLAB simulations and then partially confirmed by USRP (Universal Software Radio Peripheral) experiments. Even though Matlab's values in [5] are not perfectly matching the one obtained in practice, the two results can be considered a good approximation of the real case.

In this Section, we will provide a description and the results of the procedure we have used to estimate the values of the SIR between two packets with different SF and possibly different modulation (conventional LoRa and DLoRa) via a Matlab program, inspired by the work of [5].

A. Setting of the Simulations in Matlab

For simplicity, from now, on we will consider only two packets since the results can be easily generalized to the more common case of multiple packets. One packet will be considered as the *reference packet*, which is the packet that we desire to survive the interference, while the other one will be called the *interfering packet*.

The two packets interfere with each other when they are overlapping in time. This overlap can be partial or complete. Obviously, the results from these two situations are different. However, in our simulations, in order to have a common base to analyze and compare the results, we decided to take into consideration only the cases where the interfering packet is completely overlapping with the reference packet.

The target situation for our simulations is shown in Figure 2, where the red rectangle represents the region in which we are going to analyze the interference between the two packets. The

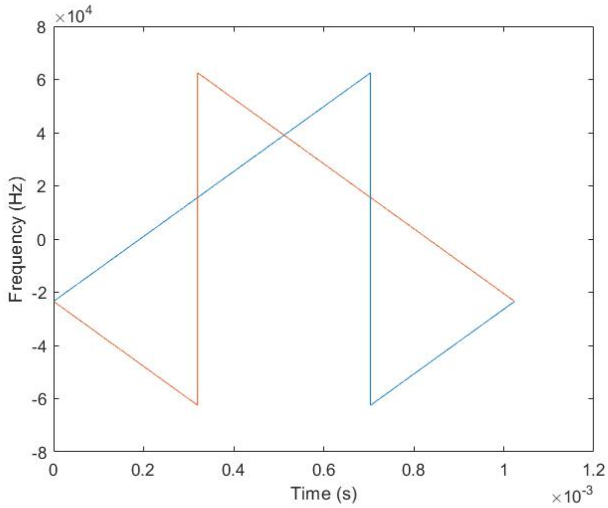

Fig. 1: Frequency behaviour of for LoRa (blue) and DLoRa (orange) signal with SF = 7 and a = 40.

SF ref \ SF int	7	8	9	10	11	12	7_D	8_D	9_D	10_D	11_D	12_D
7	0	-10	-12	-12	-13	-14	-11	-11	-11	-11	-12	-13
8	-12	0	-13	-14	-15	-16	-13	-14	-14	-14	-14	-15
9	-16	-15	0	-16	-17	-18	-15	-16	-16	-17	-17	-17
10	-18	-18	-18	0	-19	-20	-18	-18	-19	-19	-20	-20
11	-21	-21	-21	-21	0	-21	-21	-21	-21	-22	-22	-23
12	-23	-24	-24	-24	-24	0	-23	-24	-24	-24	-25	-25
7_D	-11	-11	-11	-11	-12	-13	0	-10	-12	-12	-13	-14
8_D	-13	-14	-14	-14	-14	-15	-12	0	-13	-14	-15	-16
9_D	-16	-16	-17	-17	-17	-17	-16	-15	0	-16	-17	-18
10_D	-18	-18	-19	-20	-20	-20	-18	-18	-18	0	-19	-20
11_D	-21	-21	-21	-22	-22	-23	-21	-21	-21	-21	0	-21
12_D	-23	-24	-24	-24	-25	-25	-23	-24	-24	-24	-24	0

TABLE I: Thresholds on the SIR between the desired signal and the interferer signal in order to guarantee a Bir Error Rate (BER) of 0.01. The subscript D indicates the DLoRa modulation

packet above is the desired packet, while the one below is the colliding packet. From the figure, it is clear that the two packets have different spreading factors, in fact the chirp duration of the first one T_{s_r} is twice the duration of the chirps of the second packet T_{s_i}.

Given the length (in bytes) of the reference packet's payload as a parameter N_{bytes}, the number of bits N_{bits_r} in the packet is computed as

$$N_{bits_r} = \left\lceil \frac{8N_{bytes}}{(4N_{bs_r})} \right\rceil \cdot (4N_{bs_r}) \tag{3}$$

where N_{bs_r} corresponds to the number of bits contained in each symbol, which in our case corresponds to Spreading Factor of the reference packet, SF_r. From (3) it is easy to compute the number of chirps N_{chirp_r} inside every packet

$$N_{chirp_r} = \left\lceil \frac{N_{bits}(CR+4)}{4N_{bs_r}} \right\rceil \tag{4}$$

where $4/(CR+4)$ is the coding rate with $CR \in \{0, 1, 2, 3\}$.

The time on air ToA of the packet is

$$ToA = N_{chirp_r} \cdot M_r \tag{5}$$

where M_r is the duration of one single chirp. The total number of chirp that the interfering packet should have to have a complete overlap between the two packets is then

$$N_{chirp_i} = \left\lceil \frac{ToA}{M_i} \right\rceil + 1 \tag{6}$$

where the $+1$ is added to compensate the effects due to the shift of the interfering packet with respect to the desired one.

To explain how the interfering packet is shifted, we need to consider Fig. 3 that represents the reference packet, the one above, and the interfering packet, the one below. The sampling time (in multiples of $T = 1/B$ seconds) of the receiver is drawn in red and, as we can see from the figure, it is perfectly synchronized with the sampling time of the reference packet. Clearly, the receiver is sampling the signal asynchronously with respect to the interfering packet. In particular, the interfering packet is shifted randomly by

$$t_{shift} = t_{int} + t_{float} \tag{7}$$

where t_{int} is a shift of an integer number of samples, that is $t_{int} = n_{int}T$ with $n_{int} \in \{0, 1, 2, ..., M-1\}$, and this is the real reason why we have previously added one to the N_{chirp_i}.

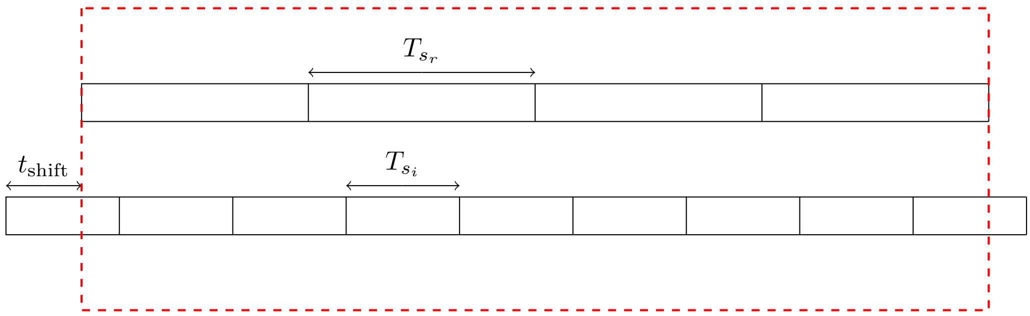

Fig. 2: Two completely colliding packets and the analysis window (in red).

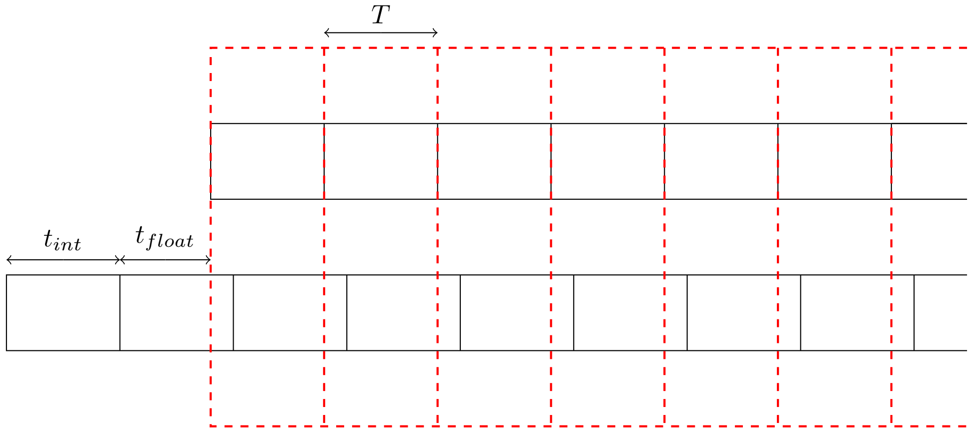

Fig. 3: Alignment of two interfering packets. The packet above is the reference packet, which is synchronized with the receiver (represented in red). The packet below is the interfering one and it is randomly shifted.

The shift f_{float} is instead a fractional part of one chip period and is defined as

$$t_{float} = n_{float}\frac{B}{SR}, \qquad n \in \{0, 1, 2, ..., SR-1\} \tag{8}$$

where SR is a variable parameter. Every time that we simulate two new interfering packets, we randomly generate t_{shift} by randomly drawing n_{int} and n_{float} from their respective set of values. The setting of the SIR is done by tuning the amplitude of the signals A_r and A_i

$$SIR = 10\log_{10}\frac{P_r}{P_i} = 10\log_{10}\frac{A_r^2}{A_i^2} \tag{9}$$

where P_r and P_i are the power of the received packet and the interference, respectively. More in detail, the two packets are built in such a way to have unitary power, then the reference packet is multiplied by $A_r = 1$, while the interfering packet is multiplied by A_i computed as follow

$$A_i = \frac{A_r}{10^{(\frac{SIR}{20})}} \tag{10}$$

To speed up the simulations, the computation of the interfering signal shifted by t_{float} is done using the continuous–time equation of the LoRa chirps in (1) for the conventional LoRa modulation and (2) for the DLora Modulation sampled only on the time instants of our interest, which means the sampling instants of the receiver (the vertical dashed red lines in Figure 3)

Parameter	**Value**
Bandwidth (kHz)	125
Coding Rate (CR)	4/5
Message Size (bytes)	20
SIR range	[-30 dB, 10 dB]
SIR step	1 dB
BER_{target}	0.01
SR	100
Minimum number of errors to be observed in each SIR level	100

TABLE II: Simulation Parameters.

B. *Results of the simulations*

We have run then simulations for every possible spreading factors combination (including both conventional LoRa modulation and DLoRa modulation) iterating over the SIR in the range$[-30, 10]dB$ with a step of $1dB$. For each SIR level, we simulated multiple collisions of the two packets, whose content is randomly generated. The interfering packet is randomly shifted every time with a different t_{shift}. After every block of simulations, the corresponding Bit Error Rate (BER) and Packet Error Rate (PER) at the specific SIR is computed, iterating until we reach the target $BER_{target} = 0.01$. The simulations parameters are summarized in Table II.

The results of the simulations are reported in Table I. We can see from Table I that:

- the results of the simulations are in agreement (within a 1-2 dB) with simulations results of [5];
- the DLoRa modulation exhibits a good isolation (at least -11dB) from the conventional LoRa modulation: this provides a new set of quasi–orthogonal channels with respect to the conventional LoRa modulation; this new set of channels is to be used to diminish the load on the conventional channels and improve the throughput.

V. Conclusions

In this paper, we have introduced a new variation of the LoRa modulation, called DLoRa, which uses a decreasing instantaneous frequency (instead of an increasing one as for the conventional LoRa modulation). We have then described a simulation environment built with Matlab, which allows a detailed assessment of the isolation of the different sub–channels (i.e., channels using different SFs). We tested it, and the results are in agreement with results provided in literature. We have then tested with the aforementioned software environment the isolation among the DLoRa channels and the conventional LoRa channels for all the different combinations of SFs. The results demonstrate that it is possible to use at the same time LoRa and DLora modulations, thus doubling the number of channels from 6 to 12. This is enabling a superior network–level performance since the End Nodes can be assigned to twice the number of subchannels, i.e., we can have half the number of End Nodes per subchannel. The net result is that a reduction of the collision probability is possible. Further investigation is in progress to quantify the network level improvement of the introduction of DLoRa via our NS3 (see https://www.nsnam.org/ for more information on the NS3 network simulation tool) based network simulation environment [10].

References

[1] Claire Goursaud and Jean-Marie Gorce. “Dedicated networks for IoT : PHY/MAC state of the art and challenges”, EAI endorsed transactions on Internet of Things, 2015,

[2] M. Centenaro, L. Vangelista, A. Zanella and M. Zorzi, “Long-range communications in unlicensed bands: the rising stars in the IoT and smart city scenarios,” in IEEE Wireless Communications, vol. 23, no. 5, pp. 60-67, October 2016.

[3] U. Raza, P. Kulkarni, and M. Sooriyabandara, “Low power wide area networks: An overview,” IEEE Communications Surveys and Tutorials, vol. 19, pp. 855–873, Second quarter 2017.

[4] J. Lim and Y. Han, “Spreading factor allocation for massive connectivity in LoRa systems,” IEEE Commun. Lett., vol. 22, no. 4, pp. 800–803, April 2018.

[5] D. Croce, M. Gucciardo, S. Mangione, G. Santaromita and I. Tinnirello, “Impact of LoRa Imperfect Orthogonality: Analysis of Link-Level Performance”, in IEEE Communications Letters, vol. 22, no. 4, pp. 796-799, April 2018.

[6] A. Mahmood, E. Sisinni, L. Guntupalli, R. Rondón, S. A. Hassan and M. Gidlund, “Scalability Analysis of a LoRa Network Under Imperfect Orthogonality,” in IEEE Transactions on Industrial Informatics, vol. 15, no. 3, pp. 1425-1436, March 2019.

[7] M. Chiani and A. Elzanaty, “On the LoRa Modulation for IoT: Waveform Properties and Spectral Analysis,” in IEEE Internet of Things Journal, vol. 6, no. 5, pp. 8463-8470, Oct. 2019.

[8] G. Bianchi and F. Cuomo and D. Garlisi and I. Tinnirello “Capture Aware Sequential Waterfilling for LoraWAN Adaptive Data Rate”, arXiv:1907.12360 [cs.NI], Nov 2019.

[9] C. Caillouet, M. Heuss and F. Rousseau “Optimal SF Allocation in LoRaWAN Considering Physical Capture and Imperfect Orthogonality”. GLOBECOM 2019 - IEEE Global Communications Conference, Dec 2019, Waikoloa,IUSA

[10] https://github.com/signetlabdei/lorawan, last retrieved 29/03/2021