Adjusting Transmission Redundancy and LoRa Parameters for Best Tradeoff Between Range and Energy Consumption

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***Abstract*—Long Range (LoRa) technology allows adjusting the Spreading Factor (SF) and Coding Rate (CR) to combat attenuation and interference. Besides, in the presence of multipath fading, spatial and frequency diversity are powerful tools for improving data reception. With energy-constrained devices, the question is to find the best set of parameters given the device environment.**

We compare various strategies for a given low energy budget, or equivalently channel footprint, for the communication between an end device and a gateway. We put forward a LoRa physical layer model with Rayleigh fading and repetitions before analysing how the LoRa parameters, including the coding rate, influence performance. We show that, typically, a 4-repetition strategy outperforms the others in most cases of LoRaWAN deployments.

***Index Terms*—LoRa; LoRaWAN; Communication Diversity.**

I. Introduction

Long Range (LoRa) is one of the most popular technologies for large-scale and low-data-rate Internet of Things (IoT) applications. It is based on the Chirp Spread Spectrum (CSS) modulation, which enables long-range communications of up to tens of kilometers and is robust against noise, fading, and interference. Often associated with the LoRa Wide Area Network (LoRaWAN) protocol stack, LoRa is a compelling solution for very low-consumption and low-cost devices, with a battery life of up to 15 years [1].

In contrast to other Low Power, Wide Area Network (LPWAN) technologies such as Sigfox or Mioty, LoRa is versatile with several parameters for adjusting data rate, energy consumption, or robustness of each transmission. Besides, in typical LoRa use cases, multipath fading heavily affects the received signal quality, usually for the worse. To fight against it, alongside changing the spreading factor (SF) and coding rate (CR), data redundancy is another tool for improving transmission reliability. It can take the form of frame retransmission (either blind or due to ARQ) or a more evolved inter-frame error correction scheme [2], [3]. In short, these parameters are various means of fighting attenuation and its variability, so the question is: *which one to modify first*?

Recent works on data [4], frame [5], and protocol [6] repetitions have shown that data redundancy is beneficial against interference in contention-based multiple access networks such as LoRaWAN networks. This paper focuses on reliability and energy consumption in the simple case of communication between a single end device and a gateway. The aim is to find the best combination of parameters for a given targeted reliability and channel footprint, which corresponds to a given level of contention [7].

The remainder of the paper is organized as follows: section II briefly presents the LoRa physical layer and section III describes our model with Rayleigh fading and repetitions. Section IV presents the results before we conclude the paper.

II. LoRa Data Transmission

LoRa frame transmission and reception incur a number of steps that we summarise below. For more details, Xu et al. [8] give a complete analysis of the LoRa PHY layer.

A. Modulation

LoRa modulation implements CSS. A chirp consists of a frequency ramp cyclically sweeping the whole channel bandwidth (*BW*). Each chirp carries a total of *SF* bits and it encodes data through $M = 2^{SF}$ possible frequency shifts.

The duration of a chirp is $t_s = M/BW$. So, for a fixed bandwidth, each increment of *SF* doubles the symbol duration and each symbol carries one more bit.

B. Frame Structure and Time on Air

LoRa frames always have the same structure. It starts with a preamble of variable length for detection and synchronization, 20 bits of optional PHY header, and it carries a payload complemented by 16 bits of CRC. The maximum payload compatible with all spreading factors is 59 bytes [9] (in Europe).

We consider Time on Air (ToA) as the main metric for energy consumption in this paper. ToA captures the total duration of the frame transmission, during which the radio is on. The *ToA* of a frame is simply $ToA = n_{\text{symbols}}\, t_s$, where n_{symbols} is the number of symbols (chirps) required to carry all the data. The formulas for the *ToA* appear in a Semtech application note [10] for $SF \geq 7$ and data sheet [11] for $SF < 7$.

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C. Decoding

Decoding a LoRa frame is subject to 2 main steps: deinterleaving and Hamming decoding.

1) Deinterleaving: interleaving is the process of distributing the bits of each codeword formed by the error-correcting code (ECC) over multiple symbols. Interleaving makes the transmission more robust to burst noise (and also noise in general). LoRa uses diagonal interleaving [12], a variation of the common scheme to write in lines and read in columns an array of $(CR + 4) \times SF$ bits.

2) Hamming Decoding: the ECC of LoRa is Hamming codes [12] with coding rates from $4/5$ to $4/8$ for respectively $CR = 1$ to 4. For each CR, there are 4 bits of data and CR bits of redundancy.

After dewhitening, the decoder checks the CRC to validate (or not) the data.

III. System Model

In this section, we present the system model. We start from the work of Ferré and Giremus [13] to estimate the LoRa PHY layer FER. Then we introduce a simple model of Rayleigh fading before considering the effect of repetitions on data delivery.

A. FER Estimation

The bit error model of Ferré and Giremus [13] assumes perfect time and frequency synchronization, the channel is AWGN, and they do not consider interference between chirps.

This work allows computing the probability of missing a symbol P_s. Moreover, to keep high precision for any SNR, it computes a Monte Carlo approximation of the probability of receiving the correct symbol rather than resorting to a Gaussian Q function approximation as in many other papers [14]–[16].

As the length of the frame is known and in the absence of ECC, the probability of receiving the whole frame successfully is that of receiving all symbols correctly:

$$P_{\mathrm{f},CR_0} = 1 - (1 - P_\mathrm{s})^{n_\mathrm{symbols}}. \tag{1}$$

B. Benefits of ECC

With ECC, not all symbols have to be correct for successful frame decoding. Unfortunately, to the best of our knowledge, no work in the literature has proposed a complete model for the performance of the whole LoRa decoding system. Thus, we choose to construct an empirical ECC model that matches both experimental measurements and the performance of advanced decoding schemes (in Table I).

Basically, with binary logic, Hamming codes $4/5$ and $4/6$ only provide error detection, whereas $4/7$ and $4/8$ manage to correct at most one error per code word. In contrast, several experiments [17], [18] show that every increment of the CR has benefits; e.g., going from CR_1 to CR_2 improves robustness, which points to the use of evolved decoding schemes in LoRa receivers.

Semtech does not specify the decoding algorithms on the receiver side and so we have to speculate how they reach the observed performance. Several approaches exist to improve decoding compared to simple binary computation [19]. The fact that all ECC levels have gradual effects on sensitivity makes it very likely that LoRa receivers use some kind of soft decoding and (or) iterative decoding.

TABLE I: Gains (in dB) compared to CR_1 for various Coding Rates and ECC models.

CR	0	1	2	3	4
Experiments [17]	/	0	-0.4	-0.88	-1.2
Bit-based ECC model [21], [22]	-0.1	0	0.08	-1.32	-1.16
List decoding q3 [20]	0.82	0	/	-1.02	/

Table I compares the benefits of ECC in experimental measurements [17] with the anticipated performance of evolved decoding schemes. We can note that the gains from the list decoding technique [20] are the closest to the experimental measurements from CR_1 to CR_3.

To match the ECC model (CR_0) to the experiments, we choose to rely on the list decoding technique model [20] for the distance between CR_0 and CR_1. This model is the most reliable one because it is the closest to the experimental values (between CR_1 and CR_3), as showed in Table I. We base the distance between all other used CRs on real-world measurements [17].

We can finally compute the FER for various CR_k, k in $\{1, 2, 3, 4\}$ where each curve is a shift from CR_0:

$$P_{\mathrm{f},CR_k}(SNR) = P_{\mathrm{f},CR_0}(SNR + \delta_{CR_k}). \tag{2}$$

Table II summarises the δ_{CR_k} shift values.

TABLE II: Empirical ECC shifts compared to CR_0.

k	1	2	3	4
δ_{CR_k} **(dB)**	0.8	1.2	1.6	2.0

C. Rayleigh Channel

Multipath occurs in the presence of many scattering objects, typically in urban scenarios, where LoRaWAN devices are likely to be deployed. We model multipath as a Rayleigh channel.

Rayleigh fading captures well the case of communication when no line-of-sight path dominates. The signal envelope is then Rayleigh distributed. So for each transmission, the power of the received signal is subject to a different gain, which follows an exponential distribution. We do not expect much mobility, so we keep the same gain for the whole frame. The probability of missing a frame with Rayleigh fading is $P_{\mathrm{f,Rayleigh}}$.

D. Frame Replication - Time and Frequency Diversity

In LoRaWAN, the frequency channel changes for each transmission. The channels are at least 200 kHz apart and this is larger than the typical coherence band for this type

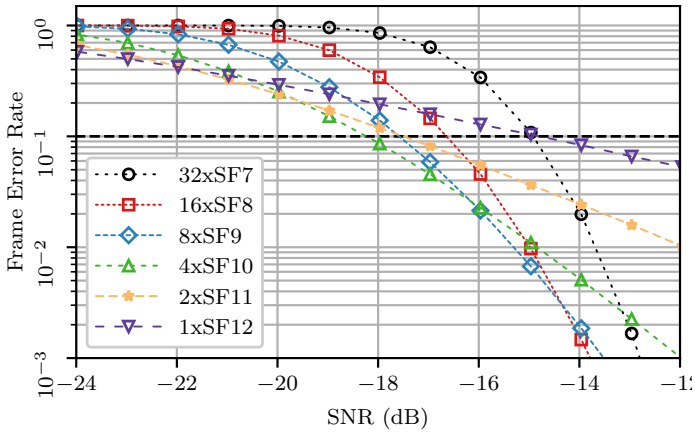


Fig. 1: *FER* performance with equivalent energy budget, same 59-byte payload, from SF7 to SF12 and respectively 32 to 1 transmissions per SF. The strategy 4xSF10 outperforms a single transmission 1xSF12 by 3.4 dB for $P_{\mathrm{f}} = 10^{-1}$.

of network [23]. Moreover, as there are relatively large gaps between successive frames caused by the duty cycle, they could be out of the coherence time window [24] even on the same channel.

Then, the frame error probabilities among frames are independent of each other. After N identical transmissions, the probability of missing all repeated frames is:

$$P_{\mathrm{f,rep}} = P^{N}_{\mathrm{f,Rayleigh}}. \tag{3}$$

The probability of receiving at least one frame is $P_{\mathrm{success}} = 1 - P_{\mathrm{f,rep}}$. Hence, repetitions increase the communication range.

IV. Analysis and Discussions

We present in this section the results from the system model. We first propose a deeper analysis of the influence of frame repetition on the FER. Then we expose what is the best strategy to apply for an efficient use of frame repetition in LoRa.

A. Effect of Repetitions

Fig. 1 shows the evolution of FER with SNR for various strategies with an equal energy budget (and, equivalently, the same level of network contention [7]). For simplicity, we assume that the ToA doubles for each *SF* increment. As expected, the use of low *SF* requires high SNR to reach satisfactory reliabilities. When the number of repetitions increases, the FER falls more quickly and the curve is steeper, which is the case here for low *SF*.

We observe one major effect: there is a Pareto front and no single optimal configuration exists. The optimal tuple (*SF*, number of repetitions) depends on the level of reliability required by the application. For instance, if 10 % of packet loss is acceptable with an energy budget equivalent to a single SF12 transmission, then 4xSF10 is the best strategy to use.

B. Optimal Strategy

Fig. 2 represents the ToA (or energy budget) as a function of the SNR for various parameters: *SF*, *CR*, and number of transmissions. The points of the same color correspond to the same number of transmissions, whereas the clusters of 4 points correspond to the configurations with the same *SF*. Within subgroups, the points with the lower *ToA* have the lower *CR* (least redundancy).

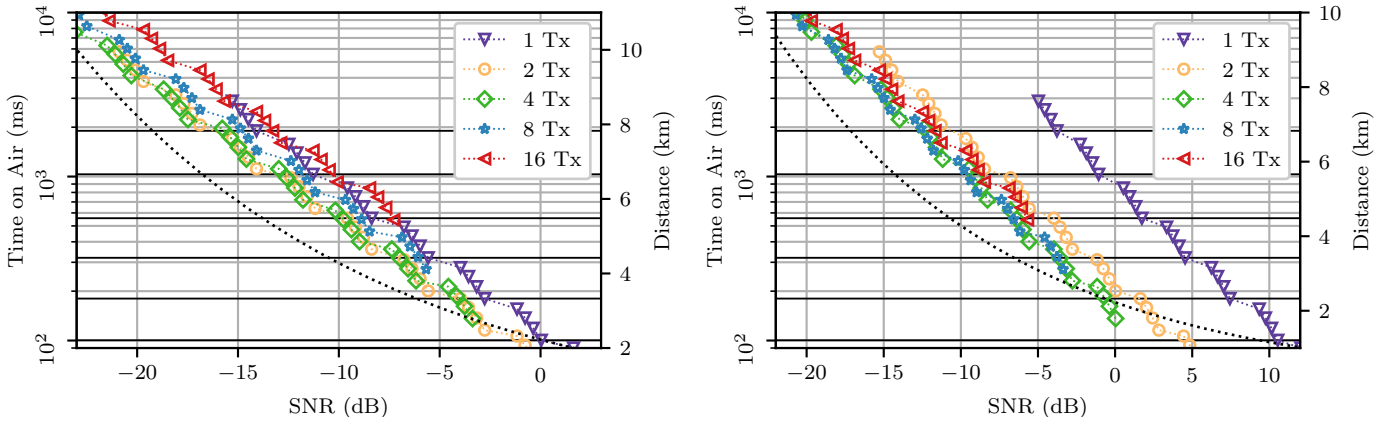
Overall, it is clear that having several repetitions allows for operating at a lower SNR than using a single transmission (lavender groups), even for a high SF. The single transmission curve is positioned to the right of most other curves, independently of targeted reliability. The gain obtained through repetitions is less marked when the reliability is low. A higher reliability target mandates more repetitions: few repetitions are relevant only when we have a very high SNR. If more losses are acceptable, as often for applications on top of LoRaWAN, the difference between the various choices of repetitions is less marked. For the given target reliabilities, the 4-repetition strategy is a safe bet; it is either the best one or never far from the Pareto front. We can also observe that, as repetitions increase the ToA, SF5 and SF6 with repetitions cover the use case of 1xSF7. These SFs allow reliable transmission even with very constrained energy budgets.

C. Macro Diversity

In LoRaWAN, any gateway can relay uplink frames as long as it belongs to the network the sender is associated with. Although for space reasons we do not show plots with macro diversity, it is relatively straightforward to assess its effect: 2 gateways at the same distance from the device represent 2 different radio channels. Thus there are 2 reception opportunities per transmission, which is akin to a 2-repetition strategy. Obviously, as soon as one of the gateways is further away than the other, the benefits of diversity are less marked.

V. Conclusion

In this paper, we started from the postulate of a low energy budget for transmitting data and light load from a single device to a gateway. With the objective to define what strategy is best in this simple case, we first derived a precise approximation of the LoRa FER in the case of a Rayleigh fading channel with constant gain per frame. We have supplemented the FER approximation with an empirical model for the performance of ECC. In this way, we can derive the set of parameters that allow to optimize the level of redundancy (by selecting ECC, spreading factor, and repetition number) for the lowest energy consumption per frame. We draw two general rules: the main observation is that with a tight energy budget, repetitions are necessary to increase reliability and a 4-repetition strategy performs best in most cases. For instance, with an energy budget of a single SF12 transmission for the data, it is advisable to avoid SF12 as well as SF11 and prefer repeating four times at SF10. The other observation is that SF5 and SF6 have great potential for a very low energy budget.



(a) $P_f = 10^{-1}$ (b) $P_f = 10^{-2}$

Fig. 2: Time on Air vs. SNR from SF7 to SF12, CR_1 to CR_4, 1 to 16 repetitions, and for various transmission reliabilities for a 59-byte payload LoRa frame. For instance, let us consider a device 3 km away from the gateway, with 1 % loss acceptance (Fig. 2b). The corresponding average SNR is then approximately -5 dB in the presence of thermal noise power of -174 dBm/Hz and for Okumura-Hata attenuation. With a single transmission, SF12 CR_4 allows reaching the objective loss rate. However, with 4 transmissions at SF7, CR_1 reaches similar performance, for a ToA more than divided by 7.

As future work, we plan to investigate piggybacking to improve reliability and to optimize the cost of the preamble and PHY header. We also plan to conduct experimental measurements to validate our system model and the behavior of repetitions.

Acknowledgment

This work was funded by the French government under the France 2030 ANR program "PEPR Networks of the Future" (ref. ANR-24-PEFT-0001).

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