

**IMT Atlantique** Bretagne-Pays de la Loire École Mines-Télécom

## Carrier and Symbol Synchronisation for LoRa Receivers

MaDeLoRa 2020

A. Marquet, N. Montavont IMT Atlantique Feb. 17th, 2020

#### OUTLINE

1. Introduction

2. System model

3. Problem statement

4. Tackling Time-Fequency Shifts

5. Conclusion



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3 modulations.



3GPP standard Multicarrier \*PSK Closed CSS Modulation Closed BPSK / GFSK





Many works on LoRa since 2018.

- Transmission chain reversed engineered.
- CSS Modulation studied (theoretical and simulations).
- Propositions for improvements (interference mitigation, LoRa-PSK, dual orthogonal LoRa, etc.).



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However :

- No non-Semtech transceivers available.
- Available software-defined radio implementations not fully reliable.

Few literature on tracking algorithms for timing and carrier frequency offsets.

Unless using very good hardware, LoRa receivers cannot be reliable without such tracking.





Contributions :

- Analysis and theoretical model of timing and carrier frequency offset impact on LoRa performance.
- Symbol-by-symbol fine frequency offset estimator.
- Symbol-by-symbol fine timing offset estimator.
- Joint demodulation and time-frequency shift correction using a tracking loop.





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- Symbols are sent using chirps
  - information is spread in time/frequency.
- Index-based modulation (same family as FSK or PPM)
  - "Energy efficient modulations".
  - Require low-SNR, cannot reach high spectral efficiency (bits/(Hz.s)).





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### As for DSSS systems : Spreading factor $SF = \log_2(B.T)$ .

- ▶  $\nearrow$ SF  $\rightarrow$   $\nearrow$  Bandwidth (*B*) (constant symbol time).
- ▶  $\nearrow$ SF  $\rightarrow$   $\nearrow$  Symbol time (*T*) (constant bandwidth).

#### With LoRa, SF is also the number of bits per symbol.

Hence, a symbol can take one of B.T = M values.





Signal is received :

- With a time delay of  $\delta t$  s.
- With a frequency offset of  $\delta f$  Hz.
- Corrupted with Additive White Gaussian Noise (AWGN) z(t).

$$r(t) = s(t - \delta t)e^{j2\pi\delta ft} + z(t).$$
(1)

How does  $\delta t$  and  $\delta f$  affect the quality of the transmission?



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Chapter 3: Problem statement Problem statement – CSS Demodulation				
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- $\text{CSS} \in \text{Orthogonal modulation}$ 
  - $\blacktriangleright$   $\rightarrow$  *M* waveforms for *M* possible symbol values.
  - ▶ Denoted  $g_c(t) \forall c \in [0; M 1[.$

Symbols recovery : find waveform that correlates the best with r(t).

$$\hat{c}_{q} = \operatorname*{argmax}_{\hat{c} \in [0; \mathcal{M}-1]} \left| \int_{-\infty}^{+\infty} g_{\hat{c}}^{*}(t - qT) r(t) \mathrm{d}t \right|$$
(2)

In the following, we denote :

$$\gamma_{q,\hat{c}} = \int_{-\infty}^{+\infty} g_{\hat{c}}^*(t - qT) r(t) \mathrm{d}t$$
(3)





Let us observe correlator output for  $\hat{c} = c_q$ , with normalized :

- time-shift B.δt
- frequency-shift T.δf

and no noise.

Then :

$$|\gamma_{q,c_q}| \approx T|\operatorname{sinc}(\pi(T\delta f - B\delta t))|$$
(4)



















- Fine frequency offset :  $|\delta f| < 0.5/T$ .
- Fine timing offset :  $|\delta t| < 0.5/B$ .
- Coarse frequency offset :  $|\delta f| \ge 0.5/T$ .
- Coarse timing offset :  $|\delta t| \ge 0.5/B$ .



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Our strategy :

- Find estimators for *fine* time/frequency shifts.
- Iteratively correct time/frequency shifts using a closed loop system.







Quadrature detection on correlator outputs :

$$\hat{\delta f}_{q} = rac{T}{2\pi} \arg \gamma_{q, \hat{c}_{q}} \cdot \gamma^{*}_{q-1, \hat{c}_{q-1}}$$

(5)

Symbol-by-symbol.

Direction directed (needs  $\hat{c}_q$  and  $\hat{c}_{q-1}$ ).



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#### Chapter 4: Tackling Time-Fequency Shifts 21 Fine frequency shift estimator



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Find delay that correlates the best :

$$\hat{\delta t} = \operatorname*{argmax}_{\hat{\delta t} \in [-0.5/B; 0.5/B[} \left| \int_{-\infty}^{+\infty} g^*_{\hat{c}_q}(t - qT - \hat{\delta t}) r(t) \mathrm{d}t \right|.$$
(6)

 $\Rightarrow$  Intractable !





Try *N* different delays in [-0.5/B; 0.5/B], and compare correlator outputs.

$$\hat{\delta t} = -\frac{1}{2} + \frac{1}{N} \operatorname*{argmax}_{n \in [0; N-1]} \left| \int_{-\infty}^{+\infty} g_{\hat{c}_q}^*(t - qT - (n/N - 0.5))r(t) \mathrm{d}t \right|.$$
(7)

Symbol-by-symbol.

Direction directed (needs  $\hat{c}_q$ ).



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#### Chapter 4: Tackling Time-Feguency Shifts 25 Fine timing offset estimator Problem statement Tackling Time-Feguency Shifts $-T.\delta f = 0$ 0.4 $-T.\delta f = 0.4$ 0.2 $B. \delta t$ 0 -0.2-0.4-0.5 -0.4 -0.3 -0.2 -0.10.1 0.2 0.3 0.4 0 0.5 $B.\delta t$ M=512, no noise.



# Chapter 4: Tackling Time-Fequency Shifts 26 Putting everything in a loop



Symbol-by-symbol.

Joint Time-frequency offset estimation and correction.



#### Chapter 4: Tackling Time-Feguency Shifts Performance Tackling Time-Fequency Shifts $10^{-1}$ $10^{-2}$ BER $10^{-3}$ $- \bigcirc -a_t = 0.0, \, a_f = 0.0$ $\Delta a_t = 0.0, a_f = 0.4$ $10^{-4}$ $-a_t = 0.4, a_f = 0.0$ $-a_t = 0.4, a_f = 0.4$ → Perfect AWGN $10^{-5}$ 3 526 $E_b/N_0$ (dB)

M=512, N=4. Sampling and carrier frequency offsets simulated with gaussian random walk ( $\sigma = 10^{-6}$ ).



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- Fiming and frequency offset  $\rightarrow$  Strong impact on performance.
- Low-complexity synchronization needed for low-energy operations.

- Symbol-by-symbol timing and frequency offset estimators.
- Low-complexity, first order tracking loop.





- Get information from LoRa preamble.
- Evaluation in a real environment.



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# Thank you !

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