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

# Carrier and Symbol Synchronisation for LoRa Receivers

MaDeLoRa 2020

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# OUTLINE



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- 3 technologies
- 3 modulations.

| NB-IoT | LoRa | sigfox |
| --- | --- | --- |
| 3GPP standard<br>Multicarrier *PSK | Closed<br>CSS Modulation | Closed<br>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.).

However :

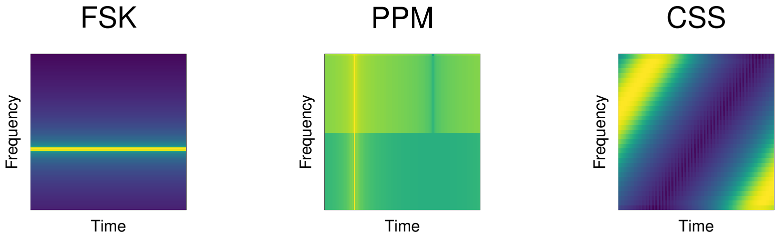
- No non-Semtech transceivers available.
- Available software-defined radio implementations not fully reliable.

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

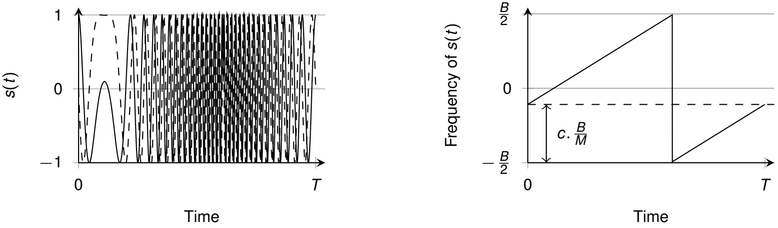
- Unless using very good hardware, LoRa receivers cannot be reliable without such tracking.

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.




- 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 $\text{SF} = \log_2(B.T)$.

- $\nearrow$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) $z(t)$.

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

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

CSS $\in$ Orthogonal modulation

- $\rightarrow$ $M$ 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 $r(t)$.

$$\hat{c}_q = \underset{\hat{c}\in[0;M-1]}{\text{argmax}} \left| \int_{-\infty}^{+\infty} g^*_{\hat{c}}(t-qT)r(t)\mathrm{d}t \right| \quad (2)$$

In the following, we denote :

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

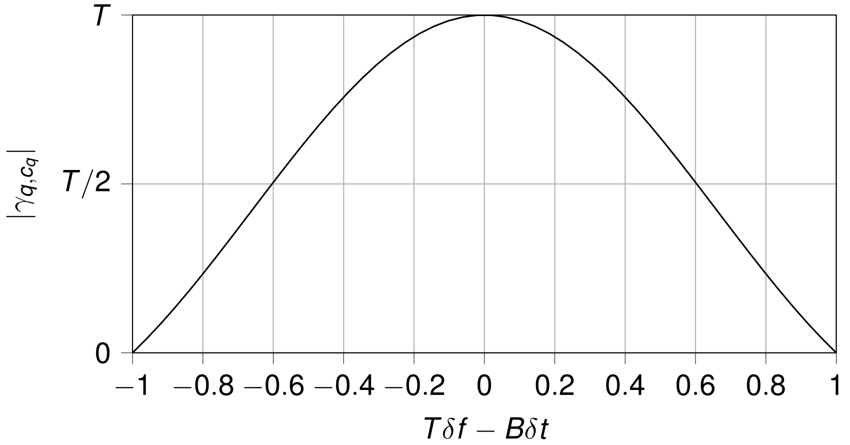
Let us observe correlator output for $\hat{c} = c_q$, with normalized :

- time-shift $B.\delta t$
- frequency-shift $T.\delta f$

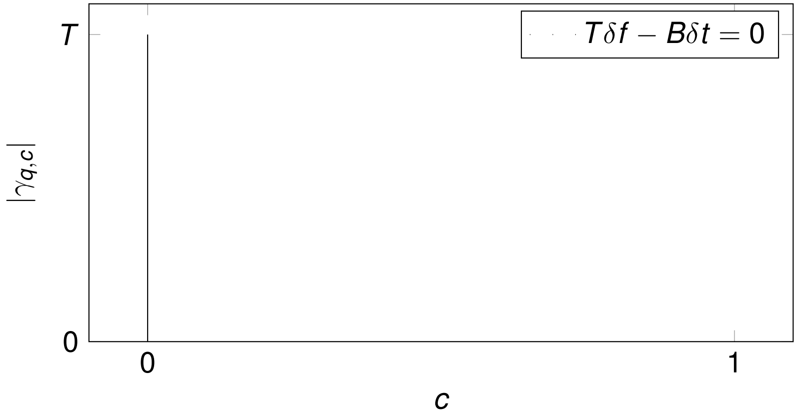
and no noise.

Then :

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


$T$
$T/2$
0
$-1$ $-0.8$ $-0.6$ $-0.4$ $-0.2$ 0 0.2 0.4 0.6 0.8 1
$|\gamma_{q,c_q}|$
$T\delta f - B\delta t$

$M = 2$, symbol sent : $c_q = 0$.



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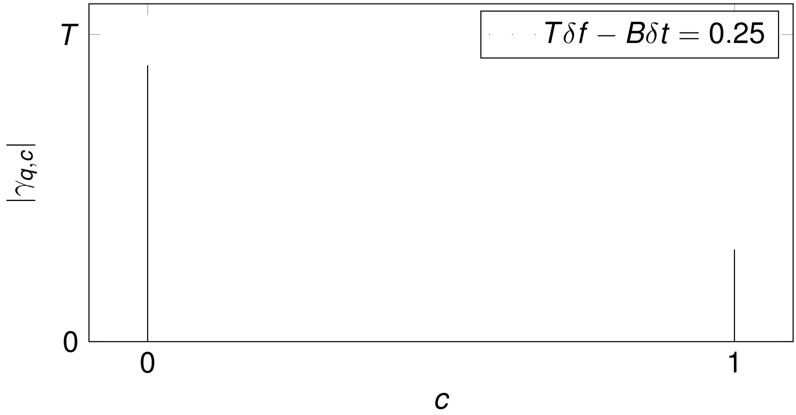

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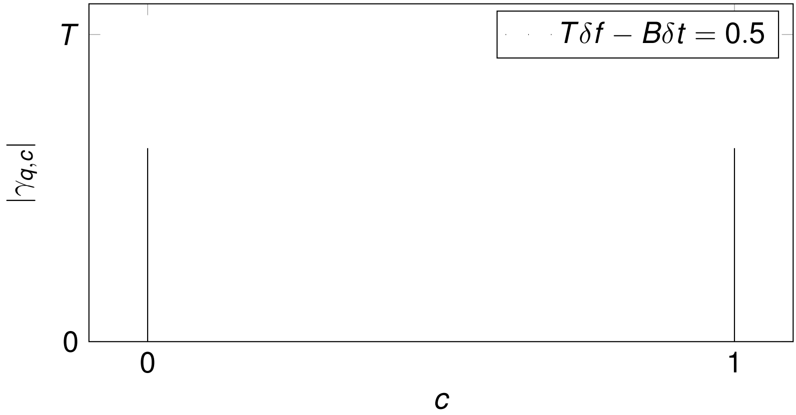

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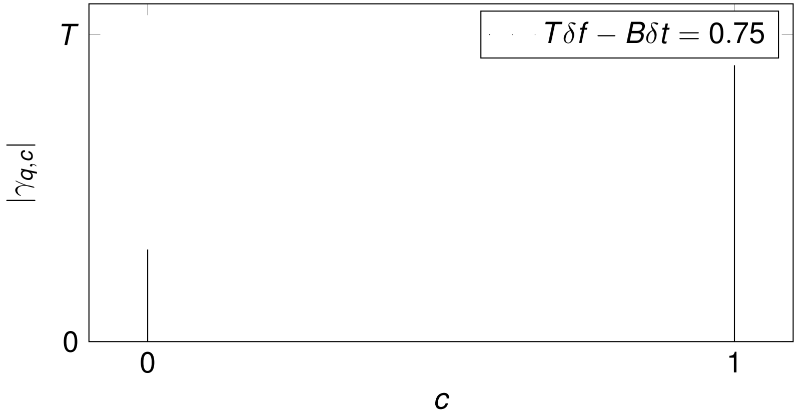

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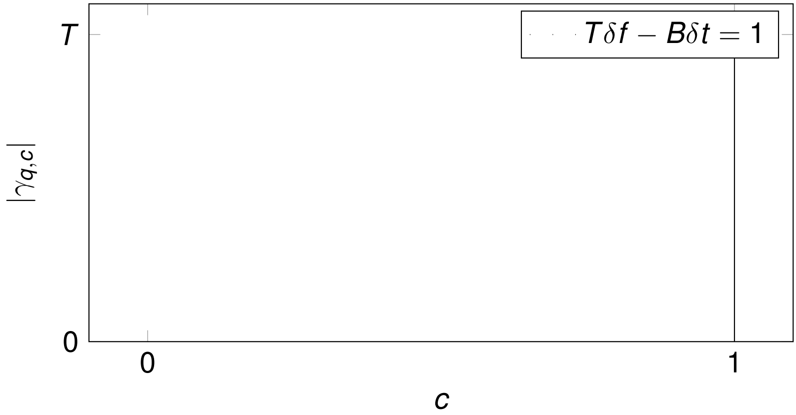
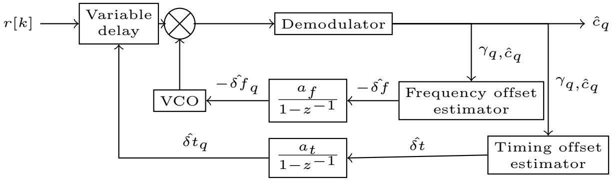


- Fine frequency offset : $|\delta f| < 0.5/T$.
- Fine timing offset : $|\delta t| < 0.5/B$.
- Coarse frequency offset : $|\delta f| \geq 0.5/T$.
- Coarse timing offset : $|\delta t| \geq 0.5/B$.

Our strategy :

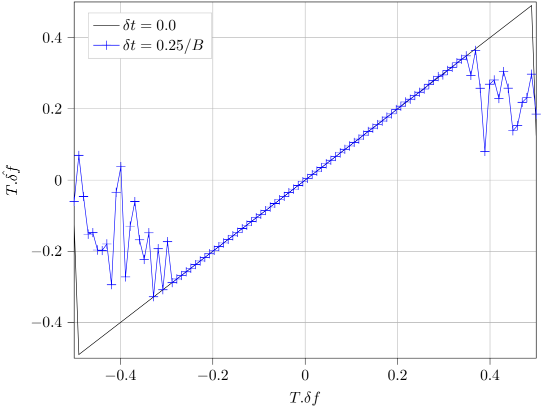
- Find estimators for *fine* time/frequency shifts.
- Iteratively correct time/frequency shifts using a *closed loop system*.



Quadrature detection on correlator outputs :

$$\hat{\delta f}_q = \frac{T}{2\pi} \arg \gamma_{q,\hat{c}_q} . \gamma^*_{q-1,\hat{c}_{q-1}} \quad (5)$$

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




M=512, no noise.

Find delay that correlates the best :

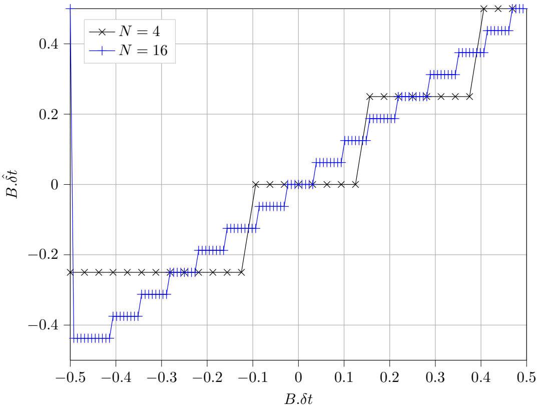
$$\hat{\delta t} = \underset{\hat{\delta t} \in [-0.5/B; 0.5/B[}{\operatorname{argmax}} \left| \int_{-\infty}^{+\infty} g^*_{\hat{c}_q}(t - qT - \hat{\delta t}) r(t) \mathrm{d}t \right|. \tag{6}$$

$\Rightarrow$ Intractable !

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

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

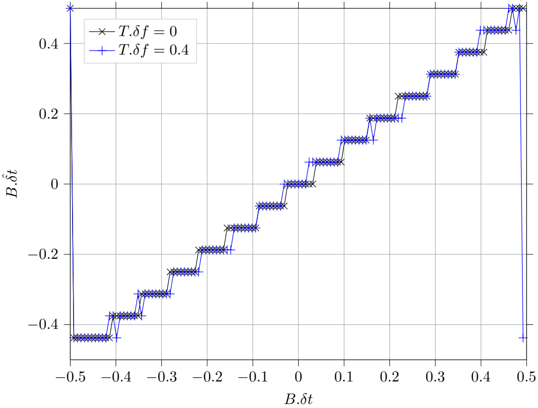
- Symbol-by-symbol.
- Direction directed (needs $\hat{c}_q$).




M=512, no noise.

## Fine timing offset estimator



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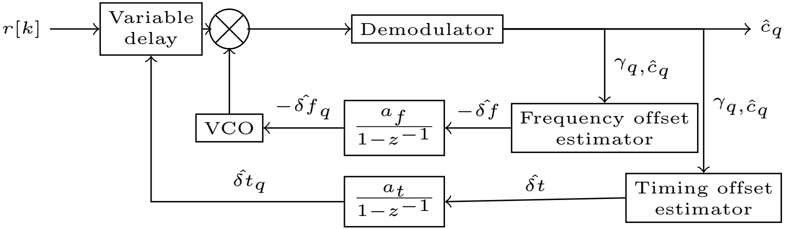
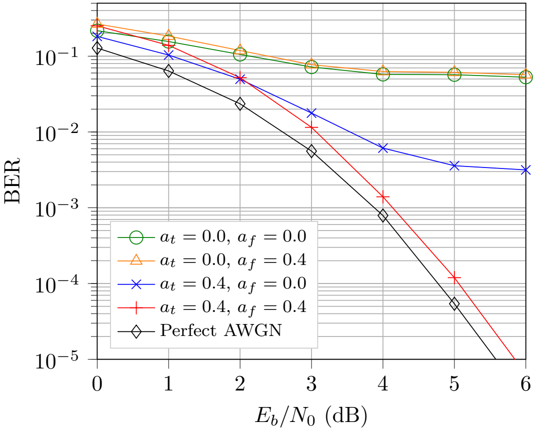



- Symbol-by-symbol.
- Joint Time-frequency offset estimation and correction.




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

- Timing and frequency offset → 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.

# Thank you !