PHYSICAL LAYER ABSTRACTION FOR PERFORMANCE EVALUATION OF LEO SATELLITE SYSTEM FOR IOT USING TIME-FREQUENCY ALOHA SCHEME

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1. Introduction

1.1. NB-IoT extension based on a Low Earth Orbit satellite constellation

This paper focuses on the use of a **LEO satellite constellation** to extend **NB-IoT** [1].

Some 3GPP LTE NB-IoT caracteristics:

- **Single-tone SC-FDMA** (equivalent to FDMA)
- 1/3 turbocode, and Rate Matching of QPSK symbols
- **Repetition** scheme is used
- Pilot symbols are spread among the transmission

As seen from the satellite, transmissions:

- suffer from **high Doppler drift and rate**;
- are **not synchronized** in the time domain.

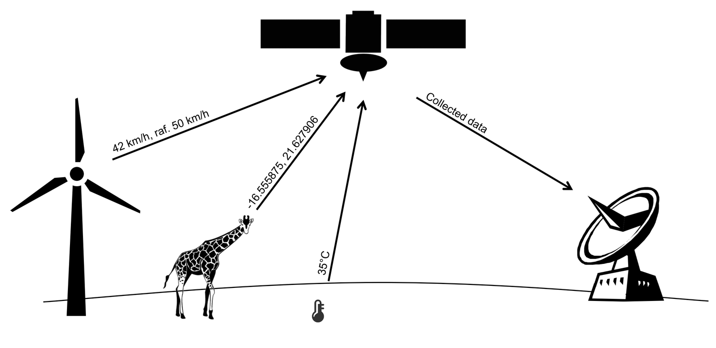


FIGURE 1 – System representation.

Channel access is modeled as **Time-Frequency Aloha Scheme**

1.2. Time-Frequency Aloha Scheme

We suppose that the receiver is **synchronized** with a packet of interest (PoI).

- The interference is not gaussian.
- Channel is time-varying.

Can we estimate **BER** (Bit Error Rate) and **PER** (Packet Error Rate) as a function of the **collision scenario?**

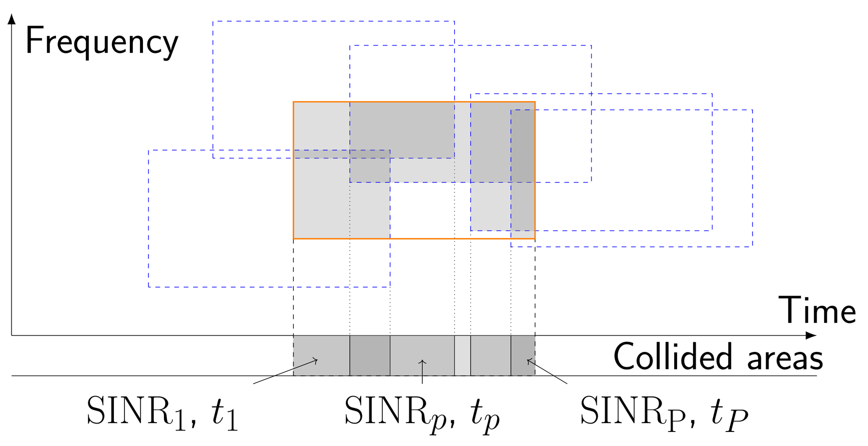
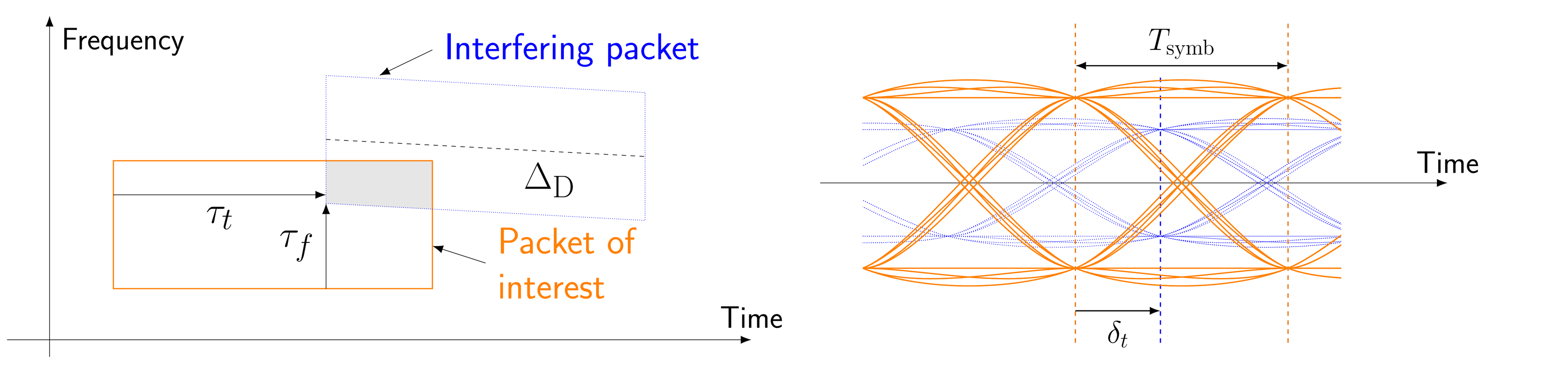


FIGURE 2 – Intrasystem interferences.

2. BER Estimation



(a) Representation of a whole packet and an interferer. (b) Representation of a noiseless eye diagram of two transmissions. Dotted lines are the optimal sampling times.

FIGURE 3 – Representation of a packet of interest (plain orange) and an interferer (dashed blue).

The k-th symbol of the received signal r:

$$r(k) = A_{\mathrm{PoI}}\, e_{\mathrm{PoI}}(k) + \alpha_{\tau_f}(k)\, e_{\mathrm{interf}}(k) + n.$$

Γ_{BER} is a function that links SNR and BER

Two different models:

Best case scenario: $\delta_t = 0.5$

Optimal sampling times are separated: Interference is equivalent to AWGN

$$\mathrm{SNR}_{\mathrm{eq},\,0.5} = \frac{P_{\mathrm{PoI}}/N_0}{1 + (1-|\tau_f|)P_{\mathrm{interf}}/N_0}$$

Worse case scenario: $\delta_t = 0$

Optimal sampling times are synchronized

$\alpha_{\tau_f}(k) = \rho(k)\, e^{j\phi(k)}$, such as

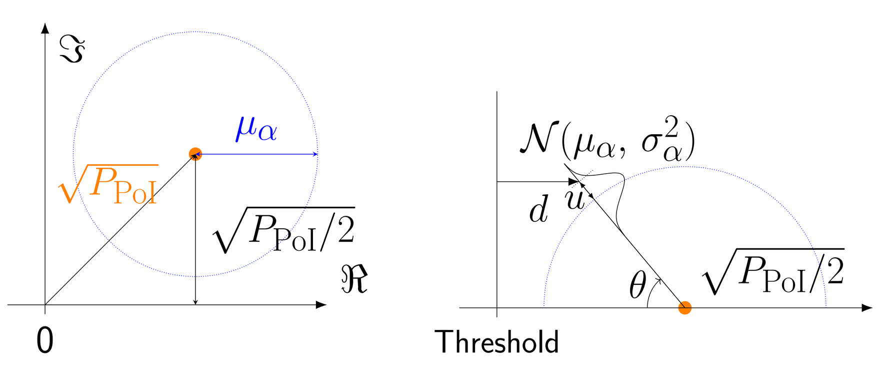
$$\forall k,\quad \phi(k) \sim \mathcal{U}_{[0,2\pi]} \text{ and } \rho(k) \sim \mathcal{N}(\mu_\alpha, \sigma_\alpha^2)$$

$$\mu_\alpha = \sqrt{P_{\mathrm{interf}}(1-|\tau_f|)}$$

σ_α^2 as a function of τ_f simulations

$$d(\theta, u) = \sqrt{\frac{P_{\mathrm{PoI}}}{2}} - (\mu_\alpha + u)\cdot\cos(\theta)$$

$$\mathrm{SNR}_{\mathrm{eq},\,0} = \Gamma_{\mathrm{BER}}^{-1}\left(E\left[Q(d(\theta,u))\right]\right)$$



(a) Sum of two symbols. (b) Distance to threshold.

FIGURE 4 – Interference parameters used for $\delta_t = 0$.

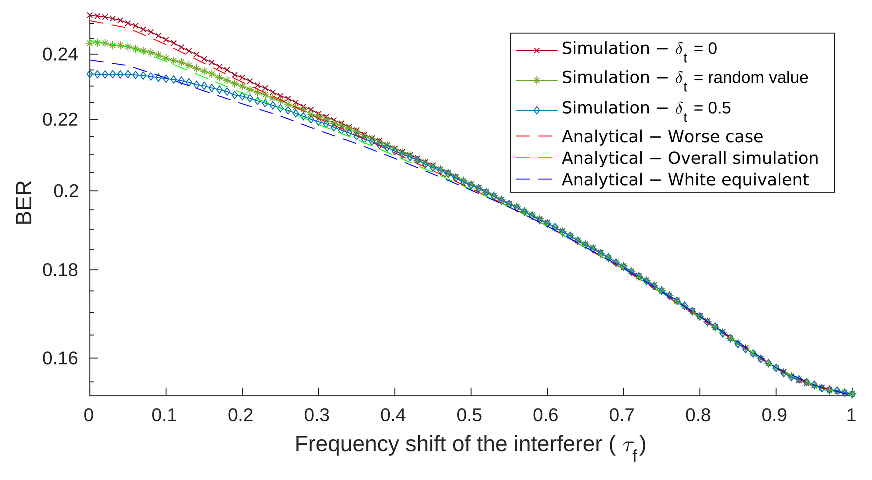


FIGURE 5 – BER abstraction, for $P_{\mathrm{PoI}} = P_{\mathrm{interf}} = N_0$.

BER estimation for a random scenario:

$$\mathrm{BER}_{\mathrm{eq}} = \Gamma_{\mathrm{BER}}\left(\frac{\mathrm{SNR}_{\mathrm{eq},\,0.5} + \mathrm{SNR}_{\mathrm{eq},\,0}}{2}\right)$$

3. Intrasystem interferences

3.1. Description of the phenomena and impact of a scrambling

The values of τ_f and Δ_D impact the interference behavior after the **coherence summation**.

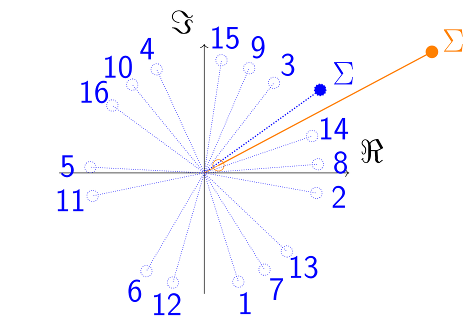


Figure 6 – Coherent summation

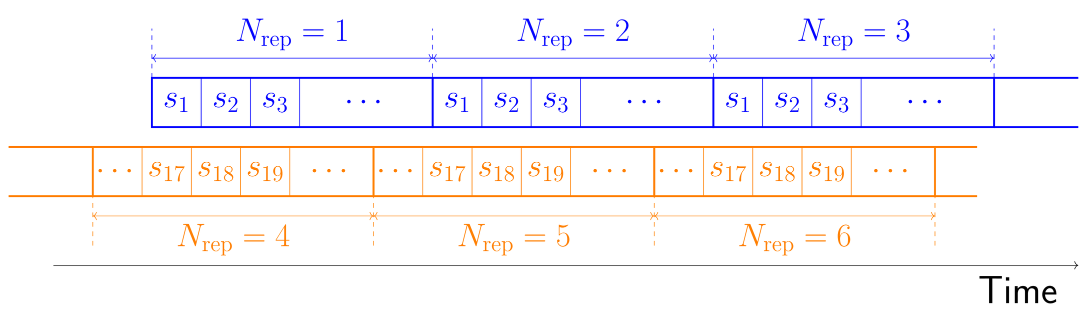


Figure 7 – Two colliding transmissions.

In 3GPP standard, a **scrambling** is performed. One of the **Gold code** seed is defined by:

$$c_{\mathrm{init}} = n_{\mathrm{RNTI}}\cdot 2^{14} + N_{\mathrm{ID}}^{\mathrm{Ncell}} + n_f \mod 2\cdot 2^{13} + \lfloor n_s/2\rfloor\cdot 2^9$$

The **frame number** and **first slot number** change every repetition:

$$n_f = n_{f,\mathrm{init}} + \lfloor(n_{\mathrm{rep}}-1)\times 6.4\rfloor$$

$$n_s = 2\times(n_{f,\mathrm{init}} + 10\,\mathrm{frac}((n_{\mathrm{rep}}-1)\times 6.4)) \mod 5$$

Every 6 repetitions, the seed c_{init} is the same.

Table: Gold code parameters for a transmission.

Repetition number n_{rep}	1	2	3	4	5	6	7	8
Frame number n_f	0	6	12	19	25	30	36	42
$n_f \mod 2$	**0**	0	0	1	1	**0**	0	0
First slot number n_s	0	3	1	4	2	0	3	1
$\lfloor n_s/2\rfloor$	**0**	1	0	2	1	**0**	1	0

3GPP scrambling doesn't prevent the phenomena as it is, but reduces it.

3.2. Summation methods

We compare different summation methods in order to use the repetitions in a time-varying channel,

Max Ratio Combining, MRC

The average power of repetition m is $P_m = P_{PoI} + P_{\mathrm{interf},\,m} + N_0$.

The summation coefficient are defined as:

$$\rho_m^{(\mathrm{MRC})} = \frac{P_{\mathrm{PoI}}}{P_{\mathrm{interf},\,m} + N_0}$$

Unweighted summation

$$\rho_m^{(\mathrm{Unw})} = \frac{P_{\mathrm{PoI}}}{N_0}$$

- **O.U** (Oracle Unweighted) uses a perfectly estimated power.
- **R.U** (Realistic Unweighted) is based on the pilot symbols power.

Optimization solving

The PoI power is: $P_{\mathrm{PoI,\,sum}}(\rho) = \left(\sum_{m=1}^{N_{\mathrm{rep}}} \rho_m A_{\mathrm{PoI}}\right)^2$

We solve the following optimization problem:

$$\rho_{\mathrm{opti}} = \underset{\rho}{\mathrm{argmin}}\ P_{\mathrm{tot}}(\rho) - P_{\mathrm{PoI,\,sum}}(\rho)$$

Table: Decoding performance of summation methods without using scrambling.

Simulation parameters			**Performance (PER)**			
N_{interf}	N_{rep}	P_{T_X}	R.U	O.U	MRC	Optim.
1	4	23 dBm	0.01	**0.01**	0.13	**0.01**
1	4	15 dBm	0.86	**0.86**	0.93	**0.86**
1	8	15 dBm	0.62	**0.57**	0.70	**0.60**

4. PER estimation

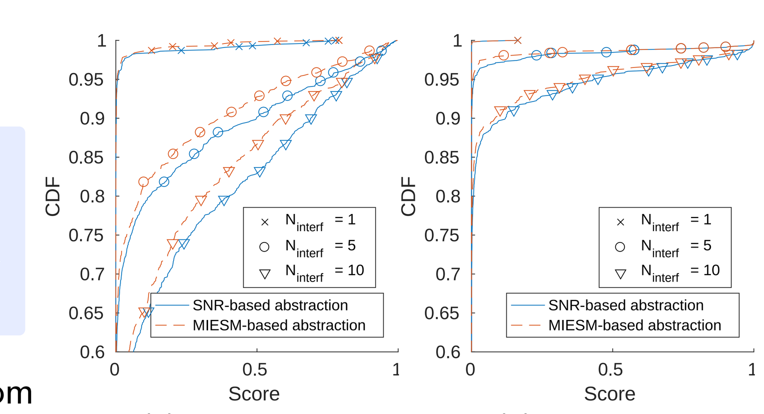
System simulations rely on physical layer abstractions.
The only existing abstraction method of the PER is [2]:

$$\mathrm{SNR}_{\mathrm{eq}}^{\mathrm{RSB\text{-}based}} = \frac{P_{\mathrm{PoI}}}{N_0 + \sum_{i=1}^{N_{\mathrm{interf}}}\left|(1-\tau_f^{(i)})(1-\tau_t^{(i)})\right| P_{\mathrm{interf}}^{(i)}}$$

Our proposed abstraction method relies is inspired from Mutual Information Effective SNR Mapping (MIESM):

$$\mathrm{SNR}_{\mathrm{eq}}^{\mathrm{MIESM\text{-}based}} = \beta_1 I^{-1}\left(\sum_{p=1}^{P} t_p I\left(\frac{\mathrm{SINR}_p}{\beta_2}\right)\right)$$

I is the mutual information ; β_1, β_2 are calibration factors ; $\mathrm{BER} = \Gamma_{\mathrm{PER}}(\mathrm{SNR})$, and Γ_{PER} is obtained *via* simulations.



(a) $N_{\mathrm{rep}} = 4$ (b) $N_{\mathrm{rep}} = 8$

Score s is $s = |\mathrm{PER}_{\mathrm{estim}} - \mathrm{PER}_{\mathrm{simu}}|$

- Both abstractions perform well when the number of collisions is low.
- The proposed abstraction shows better performance when the number of repetitions is low.

5. Conclusion and key references

Random schemes such as **TFA scheme** are said to be a challenge for next generation systems, but are not well studied when the number of collisions is low. This paper proposes a **BER estimation** and a novel **PER abstraction** under this assumption. Then, the impact of **collisions** is discussed when using **repetitions**; a **decoding method** that minimizes the PER by taking into account these repetitions is proposed.

[1] S. Cluzel et al. "3GPP NB-IoT coverage extension using LEO satellites". In : *IEEE 86th Vehicular Technology Conf. (VTC Spring)*. 2018, p. 1–5.
[2] Z. Li et al. "2D time-frequency interference modelling using stochastic geometry for performance evaluation in Low-Power Wide-Area Networks". In : *2017 IEEE Int. Conf. on Comm. (ICC)*. 2017, p. 1–7.