SLS-RFM_23-02 MFSK for very low data rates

Jorge Quintanilla (ESA/ESOC)

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- Background
- MFSK basics
- ESA study
- Way forward

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Background

Deep-space missions under certain conditions (high Doppler rate, high phase noise or very low SNR) challenging to demodulate using coherent schemes.

-> non-coherent ***MFSK*** (Multiple Frequency-Shift Keying) can be a solution for communication in these conditions.

NASA/JPL has already used MFSK:

- Mars rovers: EDL (DTE X-band)
- Juno: Deep-Space Manoeuvres and Jupiter Orbit Insertion
- Europa Clipper, …?
- *There is also a simpler "beacon tone" option to transmit basic spacecraft status*

ESA has not yet used MFSK, but:

- Now implemented in next gen deep-space transponders
- Ongoing study:
  - analyse use cases and solutions
  - implement MFSK receiver
- *DOR tones can be used as beacon tones*

Other agencies?

The topic has been for some time in the **RFM charter**:

18) Study modulation technique and position for pilot symbols of high order modulations used in conjunction with the codes of CCSDS 131.0-B-2

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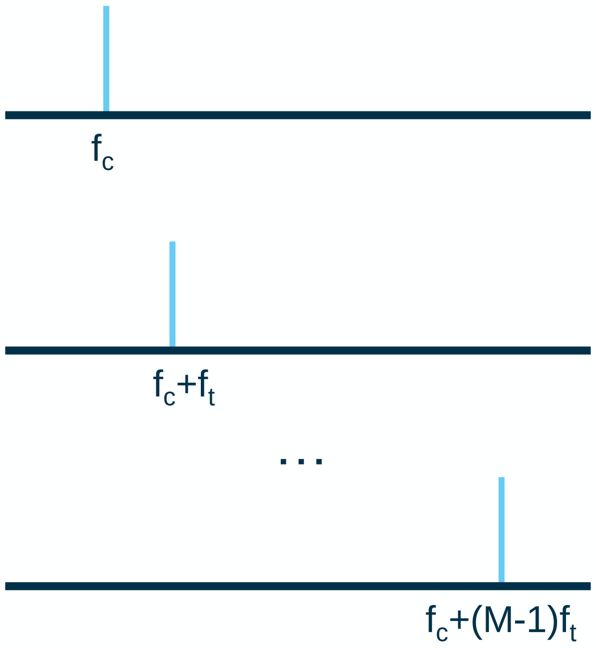
MFSK use cases

- **Entry, Descent and Landing** (high Doppler rate uncertainty)
- **Solar conjunction** (high phase and amplitude scintillation)
- **Safe/Survival mode** (very low SNR)

MFSK modulation

Classical MFSK: information resides in the **tone frequency**

$$X_i^{\mathrm{MFSK}}(t) = \sqrt{2P_T}\cos\left(2\pi\left(F_c^0 + F_i\right)t + \theta\right)$$

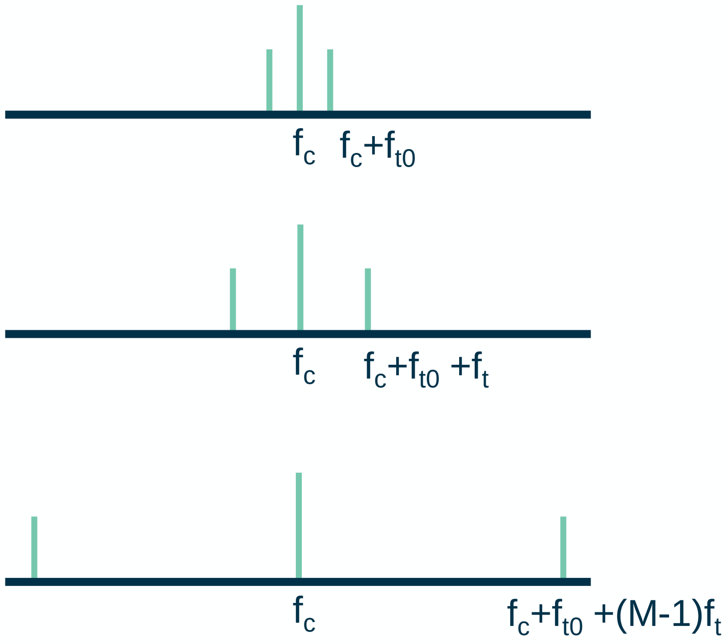


M={4,8,16,32,64,128}

Special MFSK: information resides in the **frequency separation between carrier and tone**

$$X_i^{\mathrm{SMFSK}}(t) = \sqrt{2P_T}\cos\left(2\pi F_c^0 t + \Delta \mathrm{sqr}\left(2\pi F_i t\right) + \theta\right)$$

(sinewave also possible)

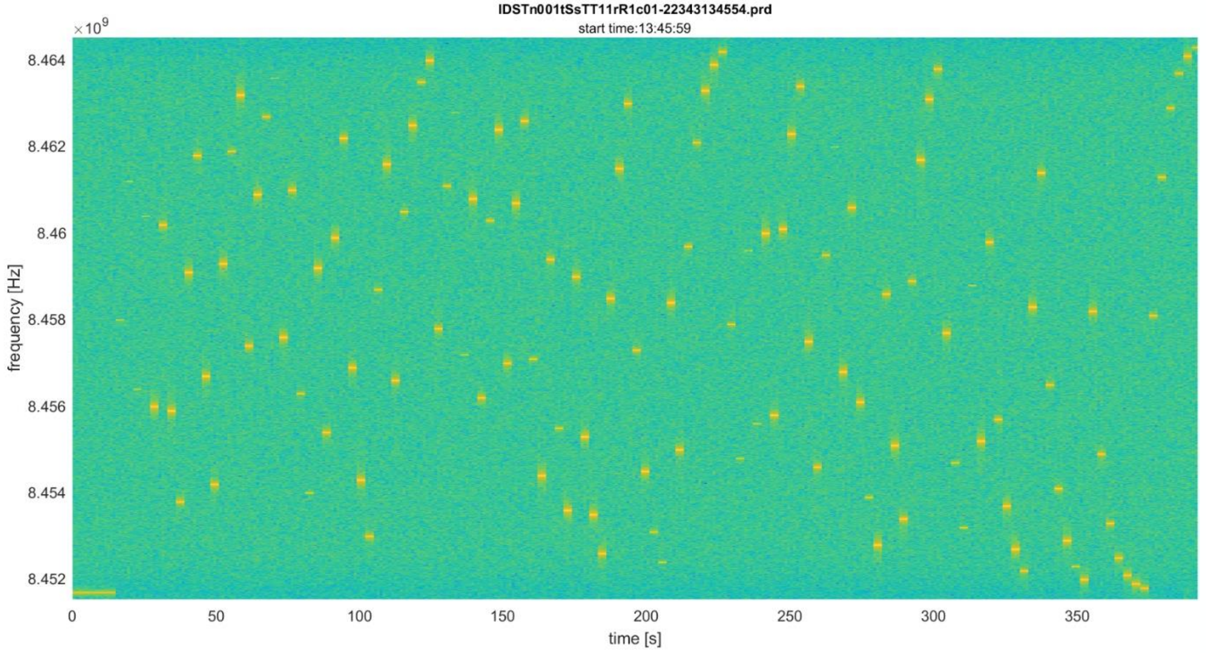


used by JPL

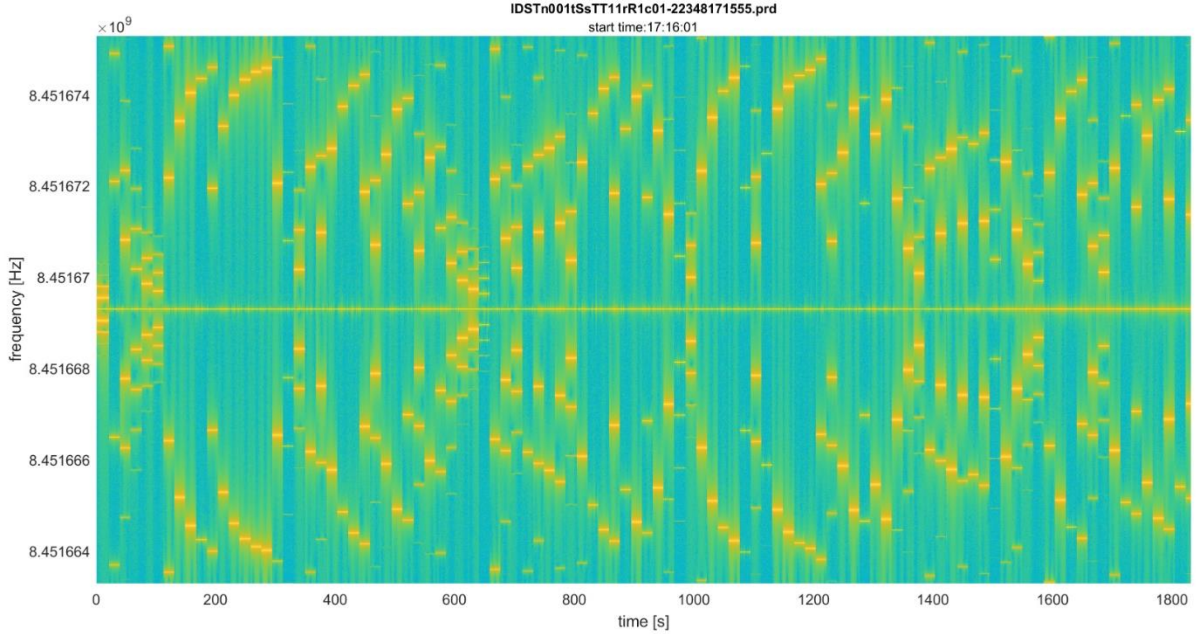
M={256,512}

MFSK modulation

Classical MFSK: information resides in the **tone frequency**



Special MFSK: information resides in the **frequency separation between carrier and tone**



[MFSK signal from IDST transponder, OL recordings performed at ESOC, Dec 2022]

MFSK modulation

Modulation parameters:

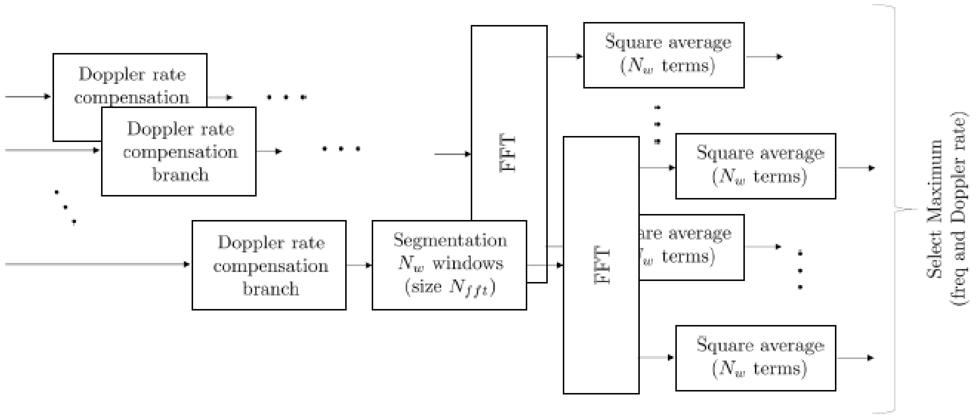
- Modulation type [classical MFSK / special MFSK]
- Modulation order: M
- Tone duration: T_S
- Separation between tones: f_T
- Separation carrier to 1st tone: f_{T0}
- Tone waveform [sine / square]
- Modulation index: Δ

only applicable to special MFSK

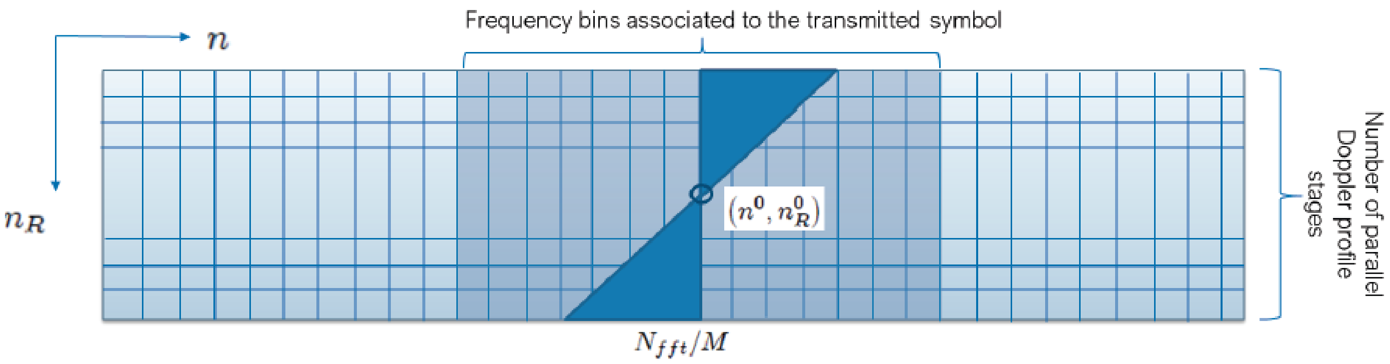
In classical MFSK, separation between tones (f_T) must be sufficient to cover the maximum Doppler error
In special MFSK, only the separation of the first tone (f_{T0}) must be higher than the maximum Doppler error

MFSK receiver architecture

- Signal recorded in open-loop, ideally Doppler-precompensated
  - Sampling frequency must cover all possible tones + Doppler uncertainty
  - Possibility to array multiple antennas to improve SNR -> potential cross-support
- Demodulation with quasi-real-time tool or offline tool
  - Depending on operational needs and processing power
  - Post-processing with finer Doppler correction might further improve detection
- Tone detection based on 2-D FFT
  - search for best **frequency** match and best **frequency rate** match



[from ESA MFSK study] Receiver structure for classical MFSK



[from ESA MFSK study] Detection of a symbol in the frequency / Doppler rate grid

MFSK and upper layers

So far, JPL use of MFSK seems limited to indication of spacecraft status or events.

Can we use it to transmit TM according to CCSDS?

Coding:

- Codes in 131.0-B are designed for AWGN and coherent demodulation, we cannot expect same coding gain
- Lack of references of performance for 131.0-B codes with MFSK
- Frame duration for standard lengths become very long
  - Risk of losing a full frame might not be acceptable, in particular for **EDL** (*7 minutes of terror!*)

Data link and upper layers:

- Overhead increases transmission time
- But without frame structure, no standard way for cross-support (SLE)

MFSK for uplink

- To our knowledge, no spacecraft has used MFSK for uplink so far
    - But there seems to be interest for future missions
- Applicable in the same scenarios as for downlink
- Simple to implement on ground station, but complexity is transferred to spacecraft
- Coding and upper layers?

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ESA MFSK study

- ESA-funded study, carried out by research institutes: CTTC + Ceit
- Inputs from previous ESA studies on EDL, solar conjunction
- Focused on downlink scenarios

- Main objectives:
    - Analysis of scenarios and selection of modulation and coding schemes
    - Implementation of MFSK receiver

ESA MFSK study - scenarios

- Worst-case scenarios considered during study:

	EDL (X band)	Solar conjunction (X-band)	Solar conjunction *(Ka band)*	Safe/Survival mode (X band)
Doppler frequency error	<±50 kHz	<±100 Hz	<±400 Hz	<±100 Hz
Doppler frequency rate error	<±700 Hz/s	<±1.5 Hz/s	<6 Hz/s	<1.5 Hz/s
S/N0	> 14.2 dBHz	≥ 30 dBHz	≥ 30 dBHz	≥ 6 dBHz
Amplitude scintillation index		< 0.85 (Sun-Earth-Probe angle = 1 deg)	< 0.4 (Sun-Earth-Probe angle = 0.5 deg)	

ESA MFSK study - preliminary results

Optimisation done for the worst-case scenarios to achieve max symbol rate with acceptable computational complexity, while keeping $P_{fd}<10^{-4}$

…this means correctly detecting **99.99%** of the tones.

Maybe too harsh!

For M2020 EDL, requirement was **90%**

[L. Mauger *et al*., "Direct to Earth Communications Using MFSK Tones during M2020 Entry, Descent, and Landing,"]

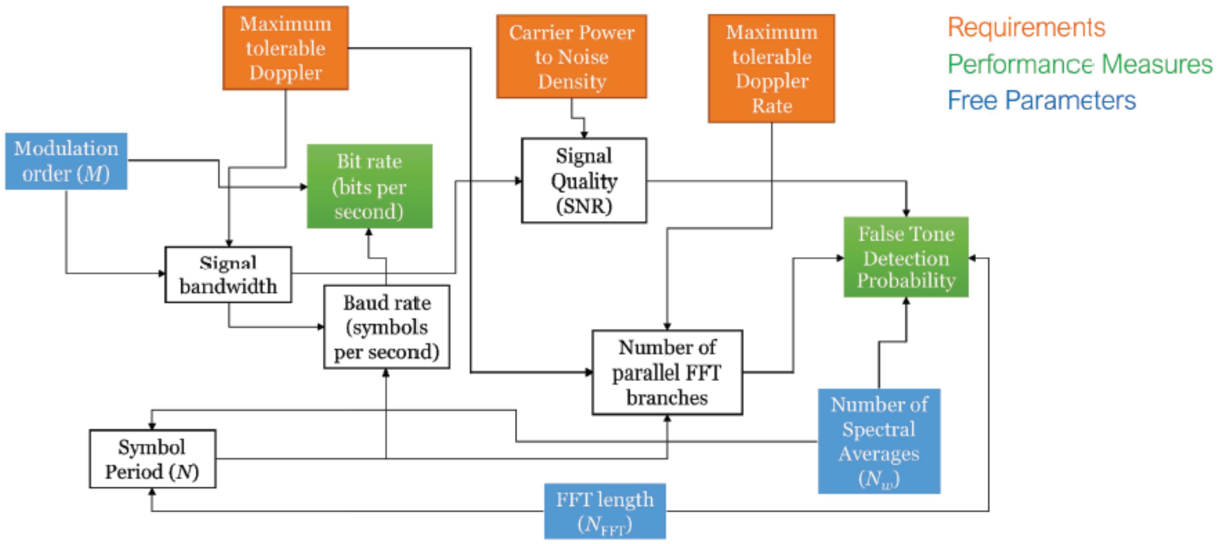
Scenario	waveform	M	Tone separation	Tone duration	Modulation index	Symbol rate (approx.)	Complexity
Safe/survival mode	Classical MFSK	128	1 kHz	14 s	NA	0.5 sps	3.4e8 op/s
	Special MFSK sinewave	512	10 Hz	17 s	80 deg	0.5 sps	1.1e8 op/s
EDL	Classical MFSK	64	100 kHz	2.8 s	NA	2 sps	1.0e11 op/s
	Special MFSK sinewave	512	200 Hz	2.9 s	70 deg	3 sps	5.1e10 op/s
Solar conjunction X-band	Classical MFSK	128	50 kHz	0.11 s	NA	63 sps	7.9e7 op/s
	Special MFSK squarewave	512	10 kHz	0.16 s	70 deg	56 sps	1.3e8 op/s
Solar conjunction Ka-band	Classical MFSK	128	10 kHz	0.04 s	NA	160 sps	1.4e7 op/s
	Special MFSK squarewave	512	1 kHz	0.06 s	70 deg	150 sps	1.2e7 op/s

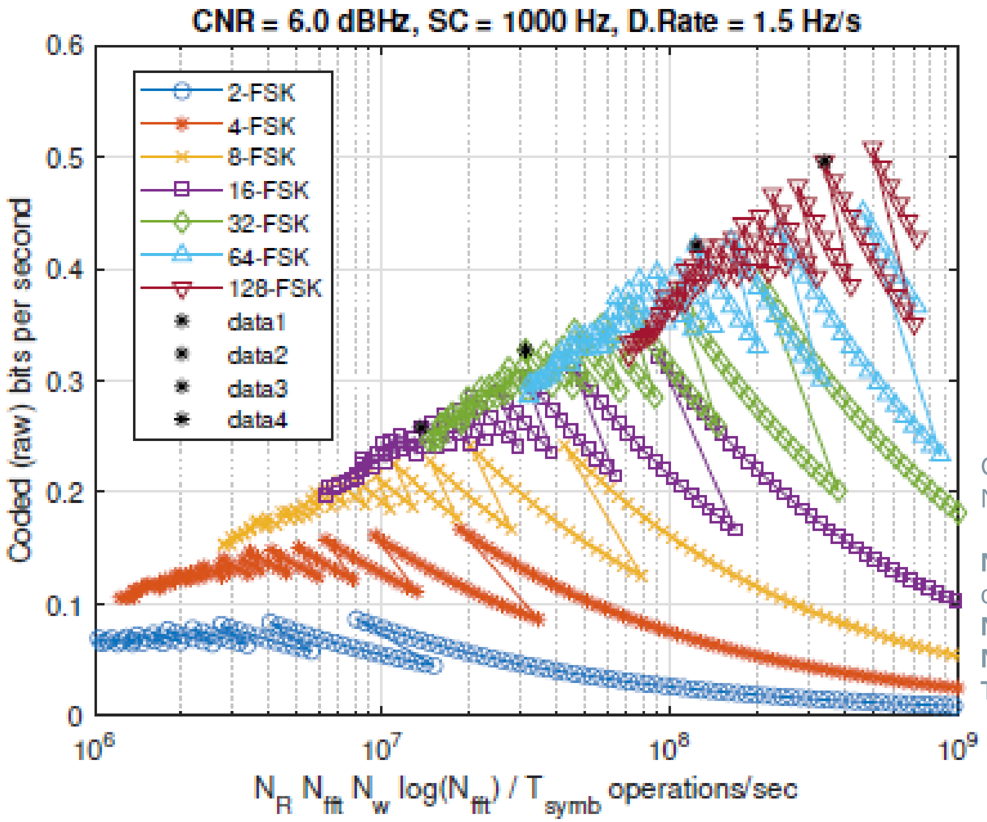
Relaxation of the Pfd to 10^{-2} would allow increase to **~0.7sps** (↑40% rate) with less complexity

Previous ESA study on EDL gave advantage to classical MFSK,but these results show opposite

ESA MFSK study - preliminary results

Example of optimisation for safe/survival scenario





(b) Coded (raw) bit rate versus complexity.

Complexity calculated as $N_R N_w N_{fft} \log N_{fft} / T_s$

N_R # of Doppler rate compensation branches
N_w # of averages
N_{fft} FFT size
T_s tone duration

[from ESA MFSK study]

ESA MFSK study - preliminary results

For coded signals, soft demapper instead of hard output of FFT detector

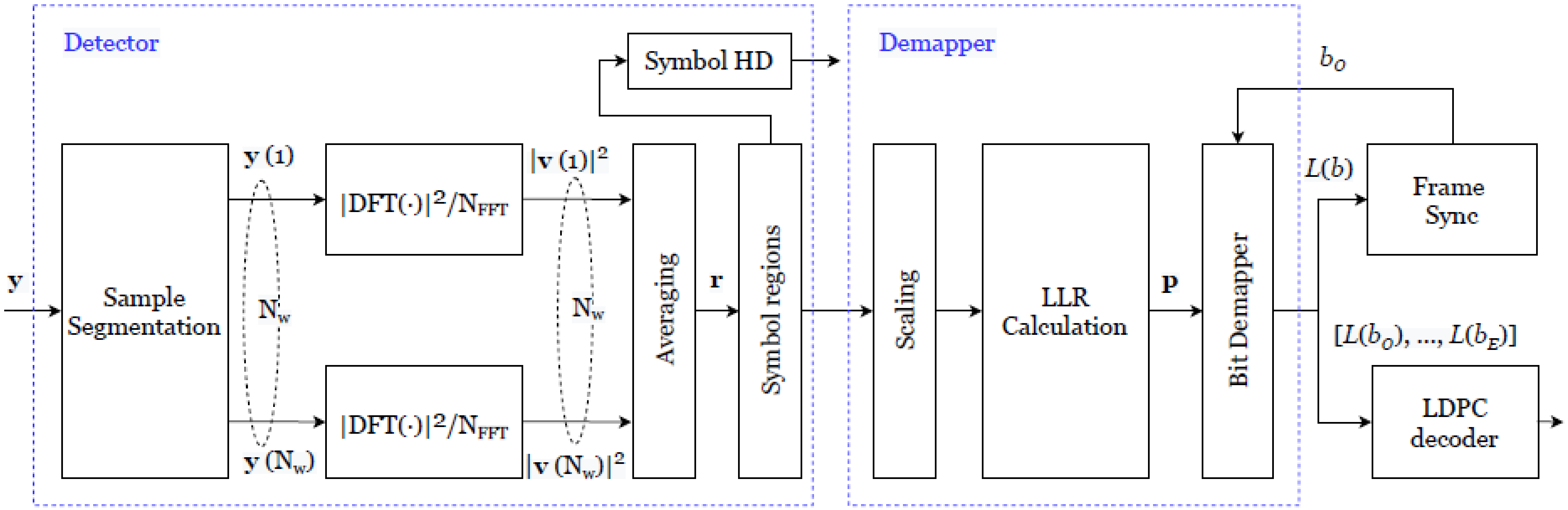


Fig. 3. Receiver architecture.

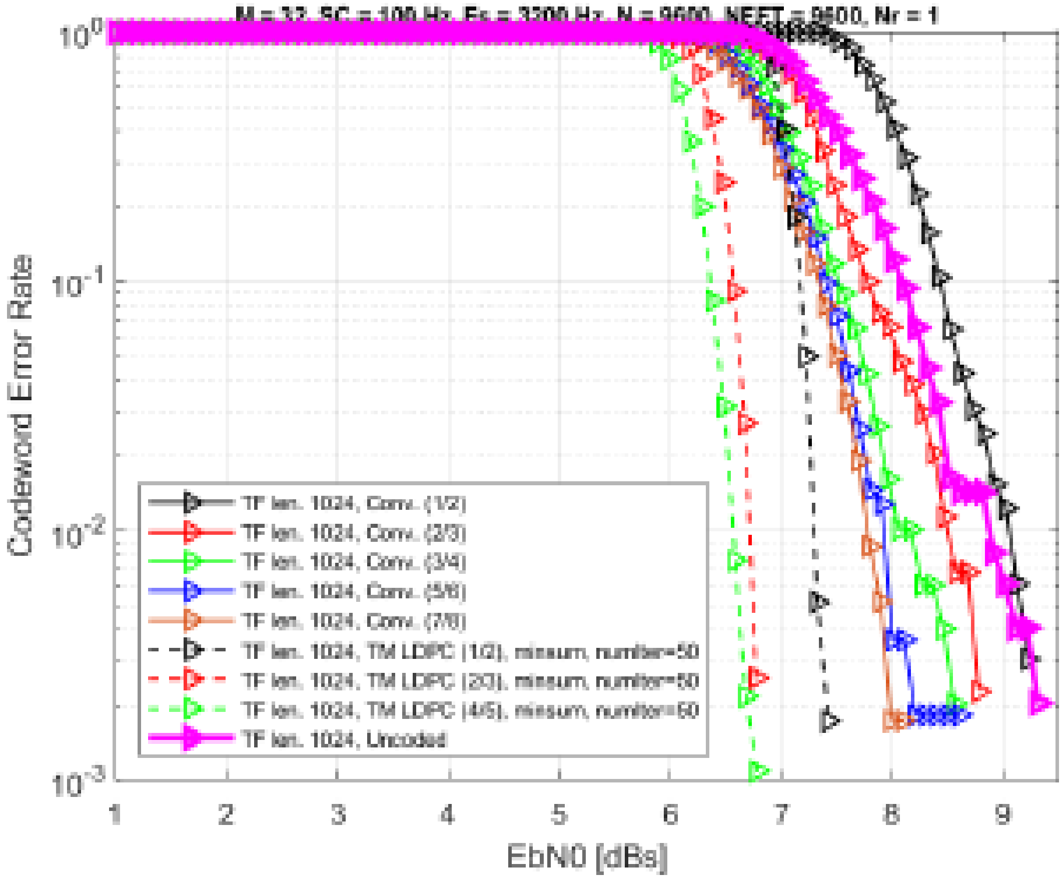
[J. Gómez-Vilardebó, X. Mestre, M. Navarro, J. F. Sevillano, R. Abelló and J. Quintanilla, "Non-Coherent Receiver Design for MFSK Modulations in Deep Space Missions,"]

ESA MFSK study - preliminary results

- Analysis focused on LDPC and convolutional, otherwise frames too long
  - Shortest LDPC frame with k=1024, r=4/5 → 1344 symbols
    - 45 min at 0.5 sps (safe mode)
    - 7.5 min at 3 sps (EDL)
    - 21 s at 63 sps (solar conjunction X-band)
  - Shorter frames possible with convolutional, but worse performance

- End-to-end simulations including coding are intensive for current Matlab-based simulator, preliminary results based on **reduced scenario**:

	Optimised scenario for safe mode	**Reduced scenario**
M	128	**32**
T_S	~14 s	**3 s**
N_{FFT}	~600000	**9600**
N_W	3	**1**
N_R	201	**1**



- ➢ Far from results for AWGN, coherent (130.1-G)
- ➢ LDPC better than convolutional (for same length)
- ➢ Higher code rates are better!
  - ➢ LDPC 4/5 would be selected for this case
- More representative results expected at end of study

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Way forward

- Wait for final results of ESA study… Fall 2023 or Spring 2024

- RFM WG position on adding MFSK to 401.0-B?
  - Only downlink or also uplink?
  - Should "beacon tones" also be included? (simpler version of MFSK)

- Coding and upper layers?
  - If no TM frames, should CCSDS define a new format for "very low rate information"?
  - Or investigate other codes outside 131.0-B?

References

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- Dutta S, Soriano M, Optimizing Multiple Frequency-Shift Keying during Spacecraft Critical Events for Future Missions. *IEEE Aerospace Conference*, 2019
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- X. Mestre, J. Gómez, M. Navarro, J. F. Sevillano, R. Abelló and J. Quintanilla, "Non-coherent Receivers for Low Data Rate Transmissions under Weak Solar Scintillation," *2022 9th International Workshop on Tracking, Telemetry and Command Systems for Space Applications (TTC)*, Noordwijk, Netherlands, 2022
- Ongoing ESA-funded study, contracted to CTTC and Ceit (Spain) "Multiple Frequency-Shift Keying Modem for Very Low Data Rates"