Design and Implementation of an Adaptive Data Rate LoRa Modem for LEO Satellites Using SDR and GNU Radio

PLAN-S SATELLITE AND SPACE TECHNOLOGIES

THE FREE & OPEN SOFTWARE RADIO ECOSYSTEM

European GNU Radio Days 2024
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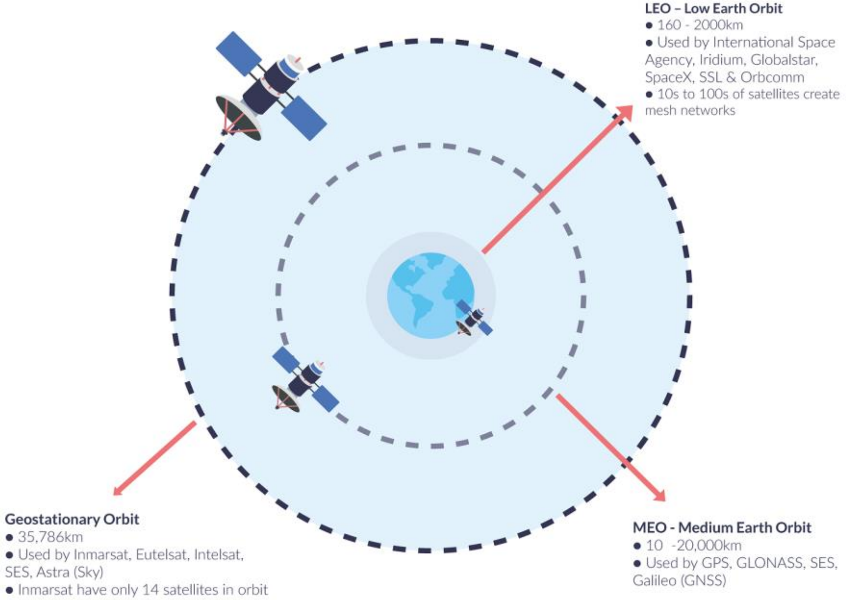
Outline

- LEO Satellites and IoT Applications
- LoRa Receiver and Transmitter Waveform Structure
- LoRa Waveform Properties
- LoRa Sensitivity Values and Data Rates
- LoRa Adaptive Data Rate Algorithm
- Link Budget Computation
- LEO Channel Model
- LoRa PER Performance and Doppler Robustness
- LoRa Waveform Parameter Estimation and Results
- Adaptive LoRa Modem GNU Flow
- Results
- Conclusion
- Plan-S Satellites and IoT Products

LEO Satellites and IoT Applications

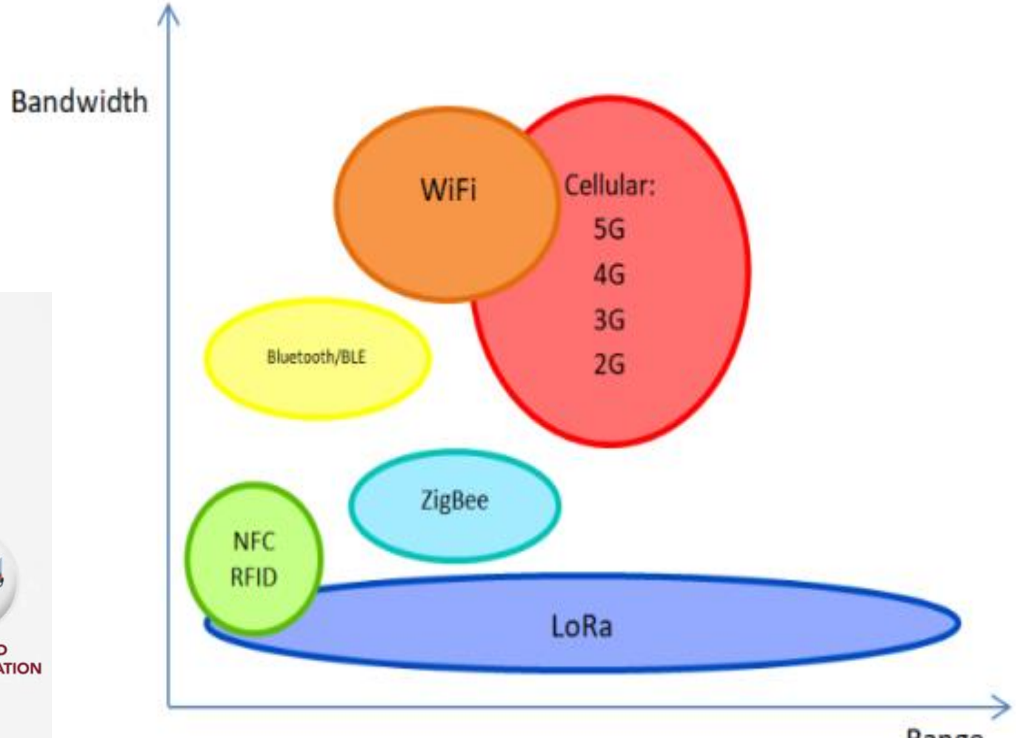


https://www.groundcontrol.com/blog/from-leo-to-geo-exploring-the-different-types-of-satellite-iot/

LoRa (Long Range) Advantages:

- High Doppler Frequency Robustness
- Low Data Rate

- Low Power Consumption
- Long Range
- Low Cost
- Multipath Resistant



https://sii.pl/blog/en/communication-over-lora-m2m-case-using-ra-01/

Purposes:

- Communications
- Earth observation
- IoT services etc.

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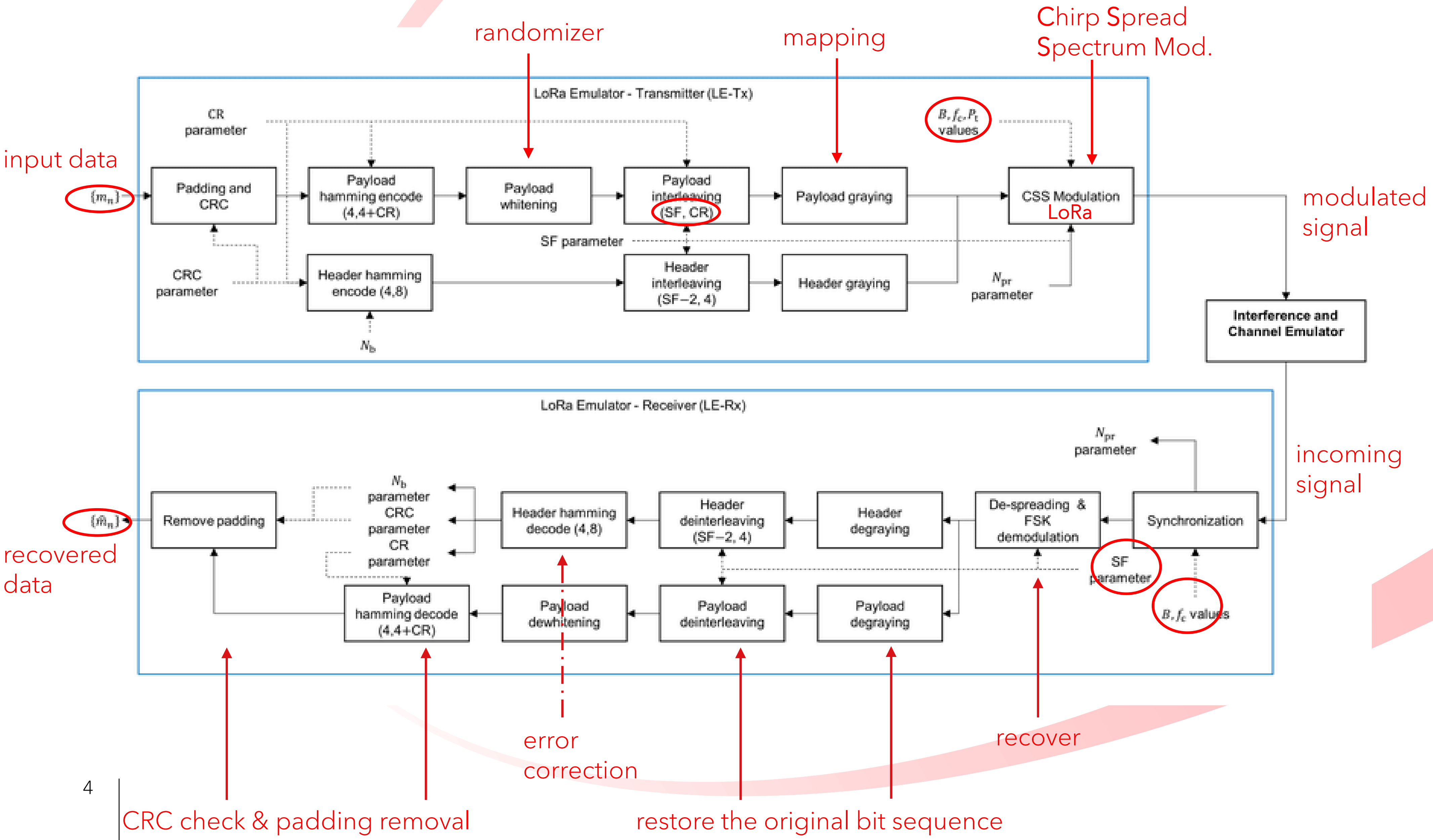
LoRa Receiver and Transmitter Waveform Structure



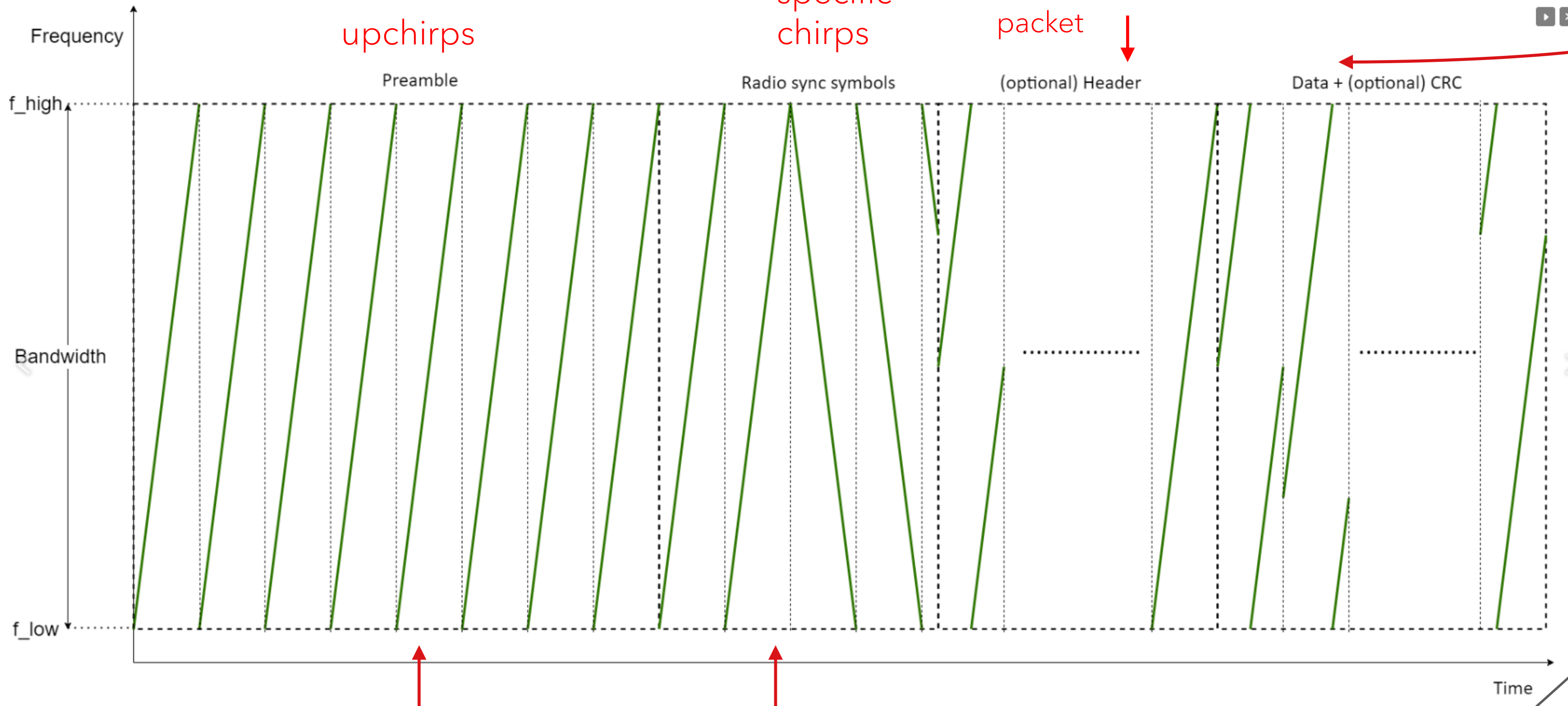
LOng RAnge (LORA) Waveform Parameters (1)

upchirps

specific chirps

contains the metadata about the packet

actual user data



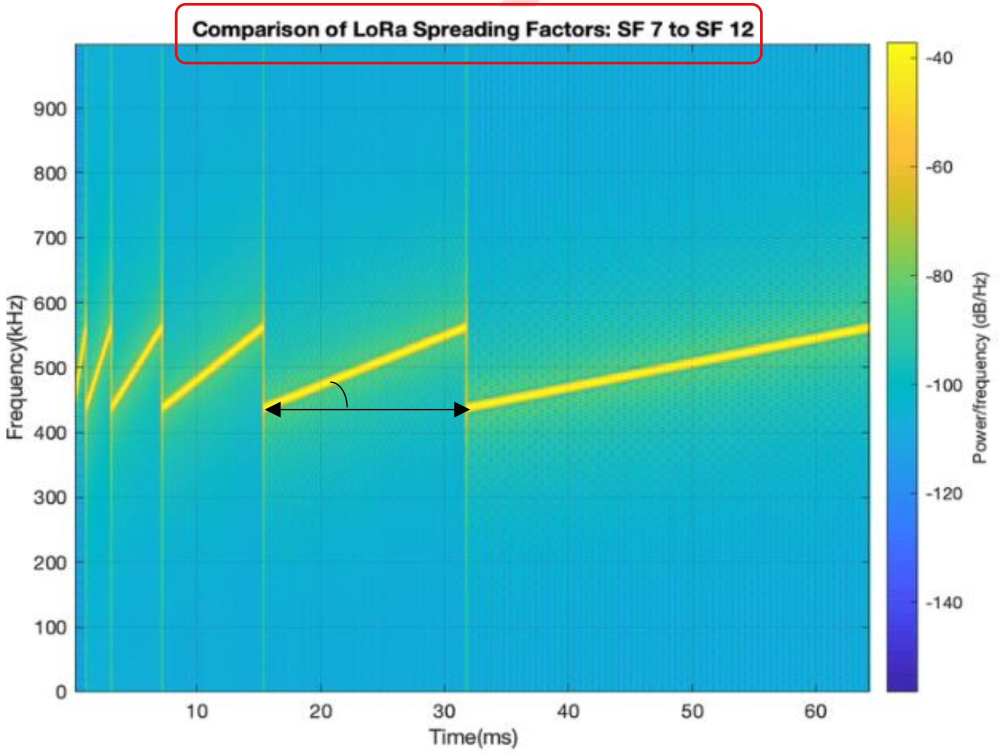
detect start of a new packet

to synchronize

*Number of symbols used to represent each bit of data
*High SF for weak signals

- Spreading Factor (SF) 7 to 12
- Bandwidth (BW) 125 KHz, 250 KHz, 500 KHz
- Coding Rate (CR) 4/5 … 4/8
- Preamble Length (Min 8)

LOng RAnge (LORA) Waveform Parameters (2)

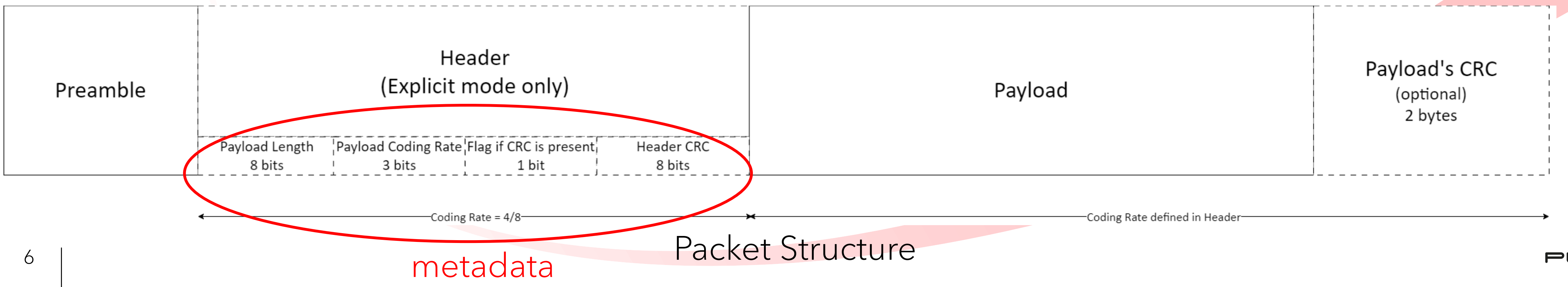


As SF increases:
- Chirp duration increases
- Data rate decreases
- Communication range increases

Symbol Period $T_s = \frac{2^{SF}}{BW}$ secs

Coding Rate $C_R = \frac{4}{4+CR}$, CR:1,2,..4

Data Rate $R_b = SF * \frac{C_R}{T_s}$, $bits/sec$



Packet Structure

LoRa Sensitivity Values and Data Rates

- Sensitivity
- Configurable parameters
  - SF and BW
- SF ranges from 7 to 12
  - Sensitivity increases
  - Data rate decreases
- Higher SF values spread the signal over time (duration):
  - improving sensitivity but
  - lowering data rate

Spreading Factor (SF)	Bandwidth (BW)	Sensitivity (dBm)	Data Rate (bps)
7	125 kHz	-120	5,469
7	250 kHz	-117	11,338
7	500 kHz	-114	22,676
8	125 kHz	-123	3,125
8	250 kHz	-120	6,250
8	500 kHz	-117	12,500
9	125 kHz	-126	1,563
9	250 kHz	-123	3,125
9	500 kHz	-120	6,250
10	125 kHz	-129	781
10	250 kHz	-126	1,563
10	500 kHz	-123	3,125
11	125 kHz	-132	391
11	250 kHz	-129	781
11	500 kHz	-126	1,563
12	125 kHz	-135	195
12	250 kHz	-132	391
12	500 kHz	-129	781

LoRa Sensitivity Values and Data Rates

- Sensitivity
- Configurable parameters
  - SF and BW
- Higher BW allows high data rate but requires more power.

Spreading Factor (SF)	Bandwidth (BW)	Sensitivity (dBm)	Data Rate (bps)
7	125 kHz	-120	5,469
7	250 kHz	-117	11,338
7	500 kHz	-114	22,676
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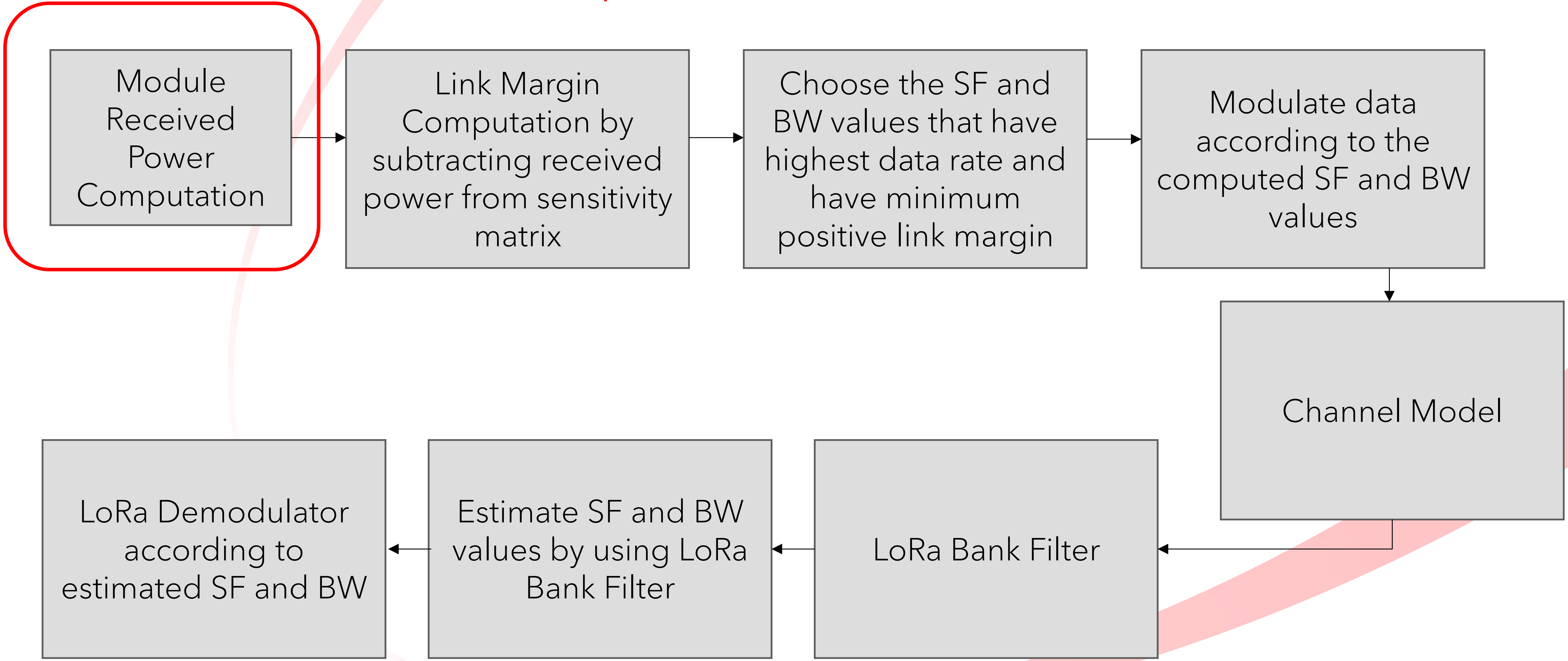
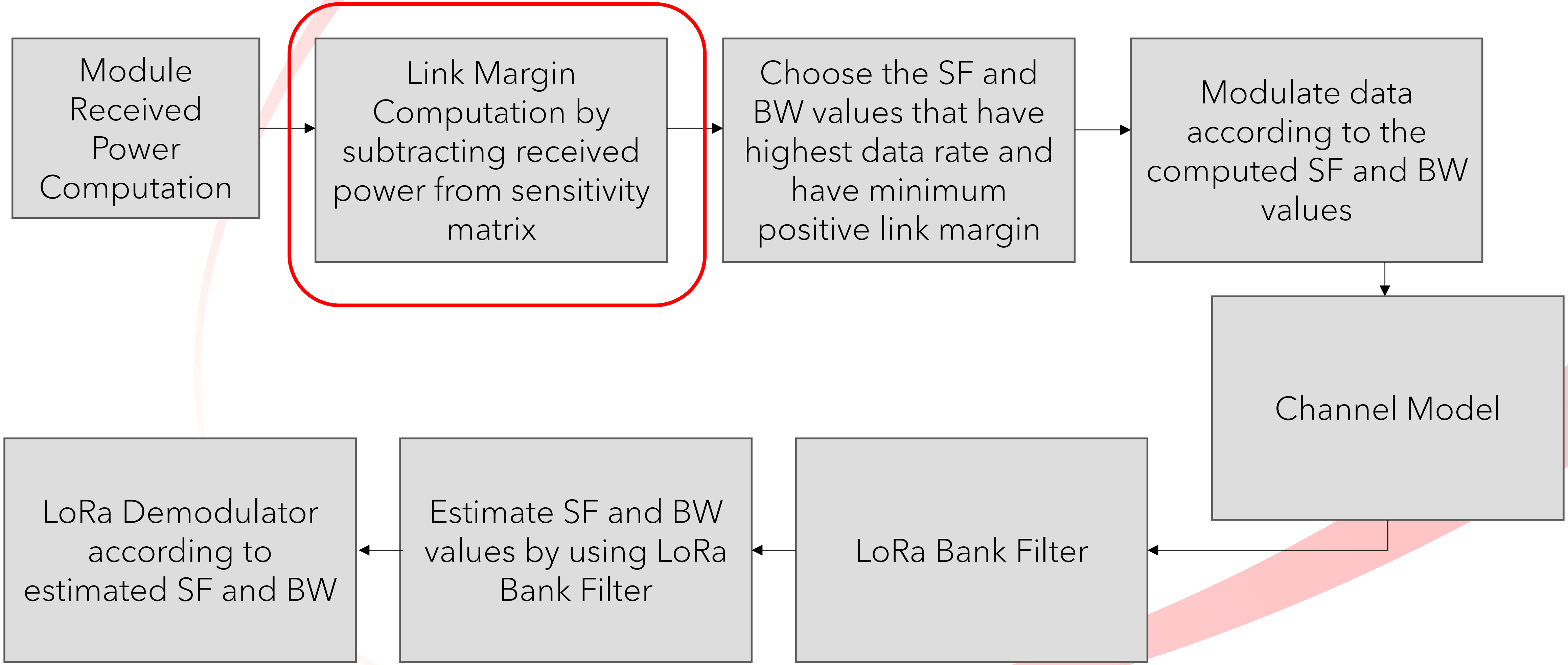
LoRa Adaptive Data Rate Algorithm

Received Power computation at the Module side



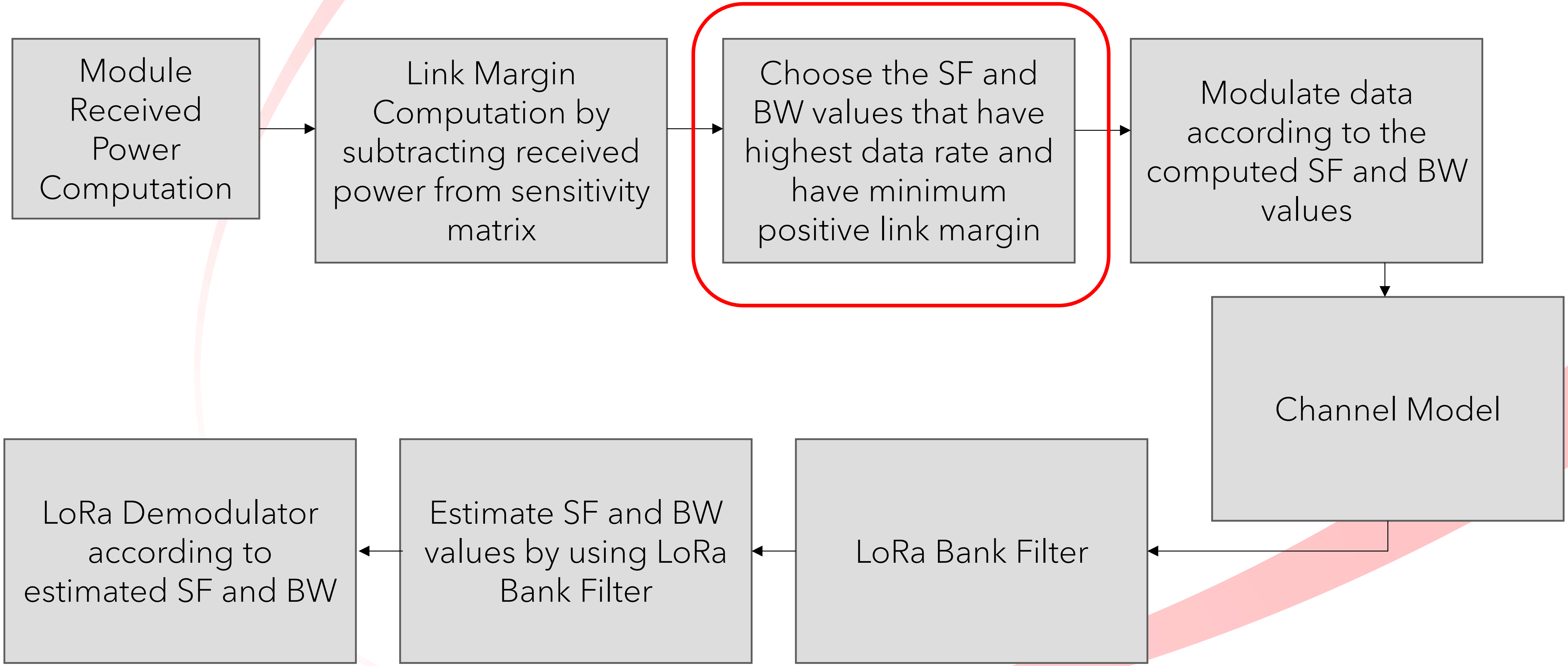
LoRa Adaptive Data Rate Algorithm

Link margin = Sensitivity – Received Power



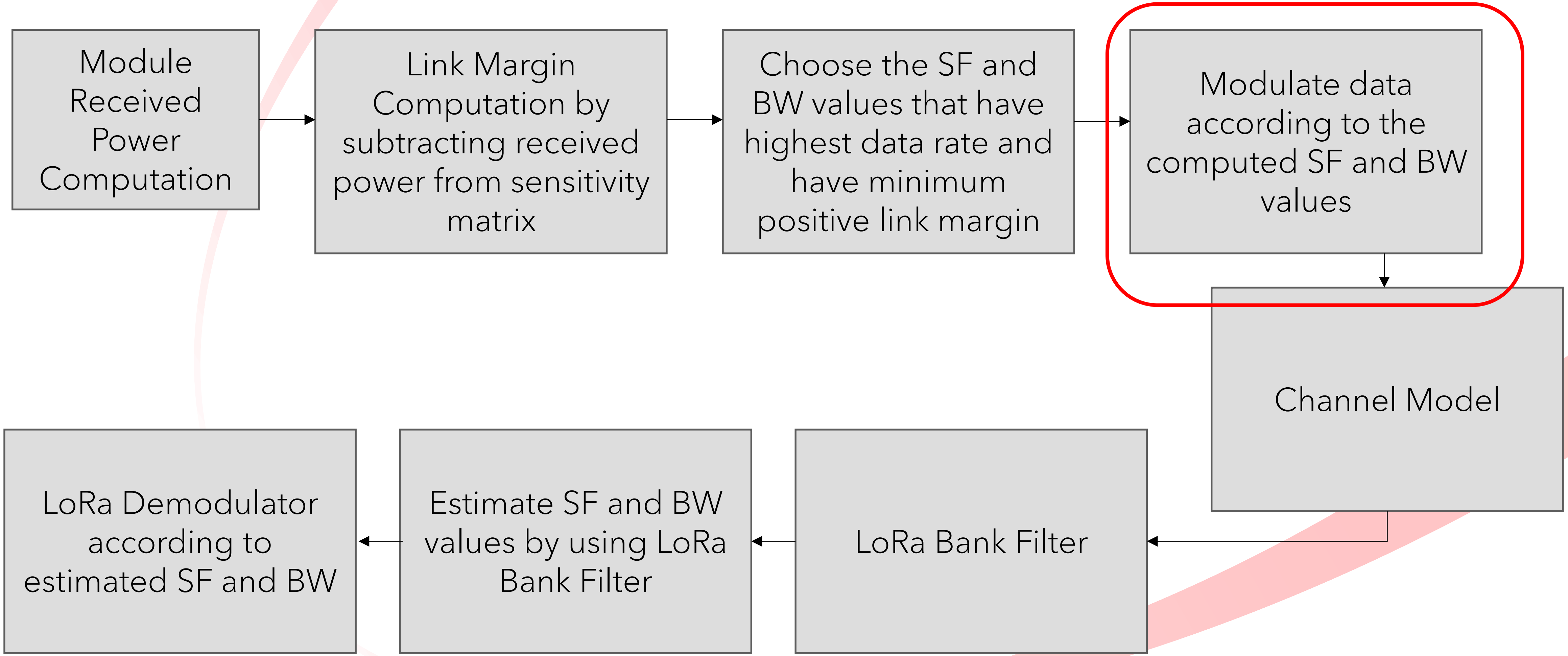
LoRa Adaptive Data Rate Algorithm

Based on link margin, select SF and BW values maximize the data rate while ensuring a positive link margin

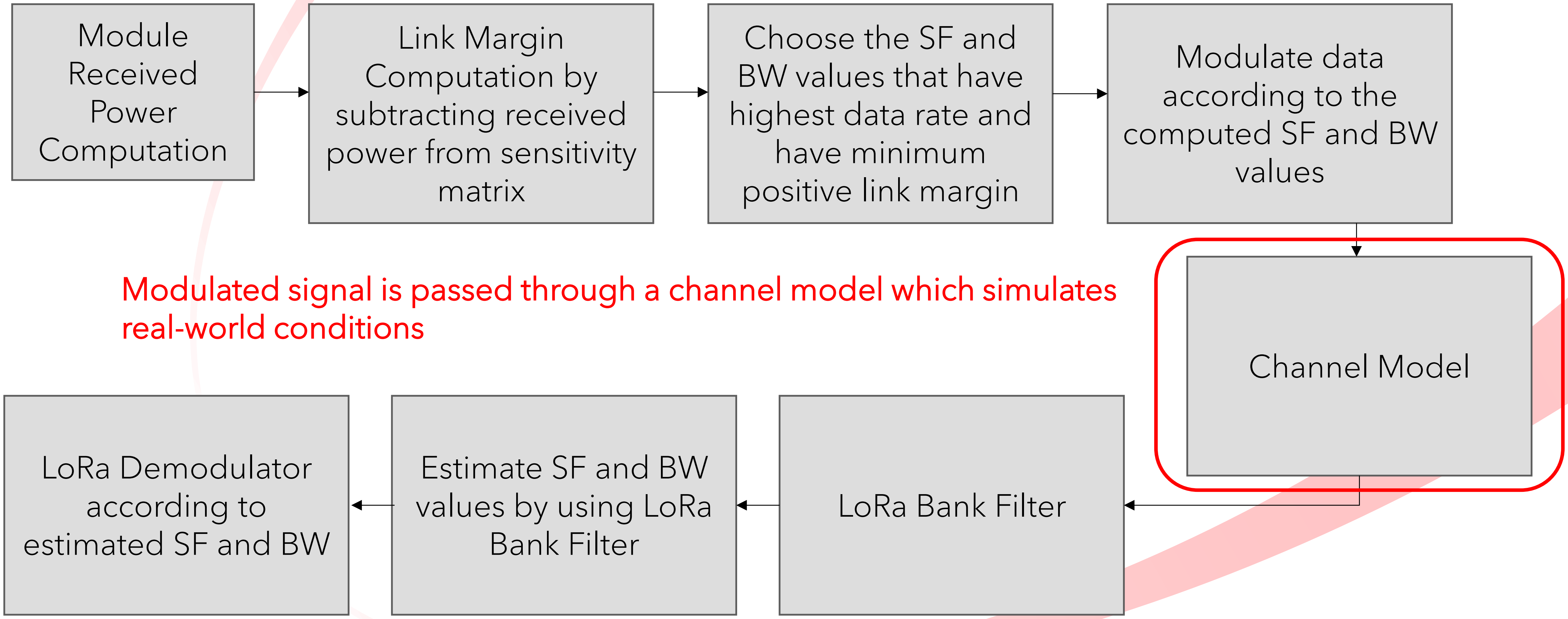


LoRa Adaptive Data Rate Algorithm

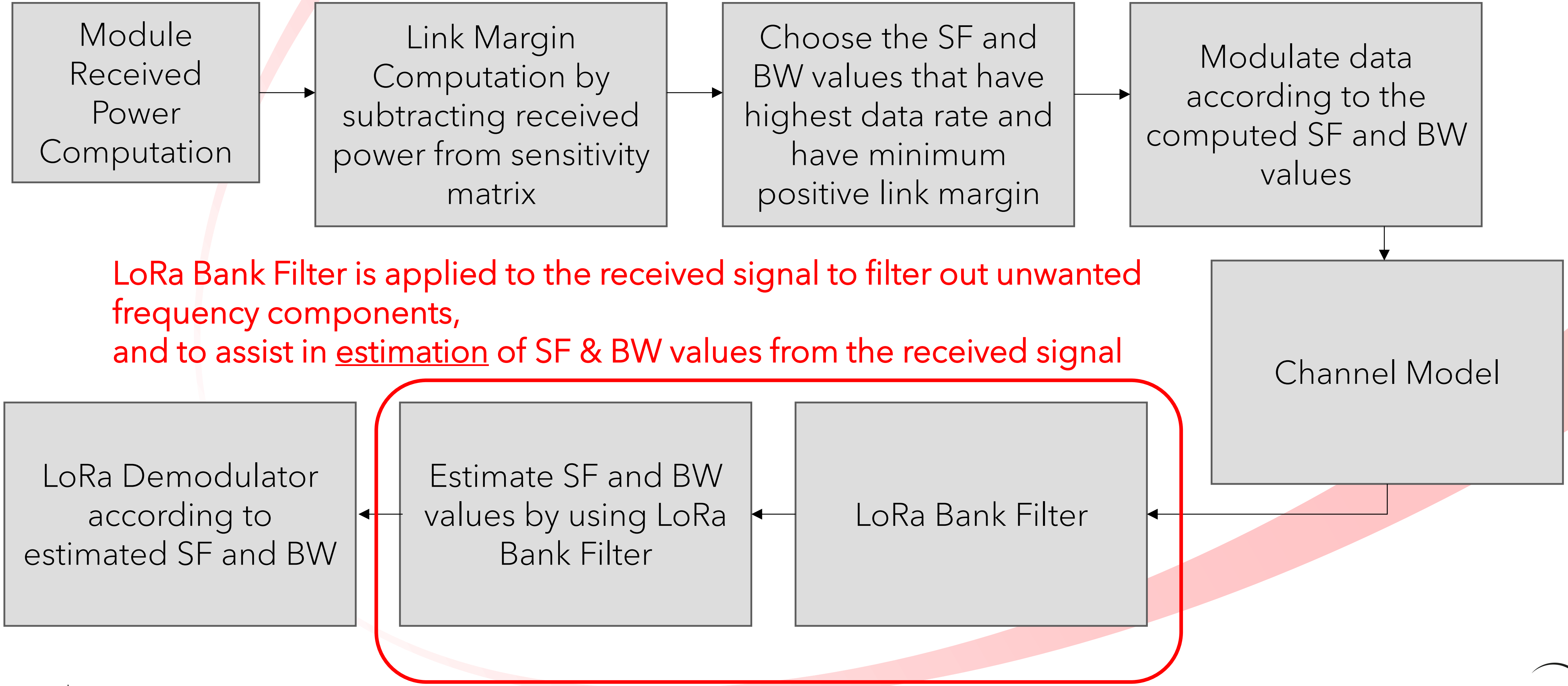
Selected SF and BW values are used to modulate (LoRa) data for transmisson



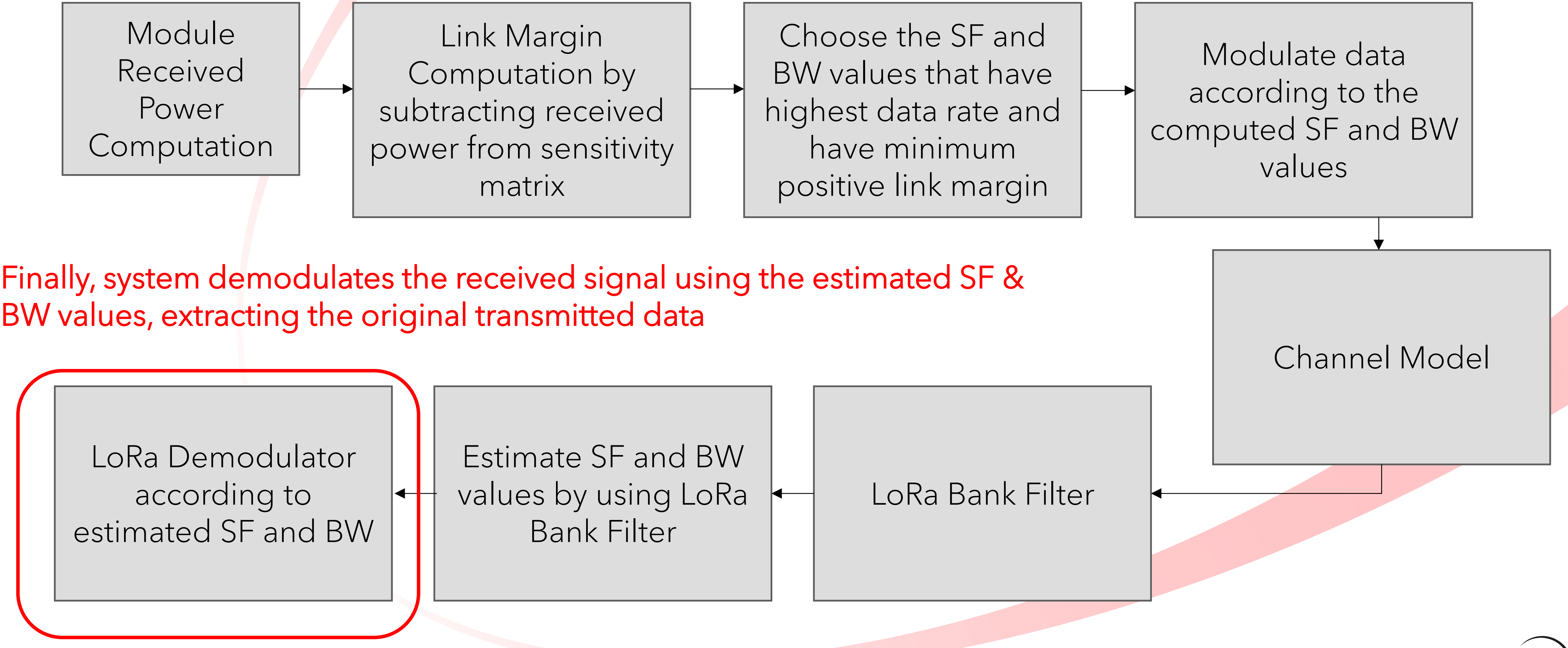
LoRa Adaptive Data Rate Algorithm



LoRa Adaptive Data Rate Algorithm



LoRa Adaptive Data Rate Algorithm



Finally, system demodulates the received signal using the estimated SF & BW values, extracting the original transmitted data

Link Budget Parameters

Parameters

- Satellite Pout: 13 dBm
- Satellite Antenna Gain: Maximum 8dBi @ nadir angle
- Satellite Tx Loss: 0.2 dB

next

- Link Free Space Path Loss (FSPL)
- Atmospheric Loss (ITU P.676-11)
- Ionospheric Loss (ITU-R P.531)

- Module Antenna Gain: Maximum 3dBi @ nadir angle
- Module Rx Loss: 0.4 dB
- Polarization Loss

Inputs

next

- Satellite TLE Data
- Simulation Start Time
- Beacon Period
- Module Latitude Longitude Altitude
- Satellite Antenna Gain CST output file
- Module Antenna Gain CST output file

Outputs

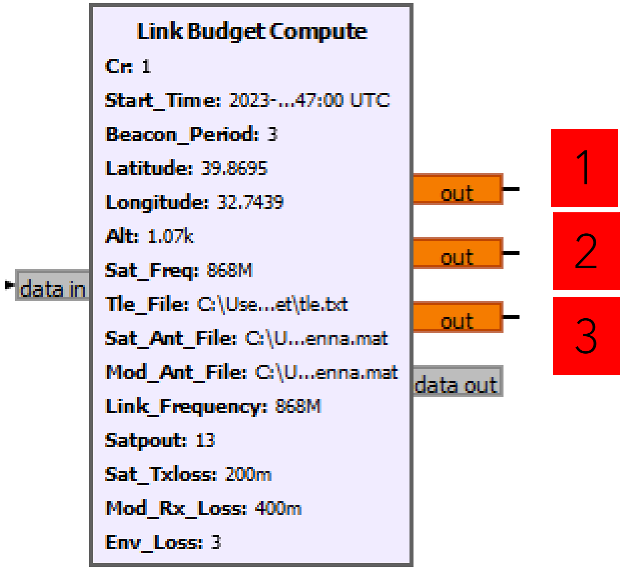
- Free Space Path Loss 1
- Module Received Power in dBm 2
- Doppler Frequency Shifts in Hz 3

PLANS

Link Budget Computations

$$FSPL = \left(\frac{4\pi * d * f_c}{c}\right)^2$$

The developed GNU Radio block uses the inputs, outputs and parameters mentioned in the previous slide



$$Noise\ Floor = 10 * log_{10}(k * T * B * 1000)\ \ (dBm)$$

$$P_{rx}\ (dBm) = P_{tx}(dBm) + G_{sat}(dB) + G_{module}(dB) \underbrace{- FSPL(dB) - L_{atm}(dB) - L_{ion}(dB) - L_{pol}(dB) - L_{env}(dB)}_{\text{Losses}}$$

$$Sensitivity\ (dBm) = Noise\ Floor + NF + SNR_{min}$$

Noise Floor = equivalent noise power (dBm)

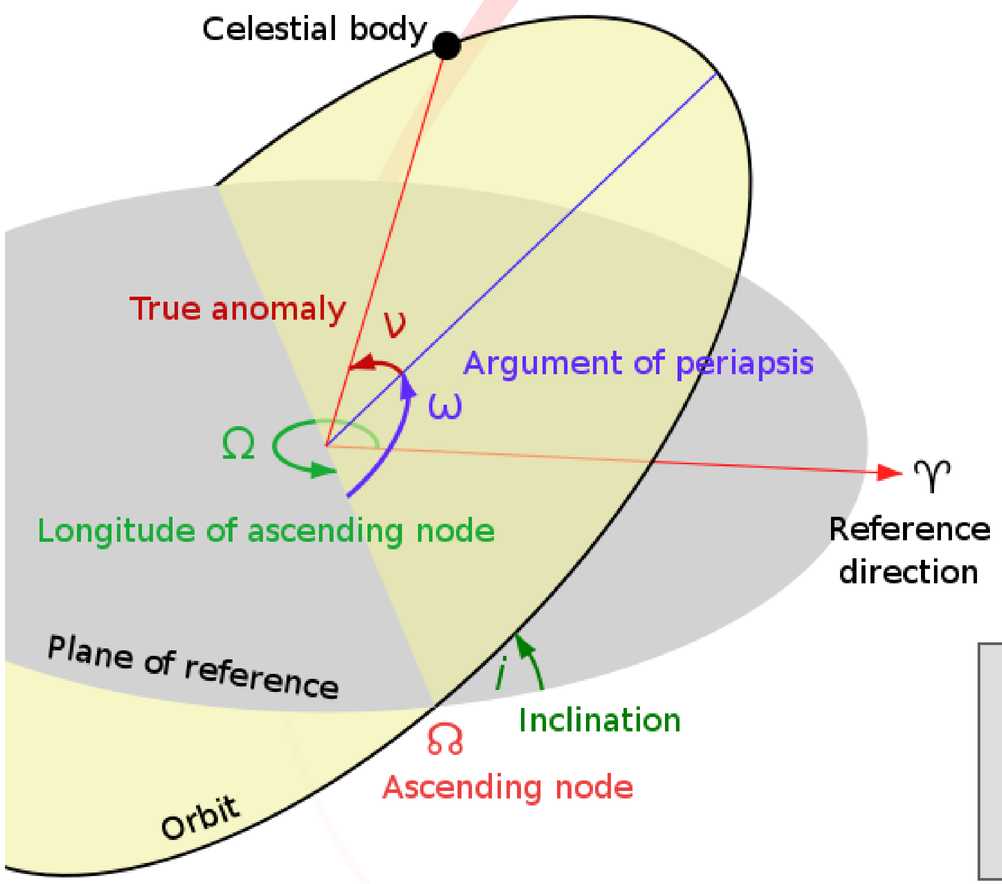
K = Boltzmann's Constant (~1.38 $*10^{-23}$)

T = 293 kelvin ("room temperature")

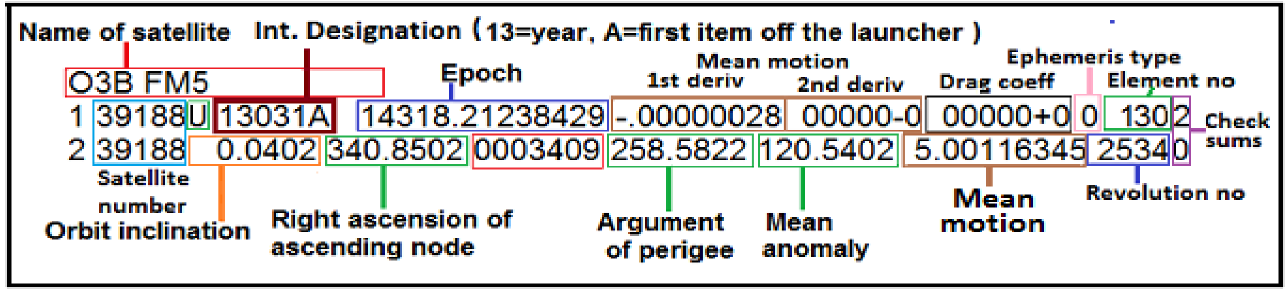
B = channel bandwidth (Hz)

1000 = scaling factor from Watts to milli-Watts

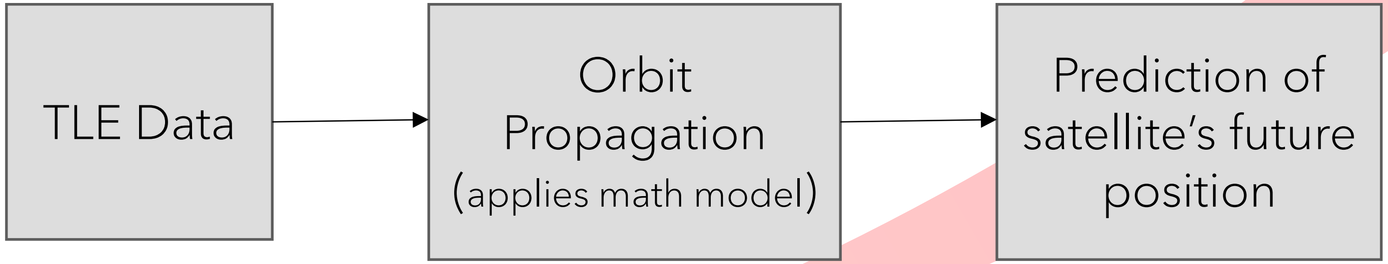
Orbit Propagation



Two Line Element (TLE) Data Format

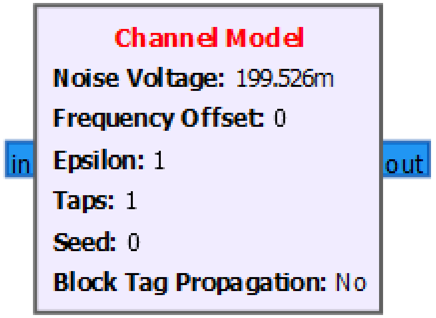


Current Orbital Parameters



GitHub - cubehub/pysattracker: Python library for calculating azimuth, elevation, doppler shift etc for satellite overflights.

Channel Model



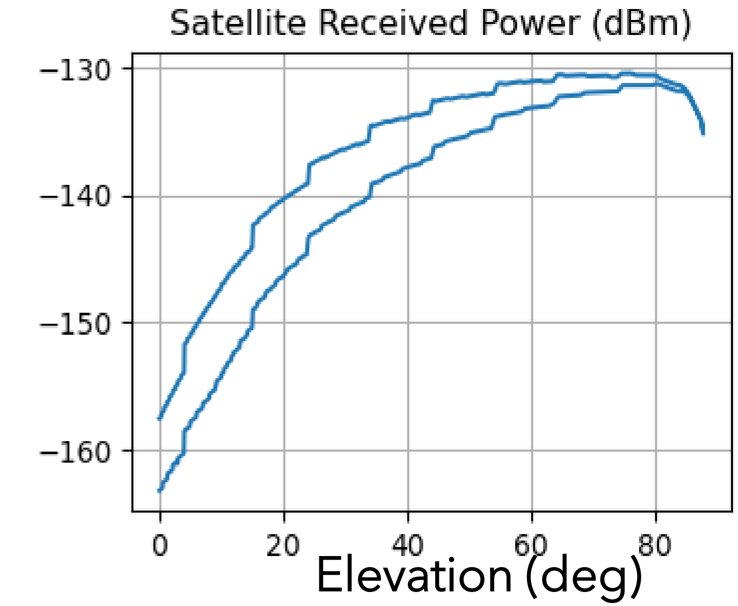
P_{Rx} :Received Power P_n :Noise Power

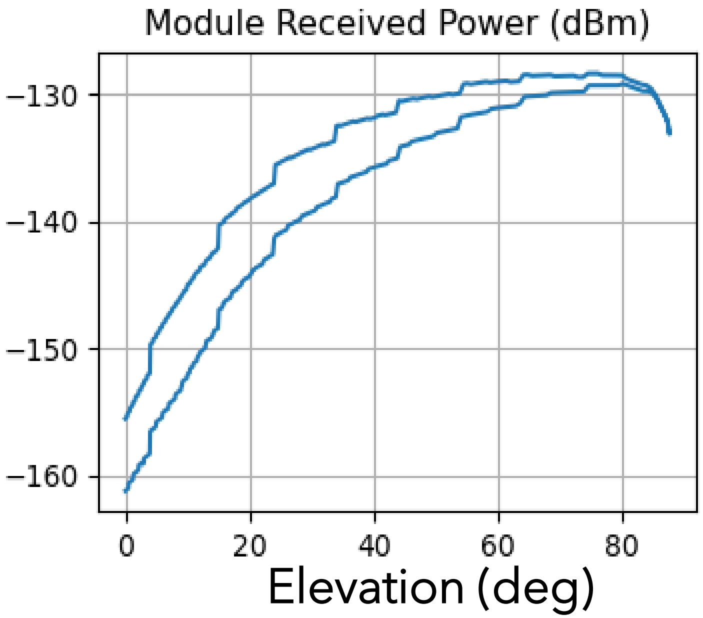
$$SNR = P_{Rx} - P_n \quad (dB)$$

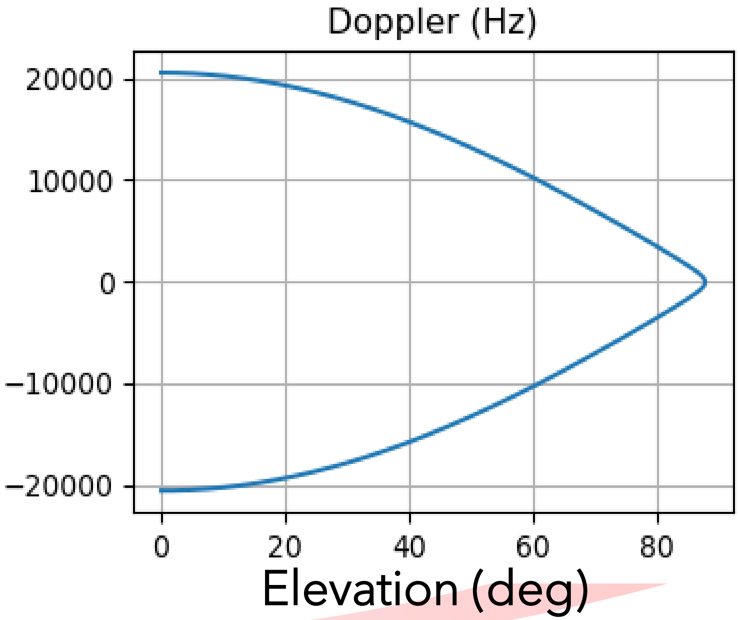
$$Noise\ Voltage = 10^{\frac{-SNR}{20}}$$

$$Clock\ offset = f_d * \frac{10^6}{f_c} \quad (ppm)$$

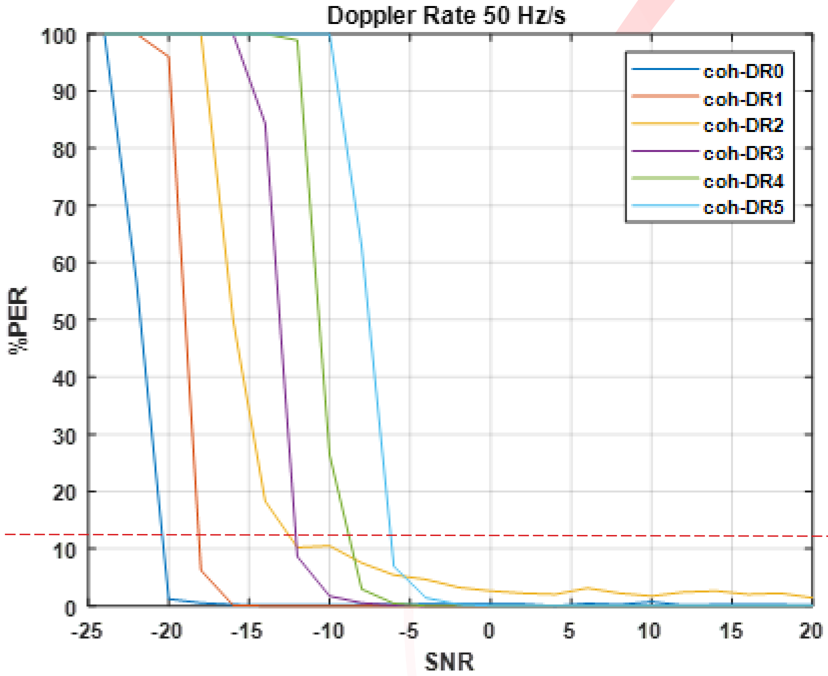
$$Freq\ offset = f_c * Clock\ Offset * \frac{10^{-6}}{f_s}$$

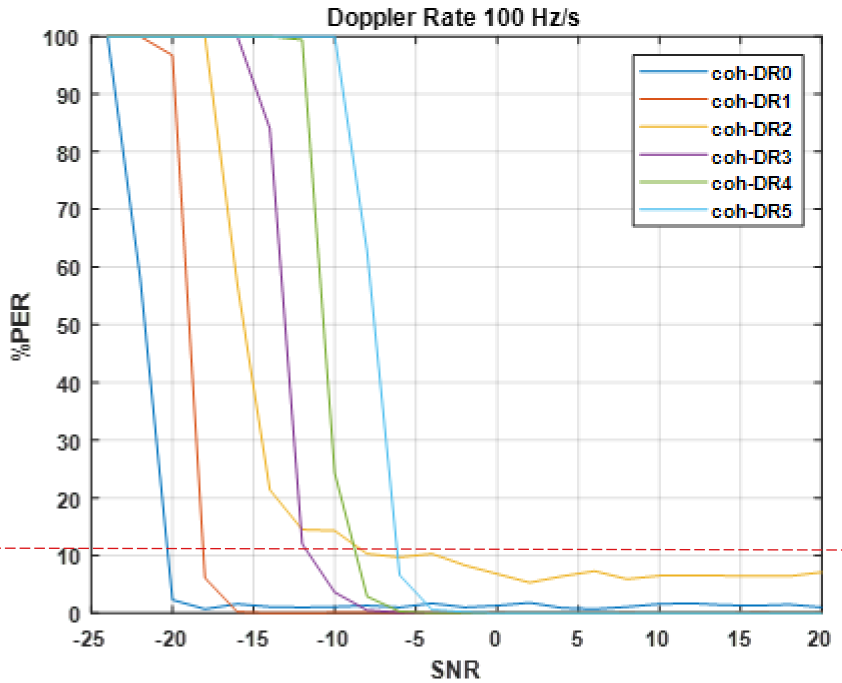


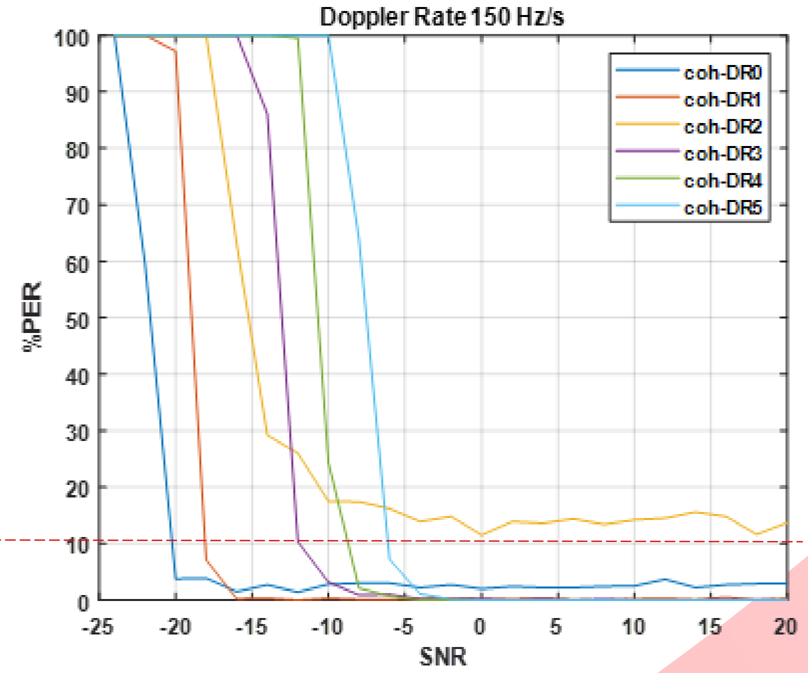




LoRa PER Performance and Doppler Robustness



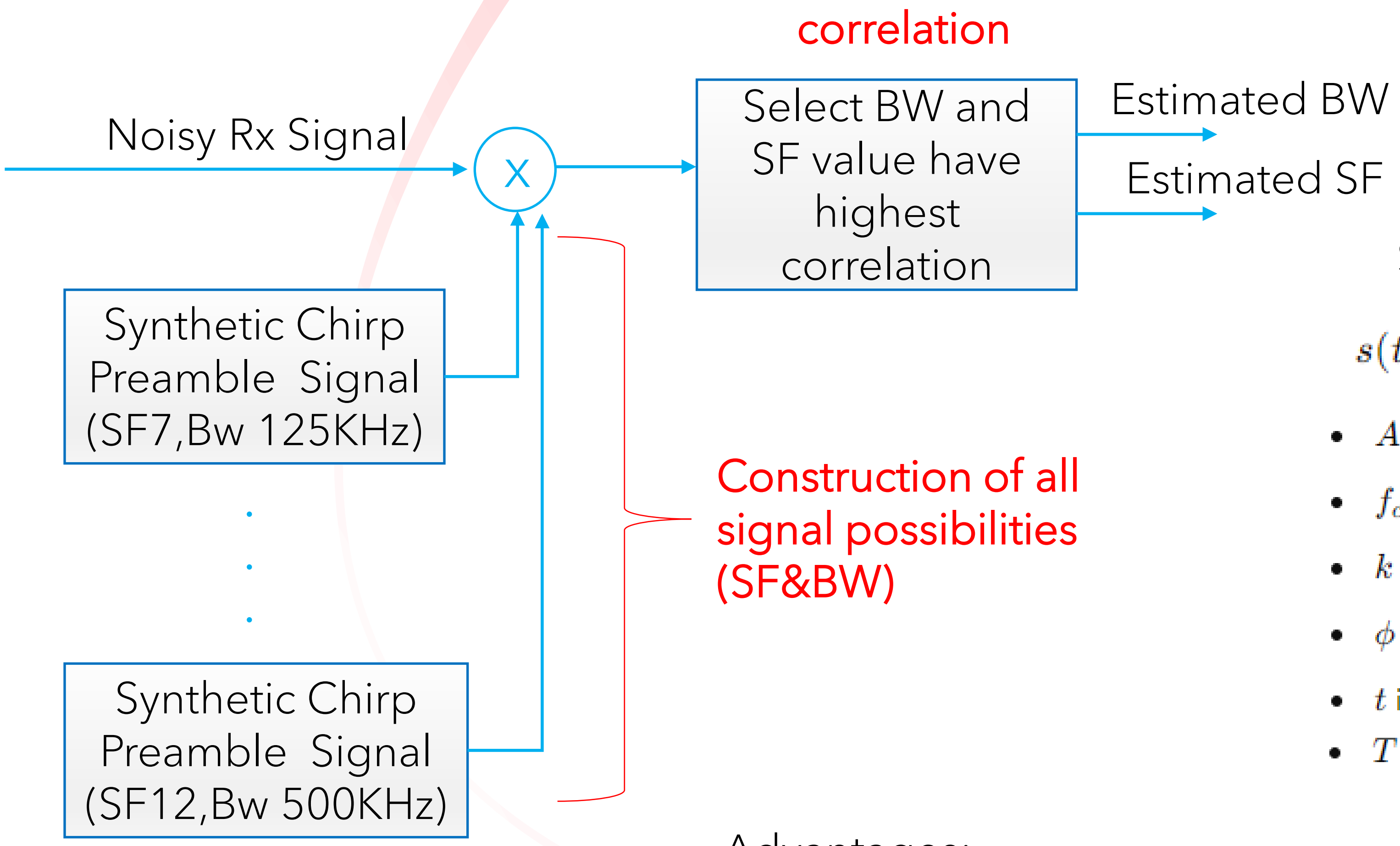




- Chirp Spread Spectrum (CSS) → Data is encoded by varying the frequency of the chirps over time → Tolerancy for frequency variations
Tolerant to Doppler effect
- Wide Bandwidth → Relative frequency shift is smaller compared to narrowband systems → Reduces the impact of Doppler shifts

Low SNR performance in higher SF values

LoRa Waveform Parameter **Estimation Algorithm**



Synthetic Preamble Chirp

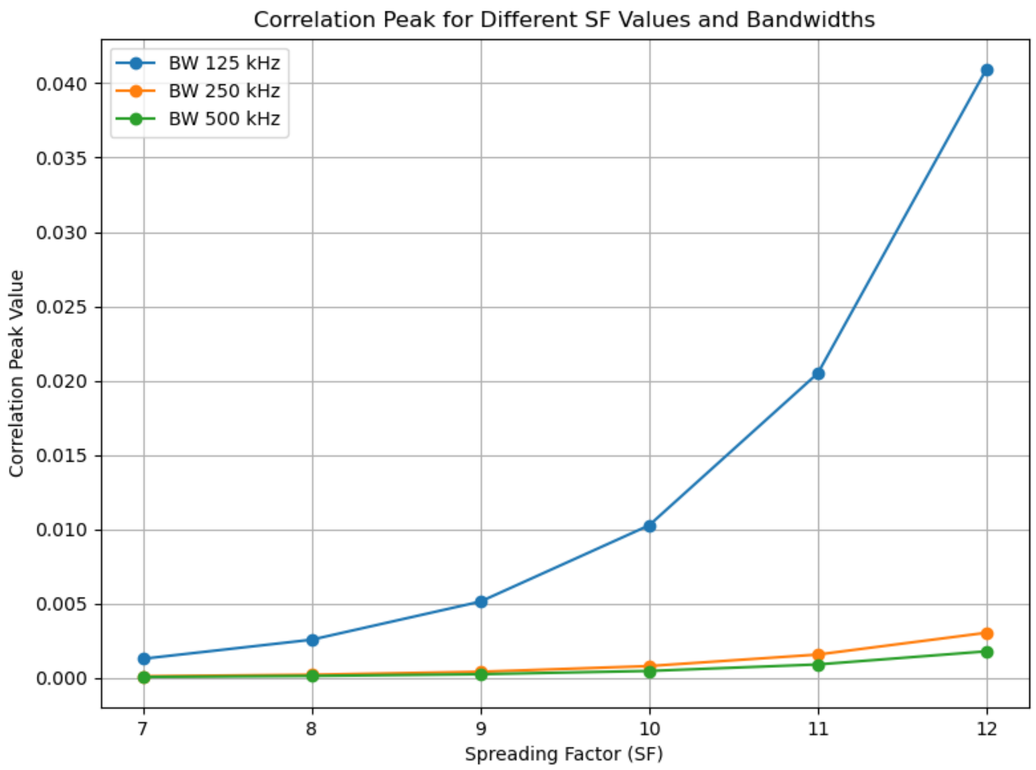
$$s(t) = A \cdot \cos\left(2\pi\left(f_c t + \frac{kt^2}{2}\right) + \phi\right) \qquad k = \frac{\mathrm{BW}}{T}$$

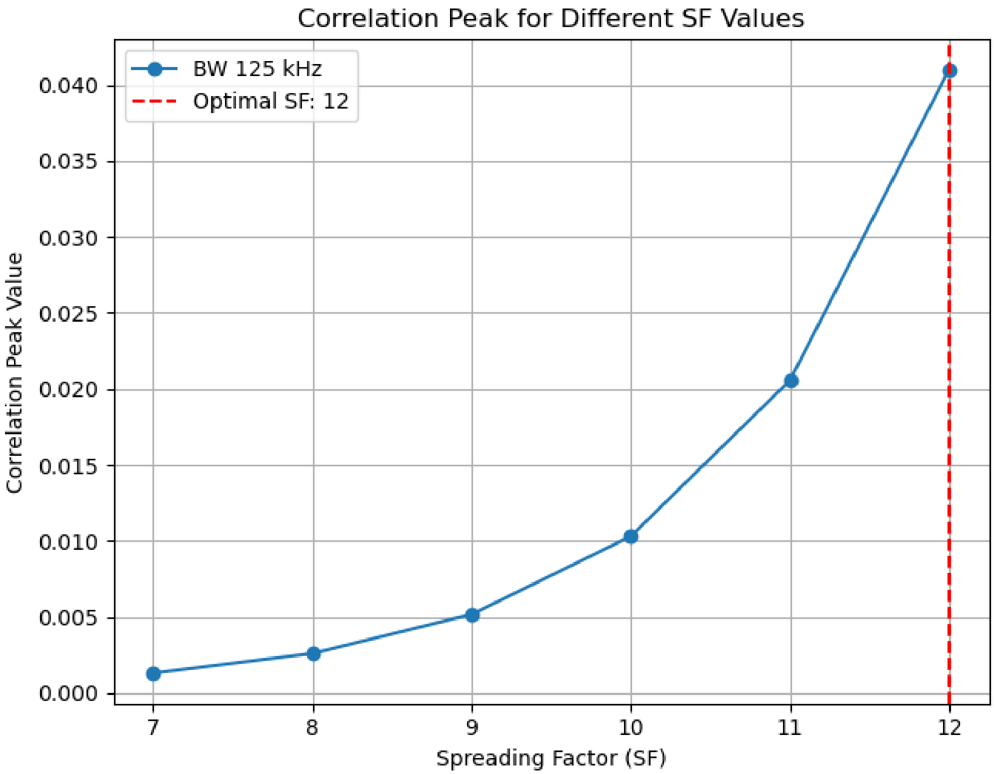
- A is the amplitude of the signal.
- f_c is the carrier frequency.
- k is the chirp rate, which is proportional to the bandwidth.
- ϕ is the phase offset.
- t is the time. $\qquad T = 2^{\mathrm{SF}} \cdot \frac{1}{\mathrm{BW}}$
- T is the duration of one chirp.

Advantages:

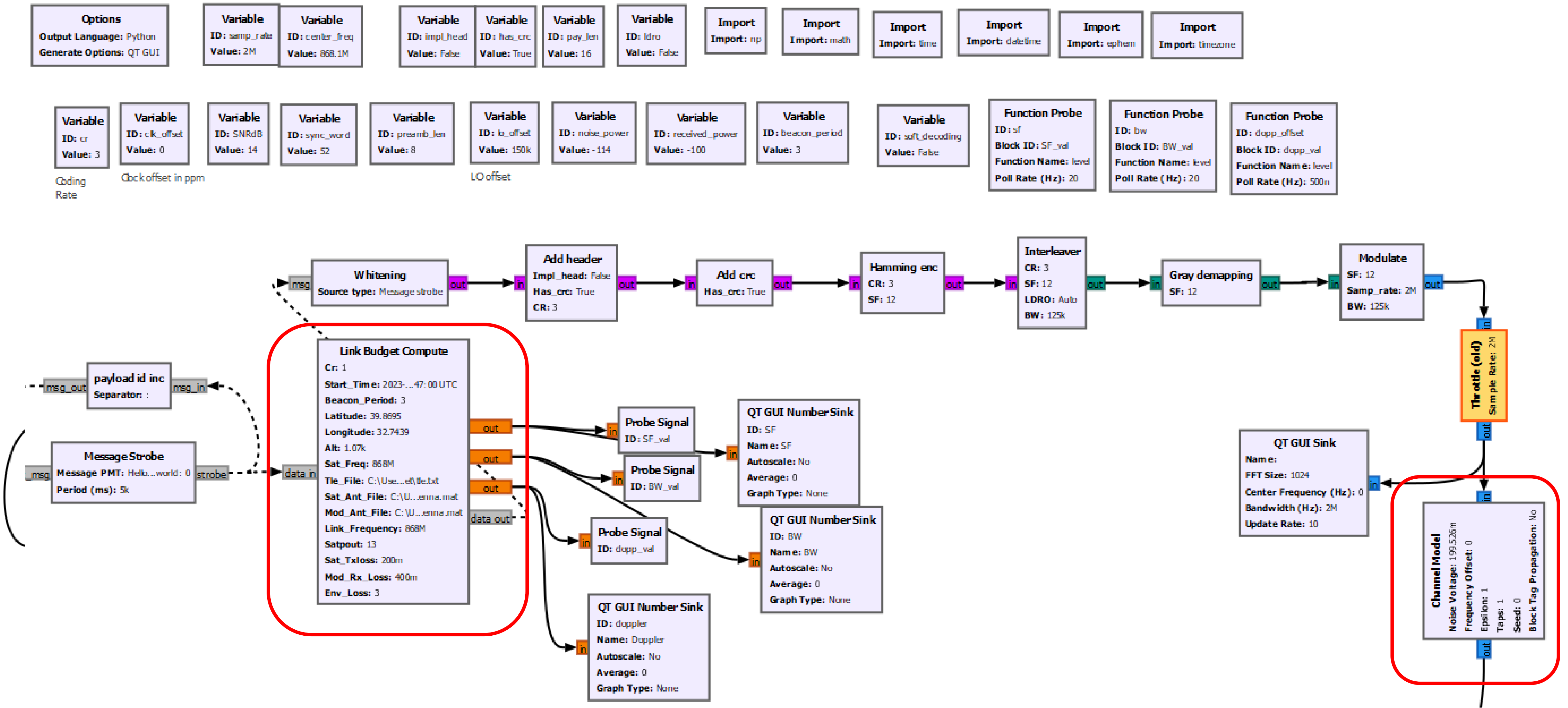
- Robust estimation in low power noisy RX conditions

LoRa Waveform Parameter Estimation Results



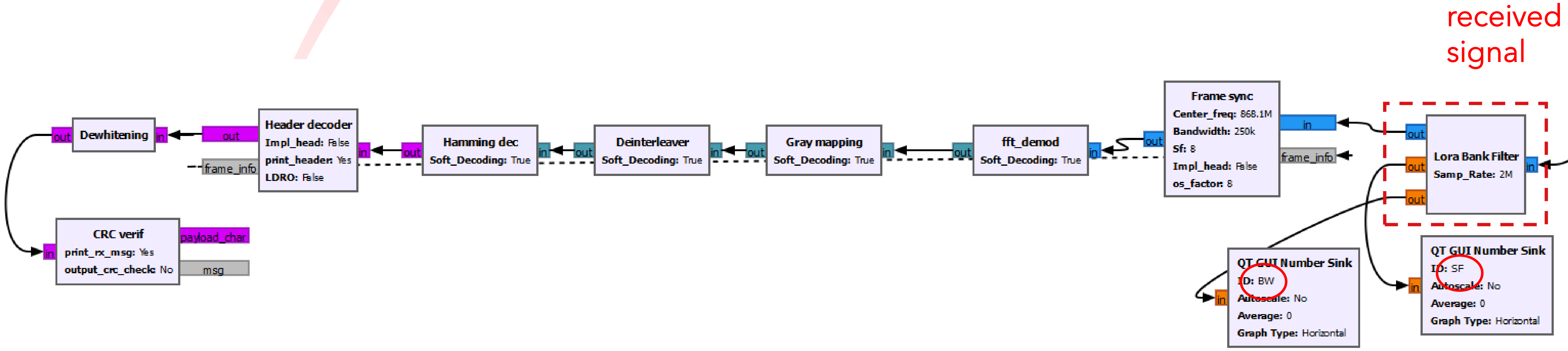


Adaptive Lora Modem GNU Radio Flow (Transmitter)

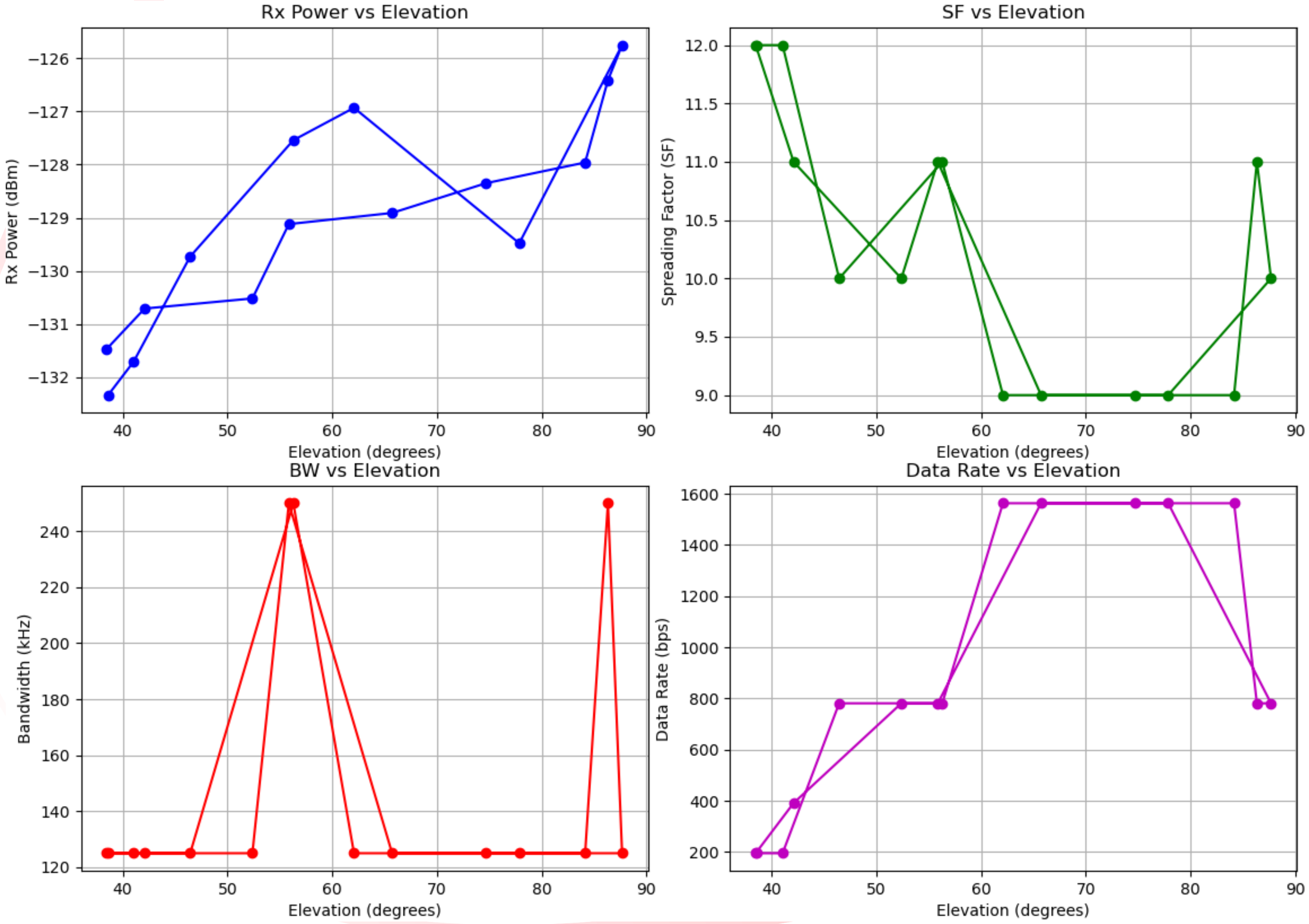


PLANS

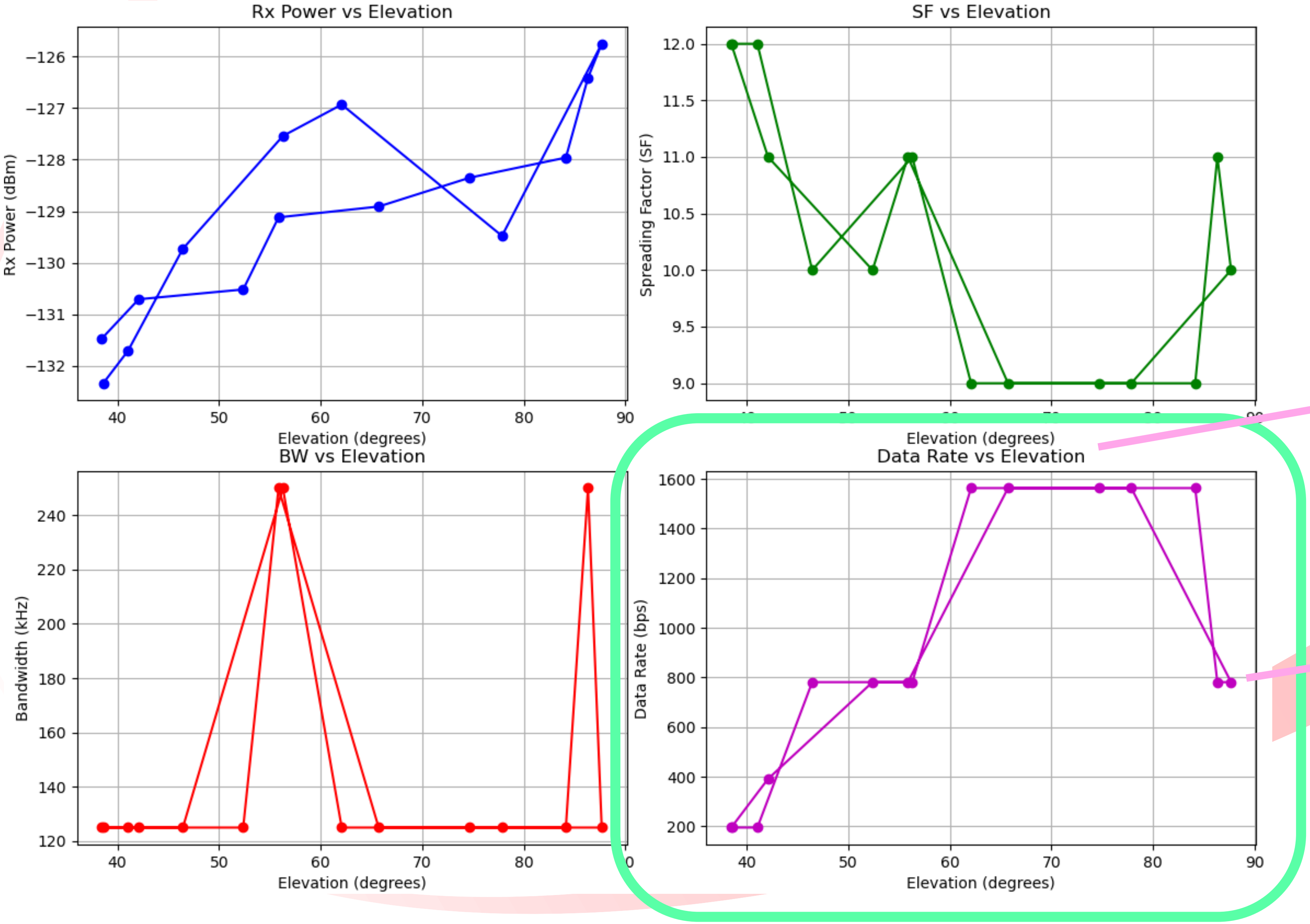
Adaptive Lora Modem GNU Radio Flow (Receiver)



Test Results



Test Results



higher elev. better link conditions

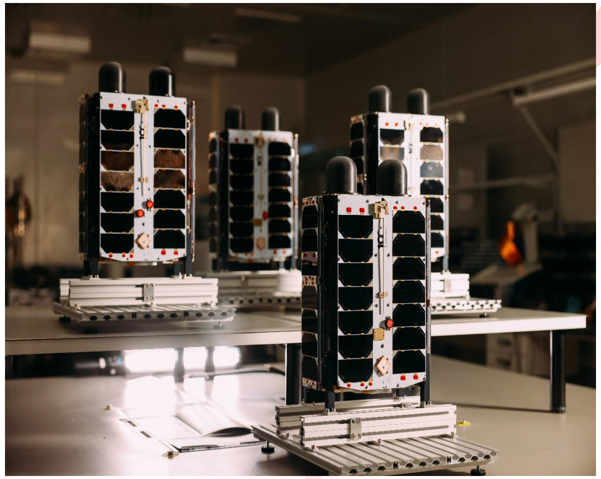
indicates a balance between link reliability and max throughput

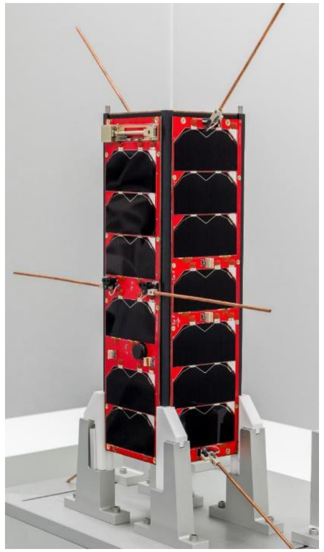
Conclusion

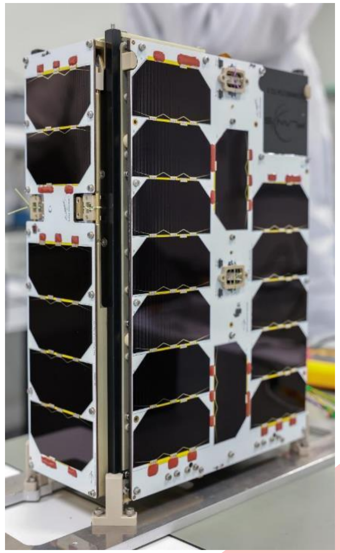
- LoRa PER performance computed according to different satellite scenarios that includes doppler shift, free space loss and noisy environment using GNU Radio and SDR
- LoRa doppler robustness is observed according to simulated satellite passes suitable with the link budget.
- Adaptive data rate mechanism is developed by using LoRa bank filter block and higher data rates can be achieved during a satellite pass.
- As the elevation angle increases, the LoRa system optimizes its parameters, such as decreasing the spreading factor and increasing the data rate, to take advantage of better signal conditions.
- The dynamic adjustment of bandwidth at certain elevations further enhances communication efficiency.
- The system is designed to maximize data throughput and maintain link quality as the satellite or transmitter's elevation relative to the receiver changes.

References

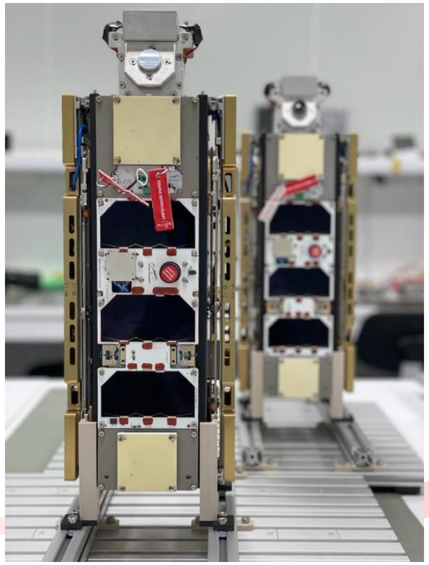
- B. Al Homssi, K. Dakic, S. Maselli, H. Wolf, S. Kandeepan and A. Al-Hourani, "IoT Network Design Using Open-Source LoRa Coverage Emulator," in IEEE Access, vol. 9, pp. 53636-53646, 2021
- Lora Modulation Basics AN1200.22 Semtech Wireless, Sensing and Timing Products, https://www.frugalprototype.com/wp-content/uploads/2016/08/an1200.22.pdf
- J. Tapparel, O. Afisiadis, P. Mayoraz, A. Balatsoukas-Stimming and A. Burg, "An Open-Source LoRa Physical Layer Prototype on GNU Radio," 2020 IEEE 21st International Workshop on Signal Processing Advances in Wireless Communications (SPAWC), Atlanta, GA, USA, 2020, pp. 1-5
- https://github.com/tapparelj/gr-lora_sdr

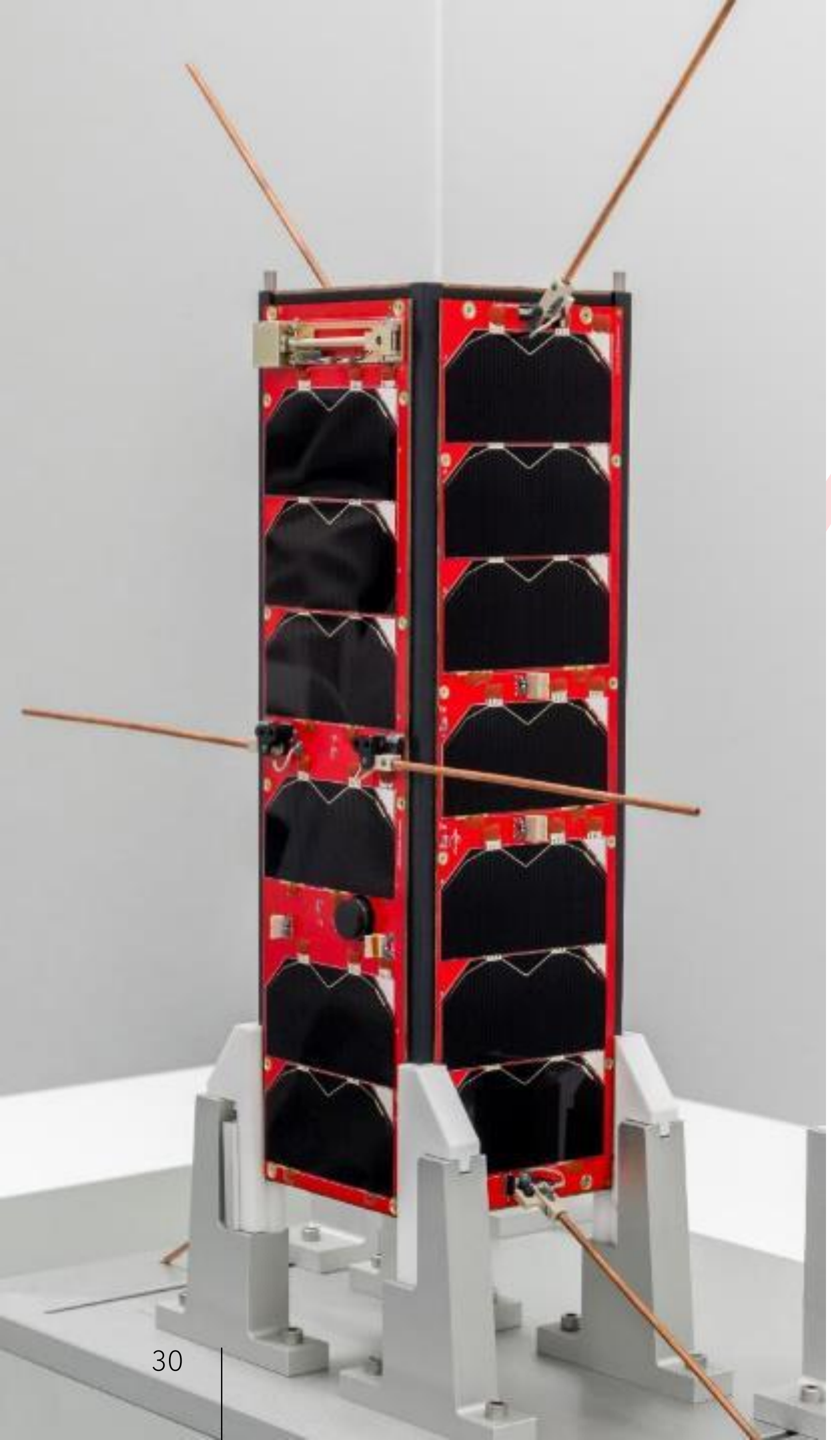






PLAN-S Satellites and IoT Modules





CONNECTA T1.1

Launch	SpaceX, Falcon 9 Transporter 5
Date	25 May 2022
Orbit	SSO
Altitude	550 km
LTDN	13:00

The design, development and verification processes were completed in less than 1 year.

IoT-based communication experiments were conducted.

Subsystems developed within Plan-S gained satellite heritage.

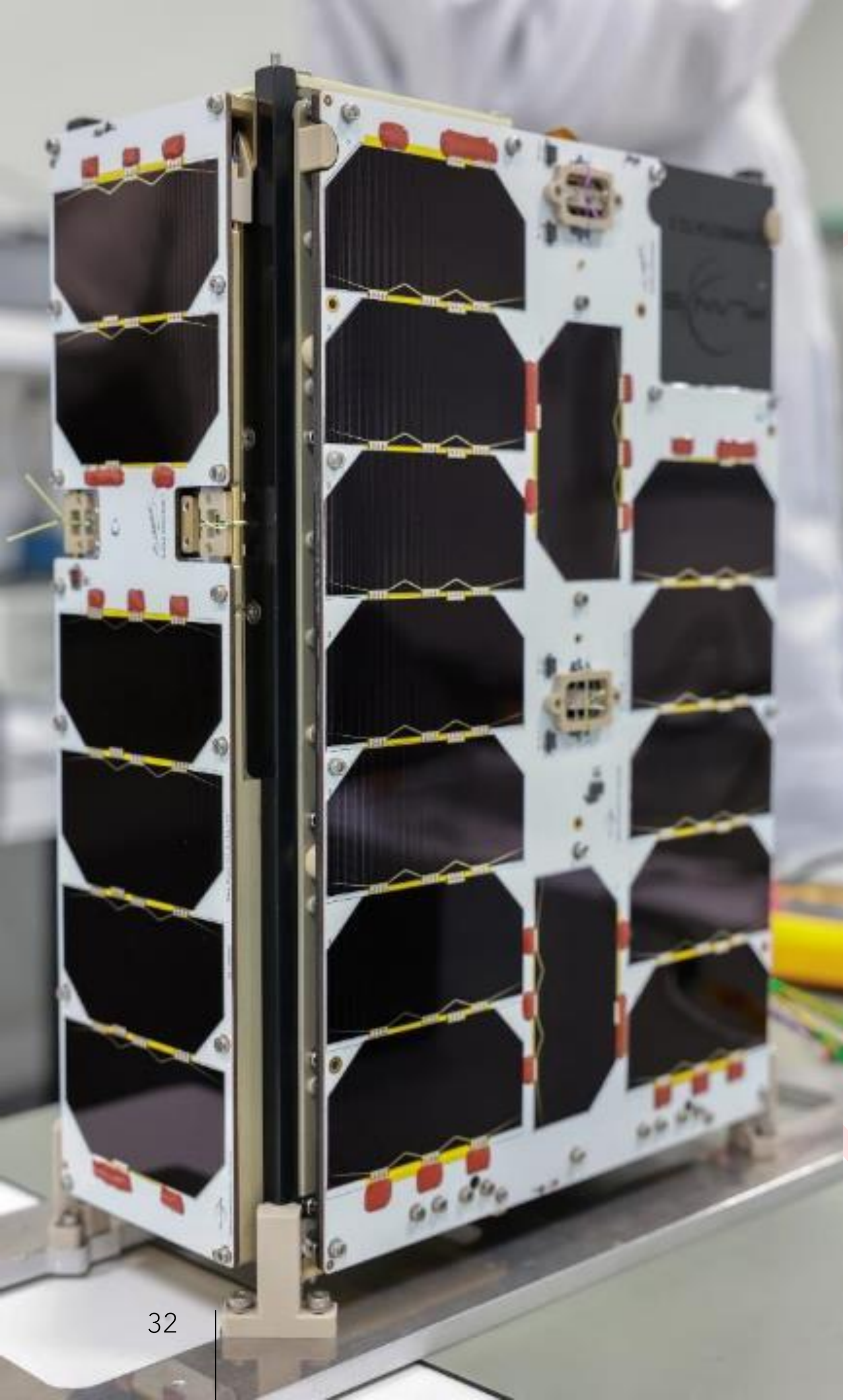
CONNECTA T1.2

Launch	SpaceX, Falcon 9 Transporter 6
Date	3 January 2023
Orbit	SSO
Altitude	550 km
LTDN	09:30

Optimized IoT payload and other subsystems with updates

It is called ‘software-based satellite’

It is sent for the development and testing of Plan-S IoT technology

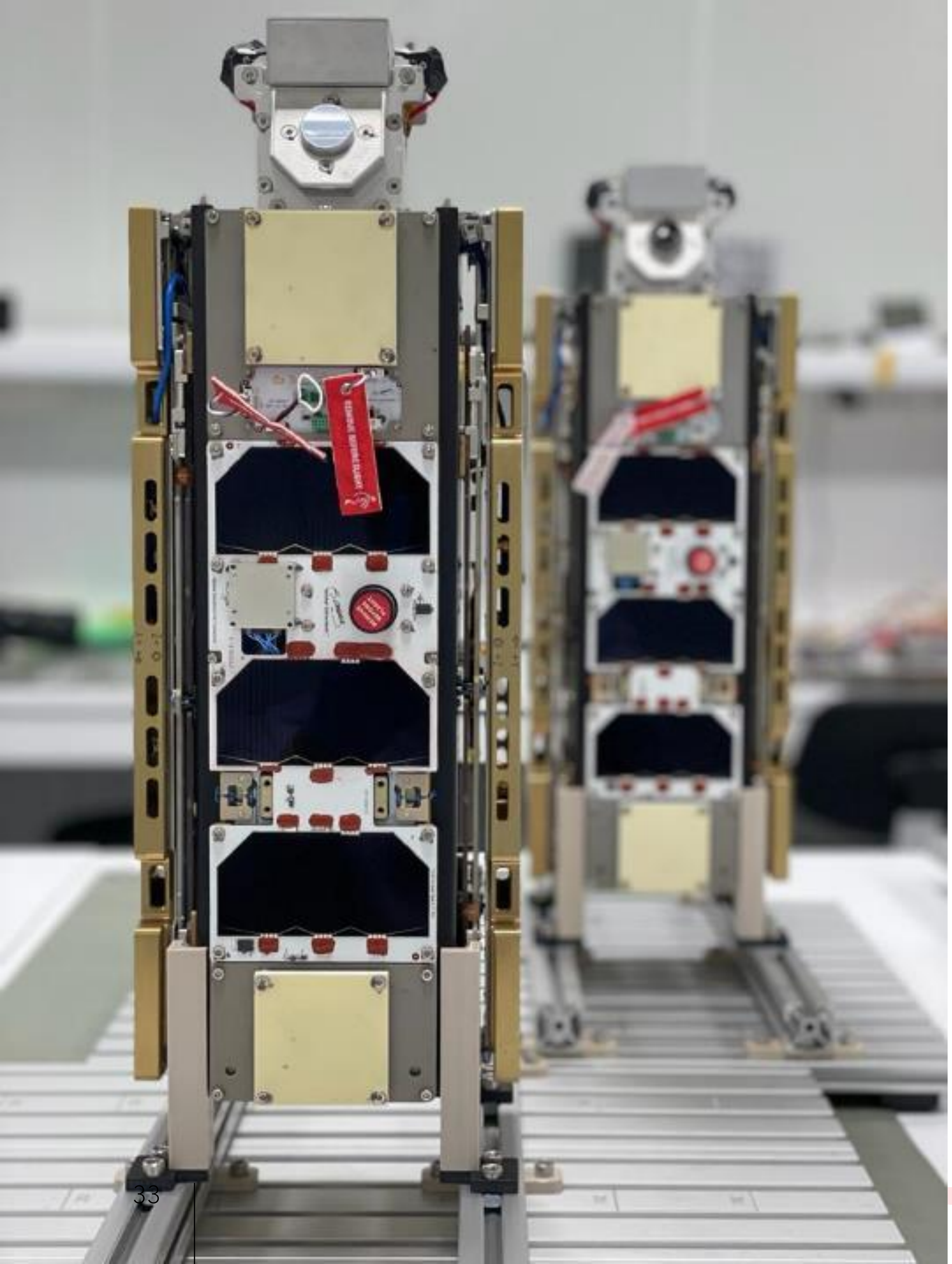


CONNECTA T2.1

Launch	SpaceX, Falcon 9 Transporter 7
Date	15 April 2023
Orbit	SSO
Altitude	550 km
LTAN	10:30

It is a test satellite equipped with a high resolution multispectral camera.

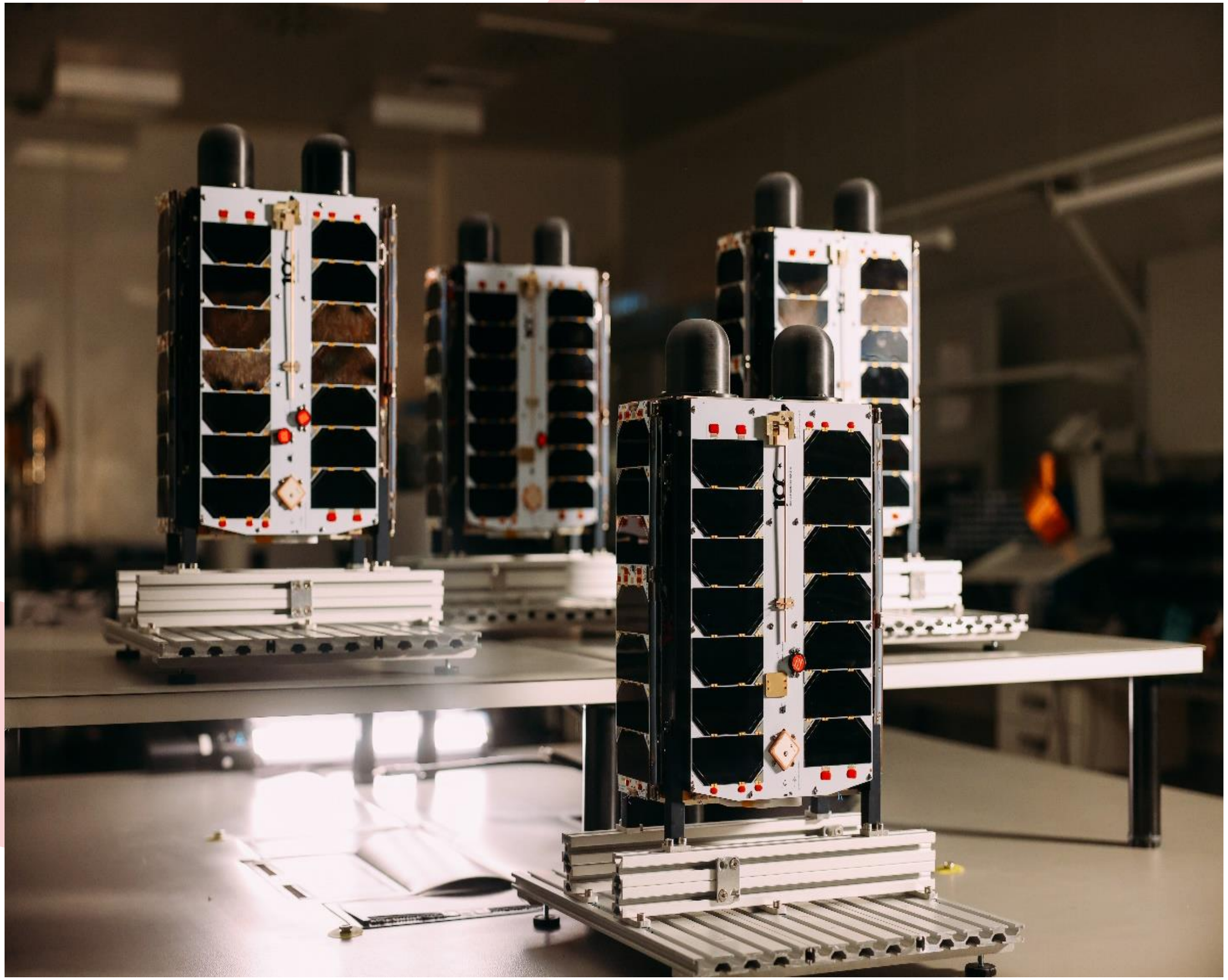
for testing innovative earth observation applications.



CONNECTA T3.1 & T3.2

Launch	SpaceX, Falcon 9 Transporter 9
Date	11 November 2023
Orbit	SSO
Altitude	550 km
LTAN	10:30

Inter Satellite Link (ISL) is verified between two satellites.



CONNECTA IOT 1-2-3-4

Launch	SpaceX, Falcon 9 Transporter 11
Date	16 August 2024
Orbit	SSO
Altitude	550 km
LTAN	10:30

Begining of the Connecta IoT Network

First Commercial IoT satellite batch for Plan-S

PLAN-S IoT Products

IoT MODULE

- IoT device manufacturers can integrate this module into their IoT devices to enable direct satellite connectivity.
- Dual Connectivity: Compatible with both LoRaWAN and the Connecta IoT Network.
- Form Factor: Surface-mount module with an edge connector.
- Size: 35x25x5 mm.
- Versions: Available with or without GPS.
- Data Encryption: Complies with AES standards for secure data transmission.

IoT MODEM

- IoT system integrators can connect their existing devices to satellites using this modem.
- Integrated Unit: A single unit with antennas for satellite communication, external LoRa devices, and GPS.
- Interfaces: Supports Serial, Ethernet, or BLE (Bluetooth Low Energy) interfaces.
- Power Backup: Includes an internal battery for short-term power outages.
- Data Encryption: Complies with AES standards for secure data transmission.

SATELLITE ACCESS TERMINAL

- IoT solution providers can connect their existing IoT devices to the Connecta IoT network using this Access Terminal.
- External Antennas: The Access Terminal comes with external antennas for satellite and device connectivity, ensuring easy integration for any type of application.
- Connectivity Options: Provides Wi-Fi, BLE (Bluetooth Low Energy), and LoRa connectivity for any IoT device.
- Data Encryption: Complies with AES standards for secure data transmission.

[How Does Connecta IoT Network Work? – YouTube]

PLAN-S IoT Products

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Thanks for your attention!

Any Questions?

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