Sisyphus

Redefining Low Power for LoRa Receiver

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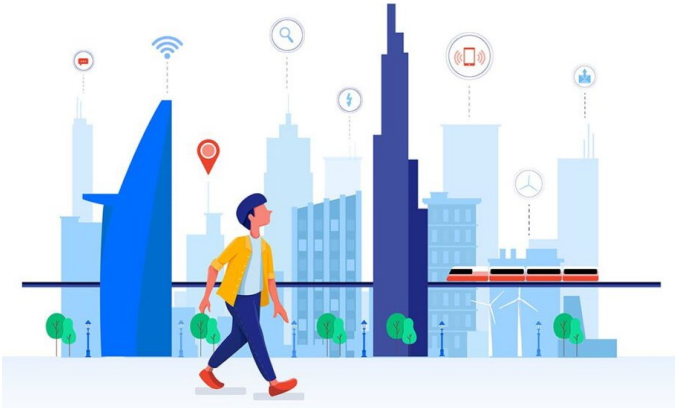
*Sisyphus is a character from ancient Greek mythology who kept pushing a boulder up a mountain and finally found special meaning in meaningless things

LoRa – *a key cog to enable the ubiquitously connected world* 🤗

The LoRa and LoRaWAN IoT market will reach **US$ 5.7 billion** in 2024, expected to surge at a CAGR of **35.6%** from 2024 to 2034 [1].

Precision Agriculture



Smart City

Industrial IoT

Long-range | **Low-power** | **Anti-interference**

[1] https://www.futuremarketinsights.com/reports/lora-and-lorawan-iot-market

– always low power? 🤔

LoRa – *always* low power?

Empirical testing reveals that:

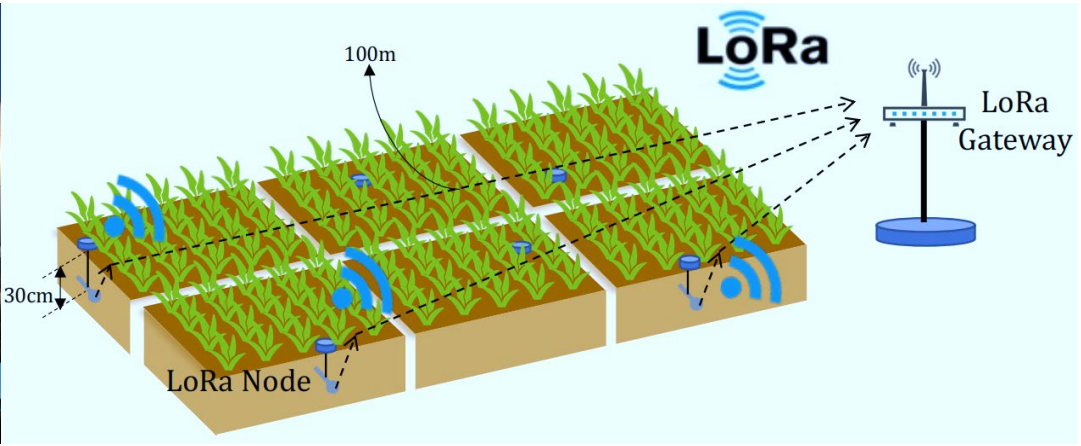
- **Class A and B** -- extremely low duty-cycle

 ~ 1500 mAh  ~ 225 mAh

battery life > 5 years 😊

- **Class C?** 🤔

LoRaWAN – *Class C mode*



Forest fire-alarm Toxic material monitoring Sensor-less sensing in the wild

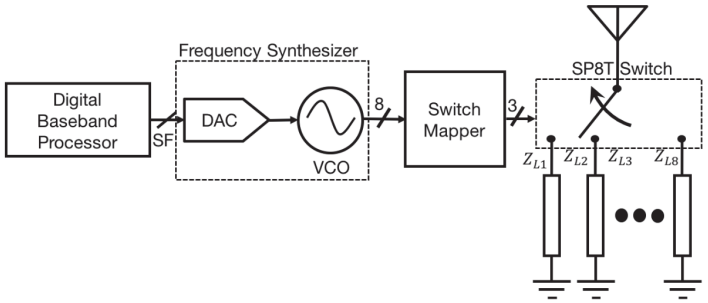
Necessitate **long-term** and **around-the-clock** operation!

Utility power is not always **available**

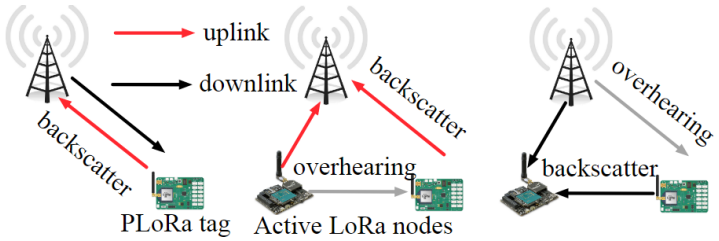
If powered by a battery, it will only sustain **a matter of hours to days** 😭

Background and Motivation

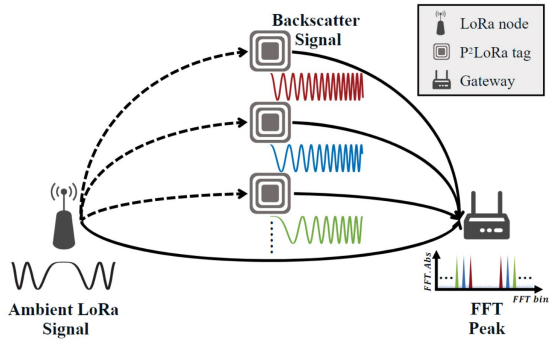
Reducing the runtime power of LoRa



LoRa Backscatter
[UbiComp '17]



PLoRa
[SIGCOMM '18]

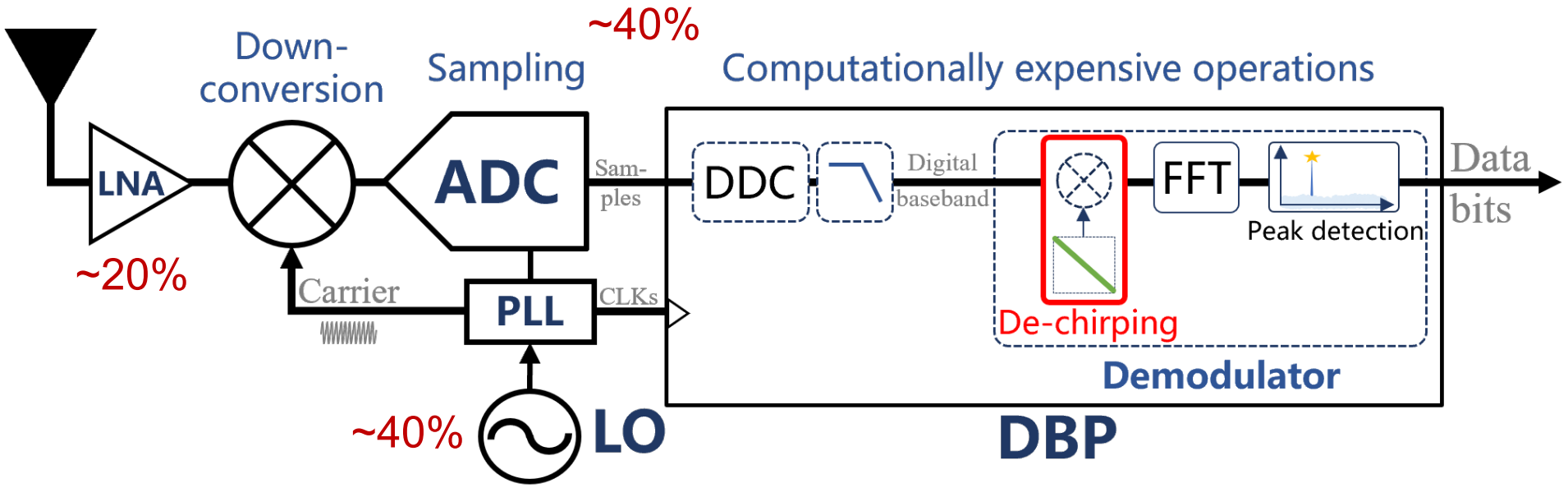


P²LoRa
[MobiCom '21]

LoRa-based backscatter systems reduce the power of **uplink** LoRa transmission by **100μW-level**

The **downlink** now becomes the power-saving bottleneck!

LoRa *Primer 1 – legacy LoRa receiver*



Superheterodyne architecture requires bulky components consuming intensive power 😟

Addressing the downlink runtime power issue of LoRa

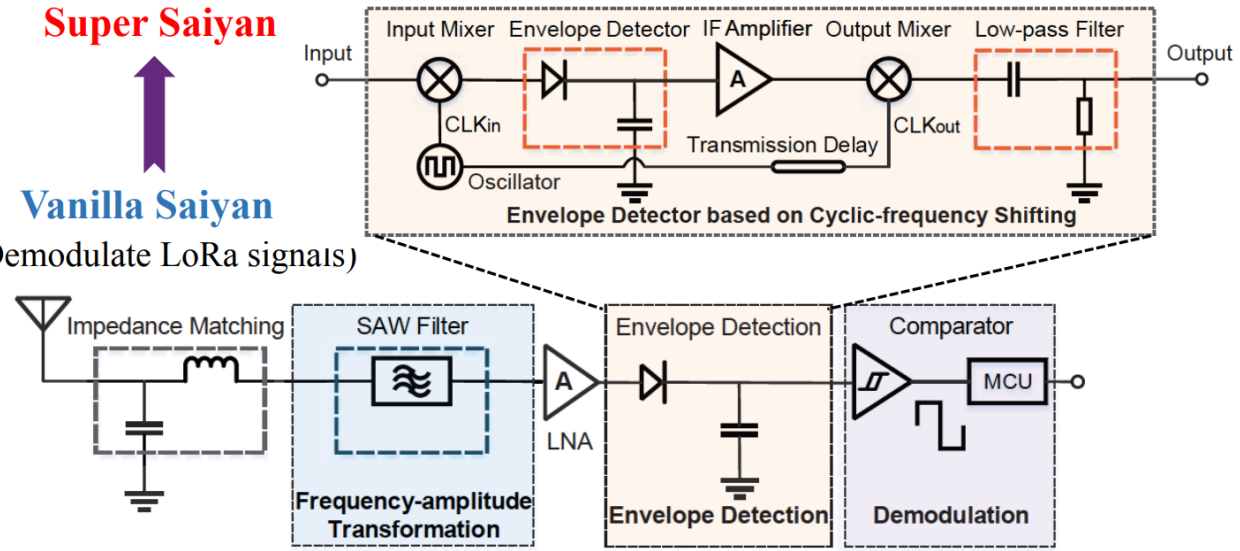
Existing work: Saiyan[1] – passive non-coherent demodulation

(Improve demodulation sensitivity)

Super Saiyan

Vanilla Saiyan

(Demodulate LoRa signals)



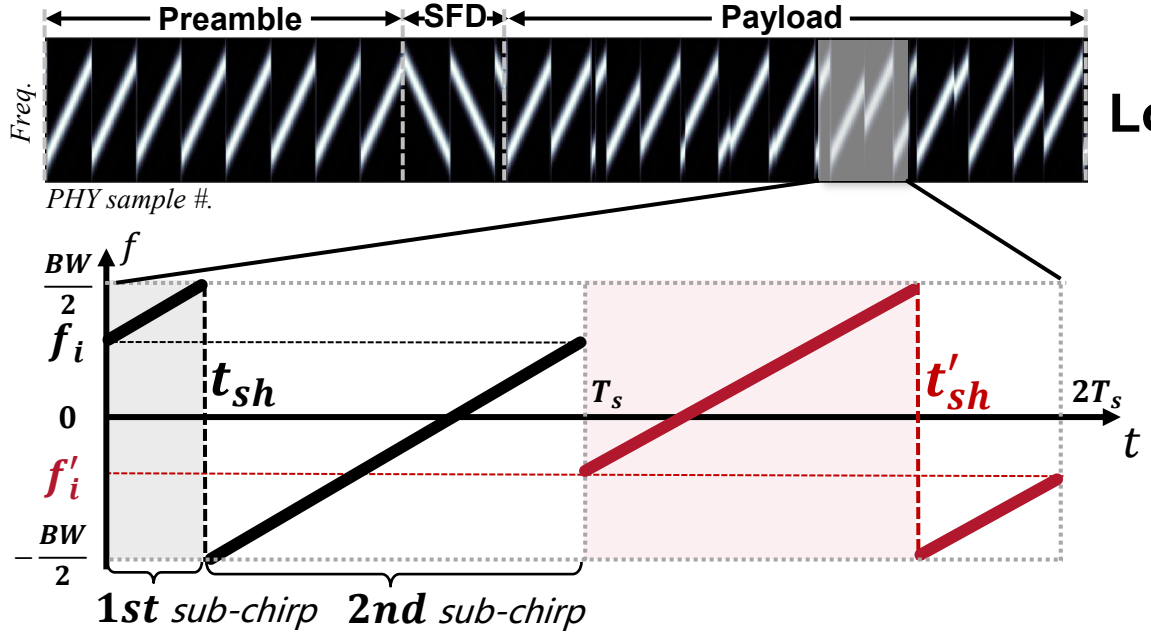
No de-chirping

Puzzling power consumption

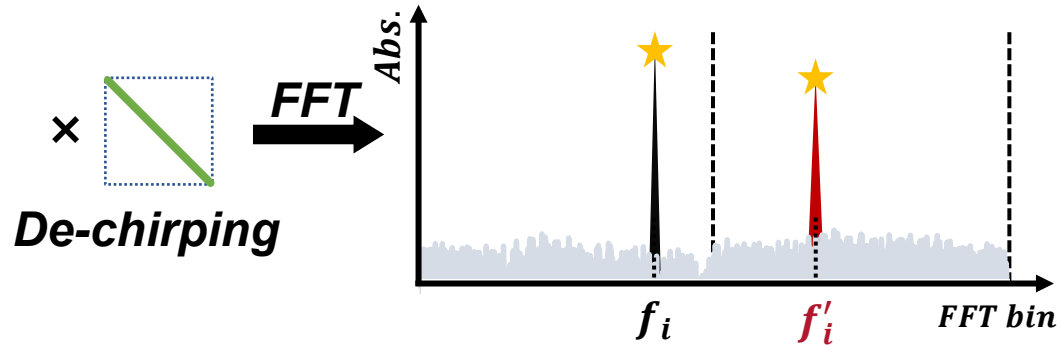
[1] **Saiyan: Design and implementation of a low-power demodulator for {LoRa} backscatter systems**. In *19th USENIX Symposium on Networked Systems Design and Implementation (NSDI 22)* (pp. 437-451).

– Can it low-power 🤔 while retaining de-chirping?

LoRa Primer 2 – chirp spread spectrum (CSS) technology



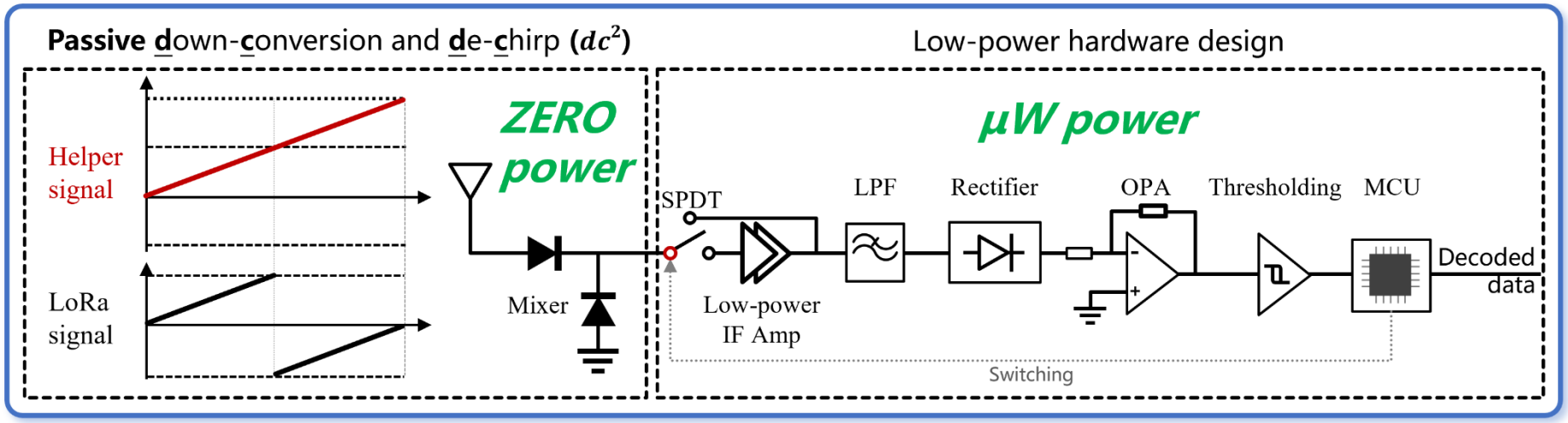
LoRa packet



Observation: an 'f_i' corresponds to a specific 't_{sh}' due to the inherent chirp **geometric** feature

$$t_i^0 = \frac{BW - f_i^0}{k} = \frac{2^{SF} - i_0}{BW}.$$

Sisyphus *addresses the downlink LoRa power issue while retaining de-chirping ability*

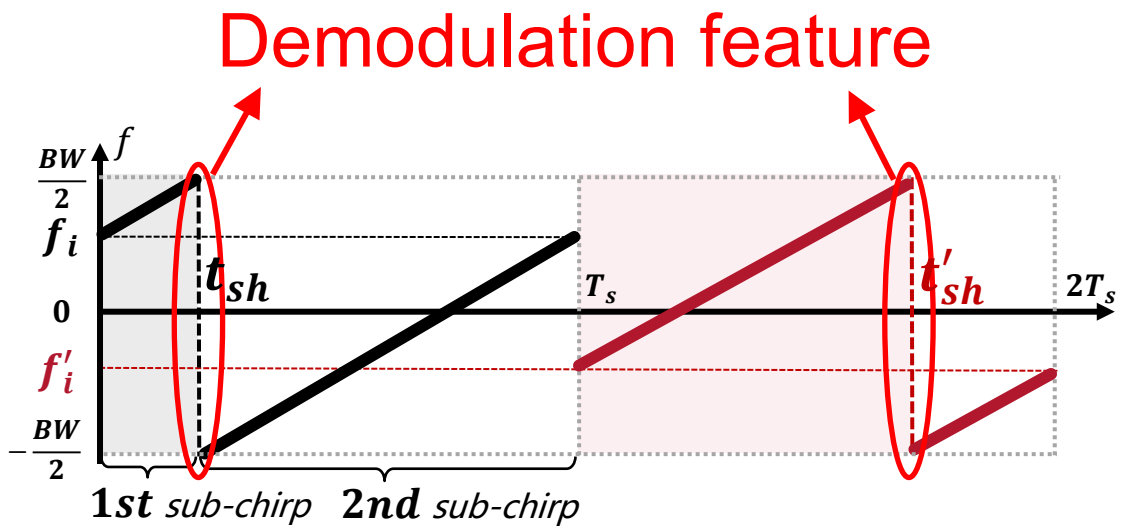


Insight: time localization LoRa demodulation

- ✓ Passive dc^2
- ✓ Low-power demodulator hardware
- ✓ Compatible with COTS LoRa

Problem:

Passive one-shot **d**own-**c**onversion and **d**e-**c**hirping (dc^2) while reserving the demodulation feature for LoRa demodulation



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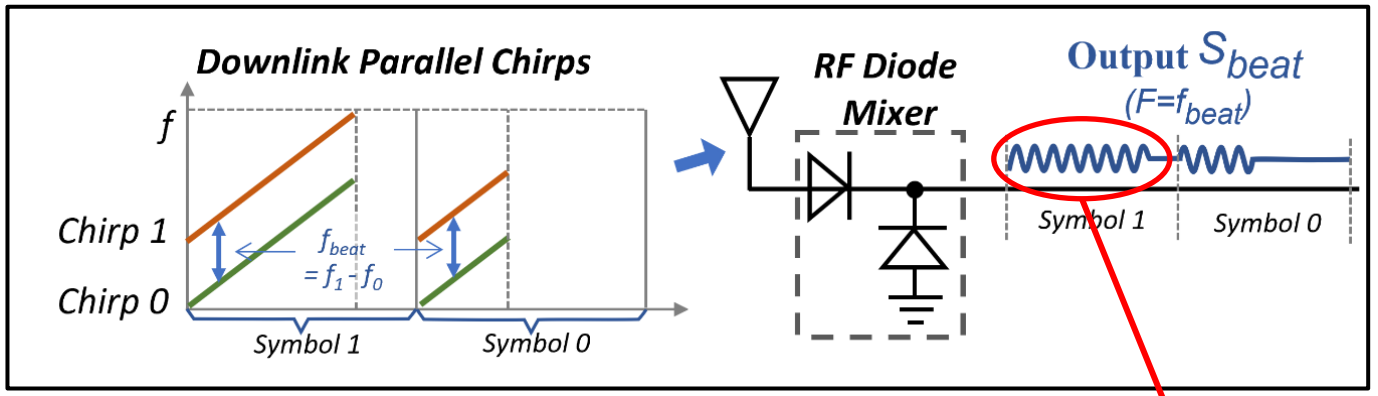
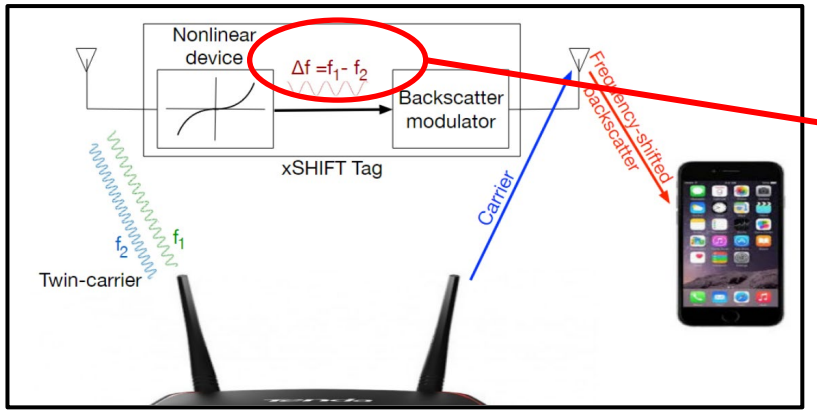


μMote
NSDI '23



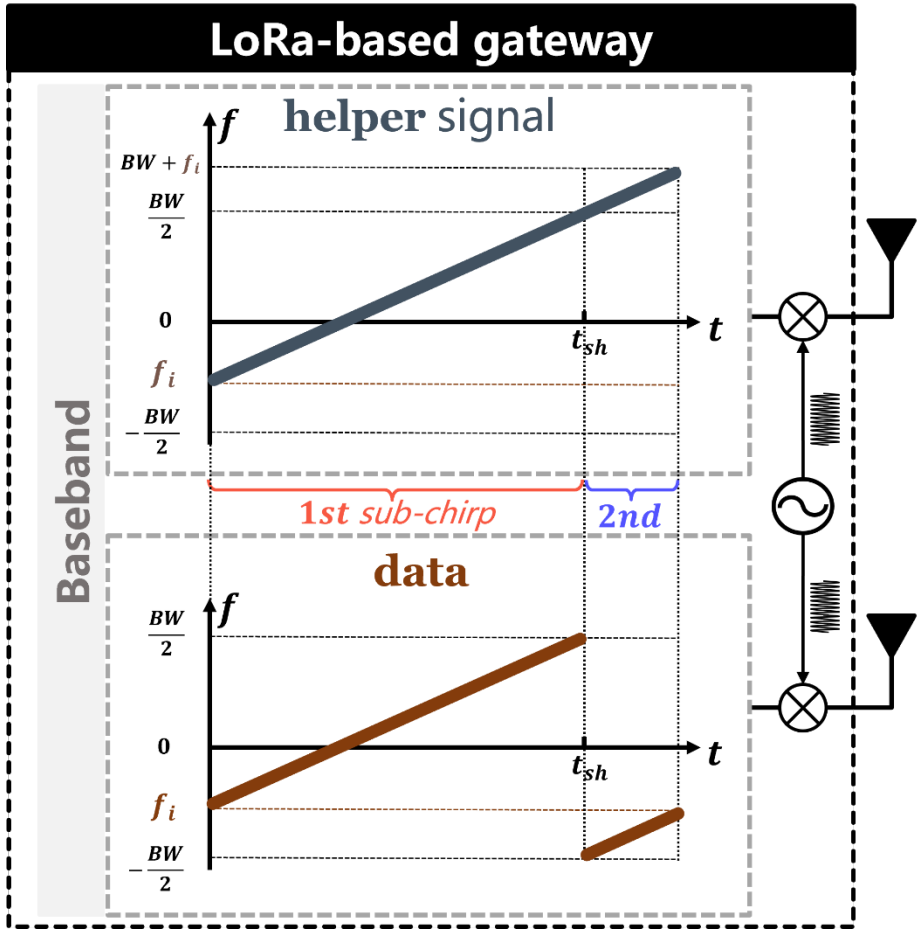
XSHIFT
MobiCom '21

Single-tone

Destroy the demodulation feature 😭

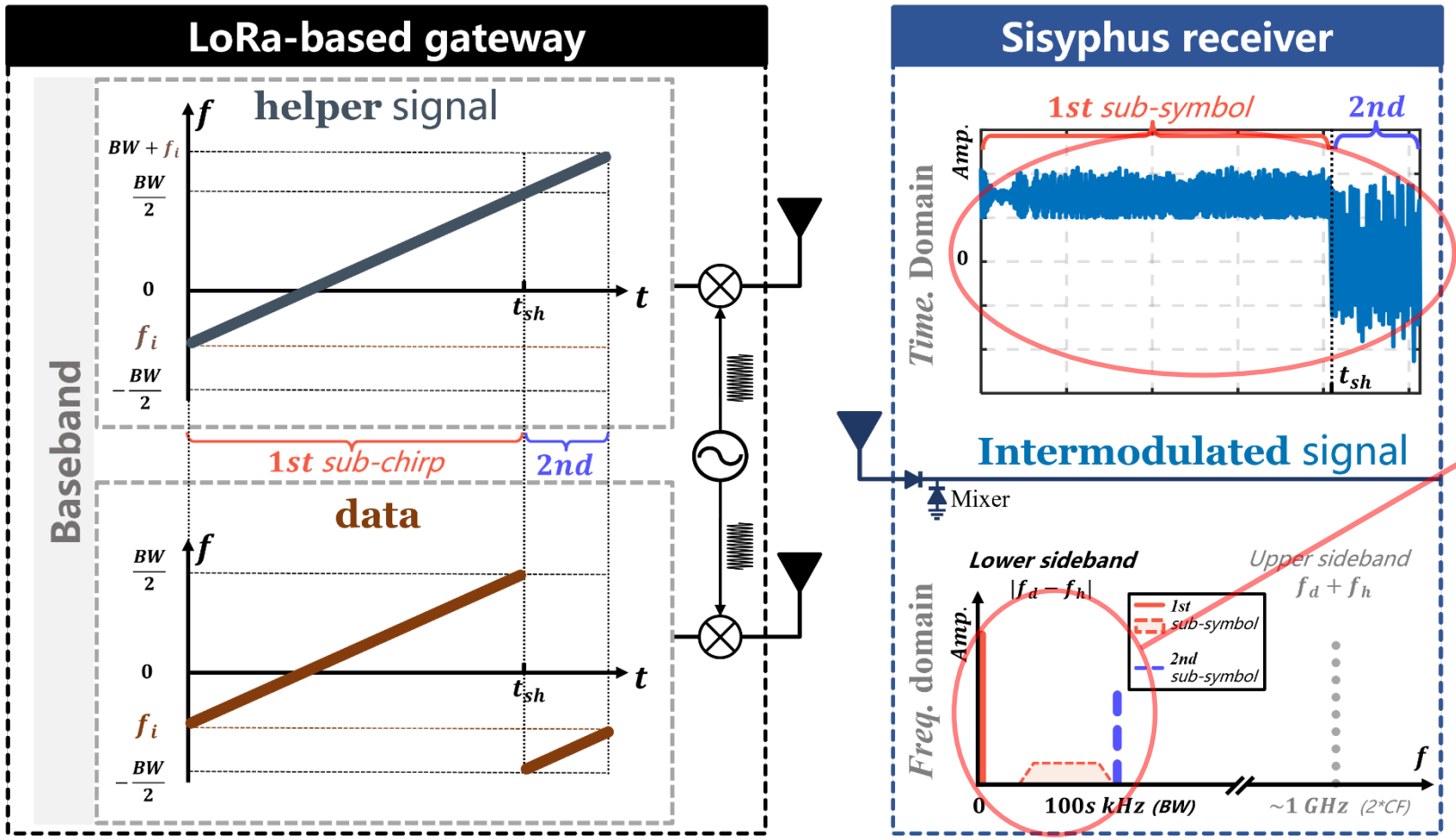
Solution:

Collaborative helper signal waveform design



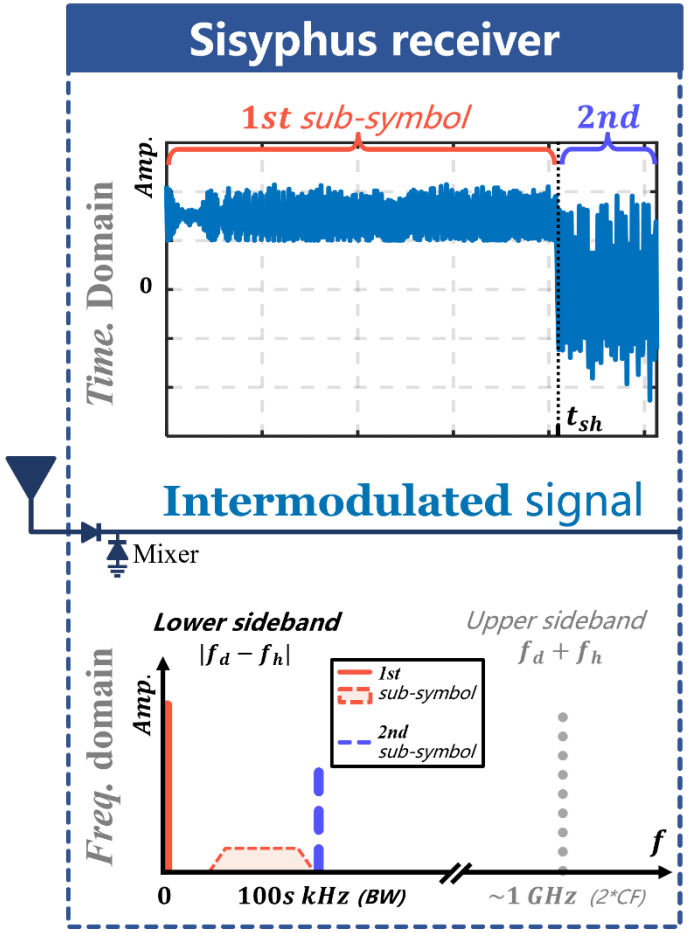
Solution:

Collaborative helper signal waveform design



Problem:

How to demodulate post-dc^2 signals with negligible power consumption



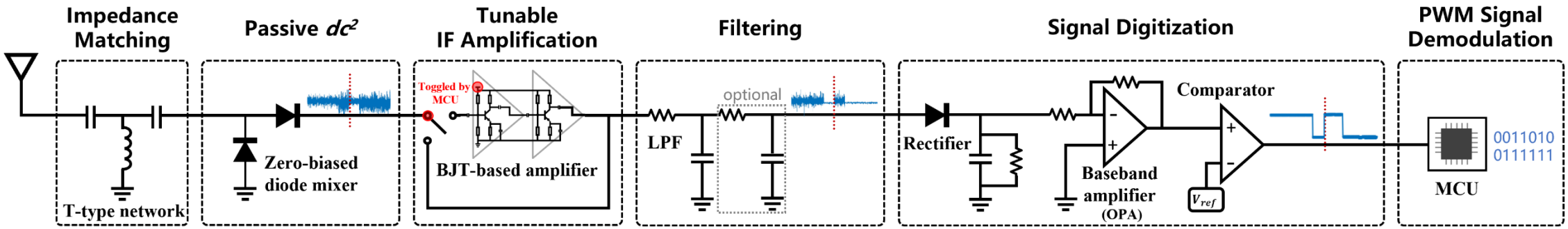
Through digital signal processing? 🤔

(*e.g.*, wavelet transform, STFT and etc.)

Power-consuming
and defeat our original purpose

Solution:

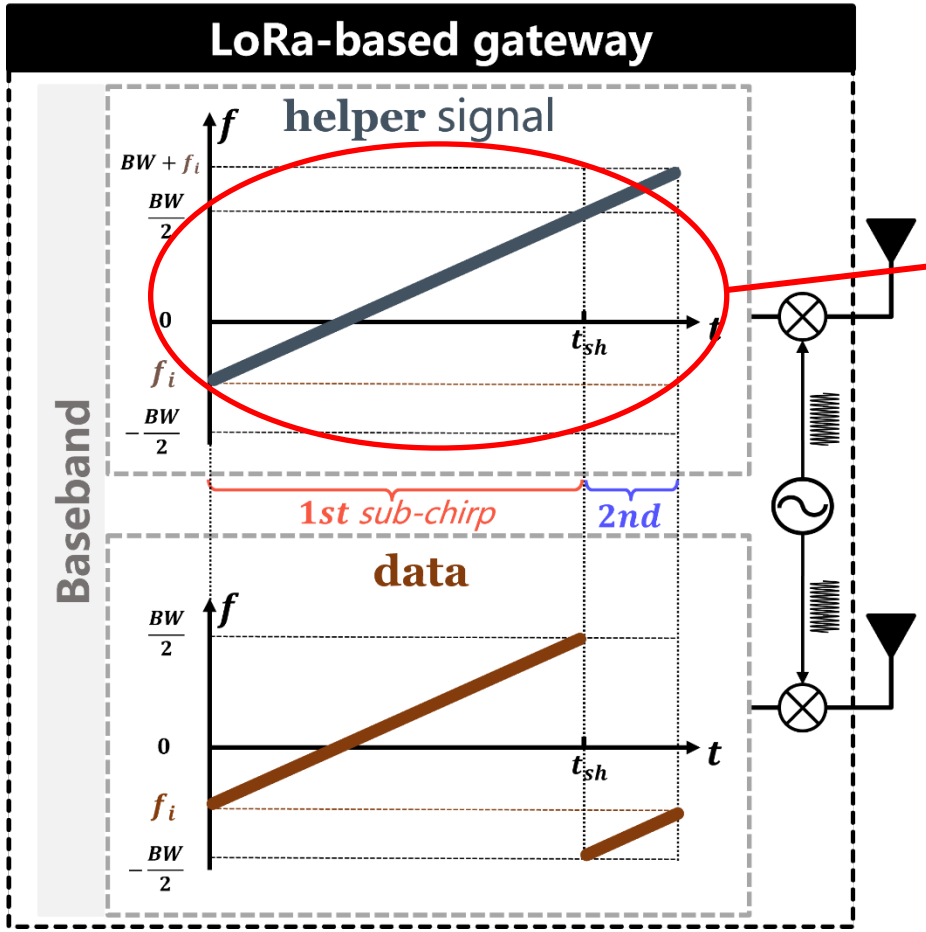
Analog-digital hybrid demodulation



- ✓ **Feature conversion** based on passive RC filter
- ✓ **Digitization** based on passive rectifier and low-power comparator
- ✓ **Data bit extraction** based on low-load PWM signal duty-cycle calculation

Problem:

Backward compatible with COTS LoRa

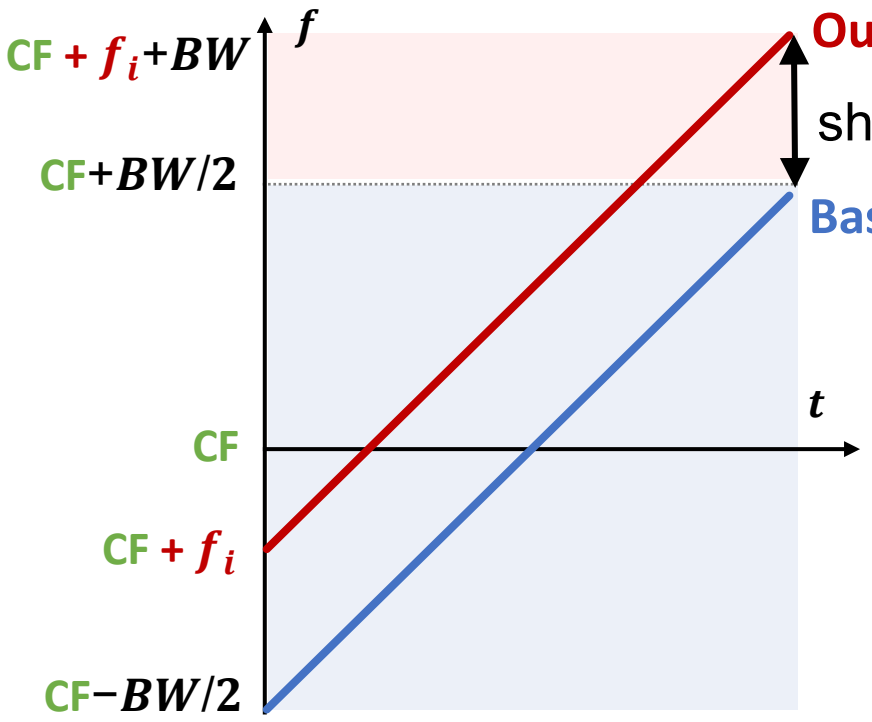


Not compliant with LoRa baseband specification!

Can we still emit helper signal **using COTS LoRa transceiver**?

Observation 1:

Signal frequency over-the-air = baseband freq. + carrier freq. (CF)



Our desired helper (LoRa-incompliance)

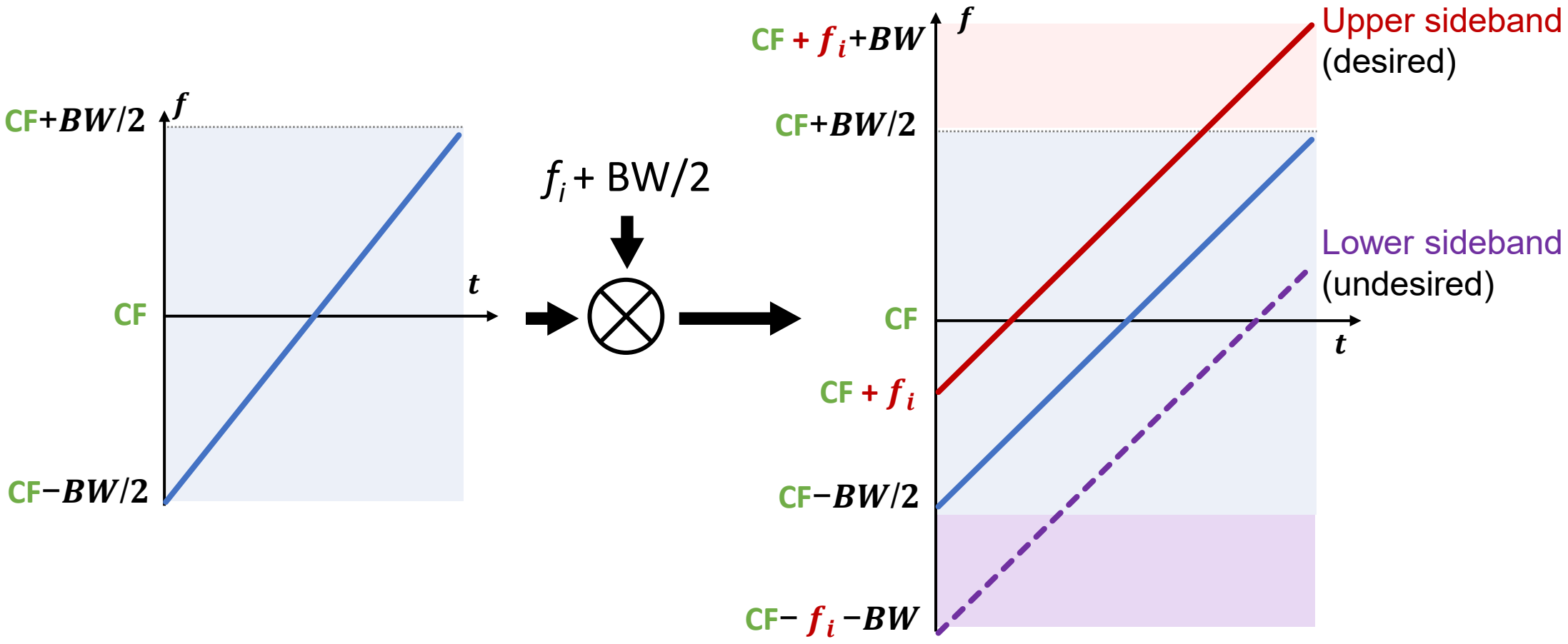
shifting frequency = f_i + **BW/2**

Base up-chirp (LoRa-compliance)

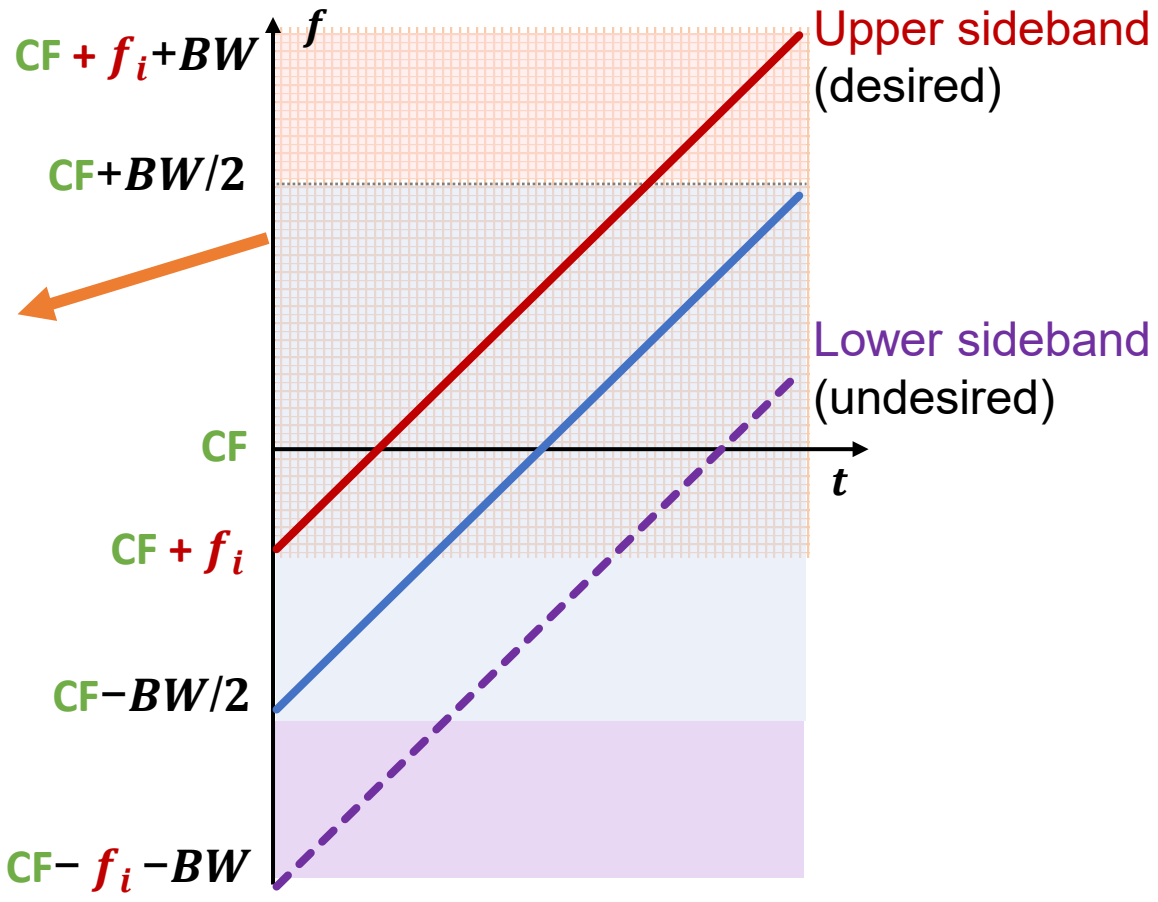
Can we get the desired helper signal by **directly applying a frequency shifting on the RF signal**?

Problem:

Double sideband overlapping



Problem:
Double sideband overlapping



We cannot pick-up the desired signal using high pass filter

Observation:

The CF of COTS LoRa module can be customized via register

4.1.4. Frequency Settings

(P36 in the datasheet of SX127X chip)

Recalling that the frequency step is given by:

$$F_{STEP} = \frac{F_{XOSC}}{2^{19}}$$

In order to set LO frequency values following registers are available.

F_{RF} is a 24-bit register which defines carrier frequency. The carrier frequency relates to the register contents by following formula:

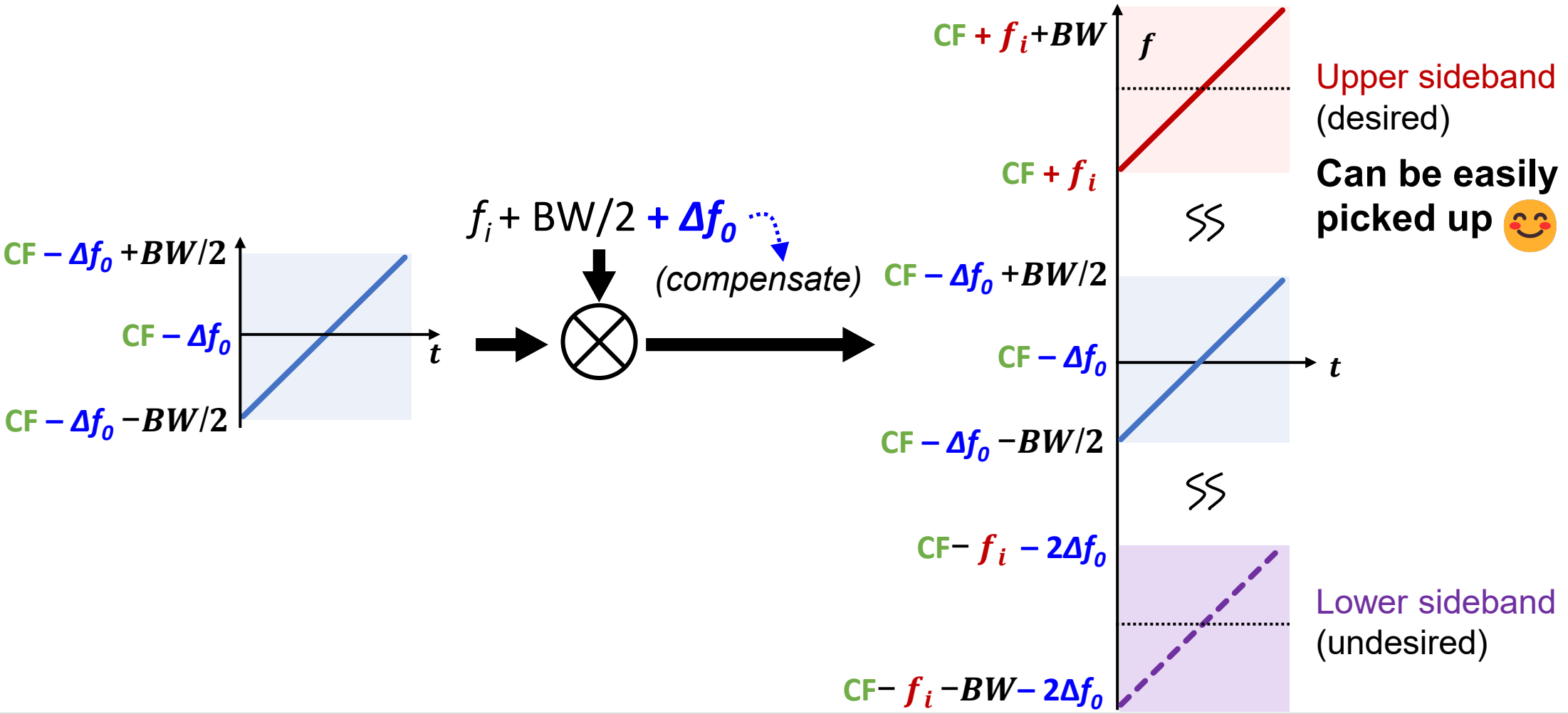
$$F_{RF} = F_{STEP} \times Frf(23,0)$$

Solution:

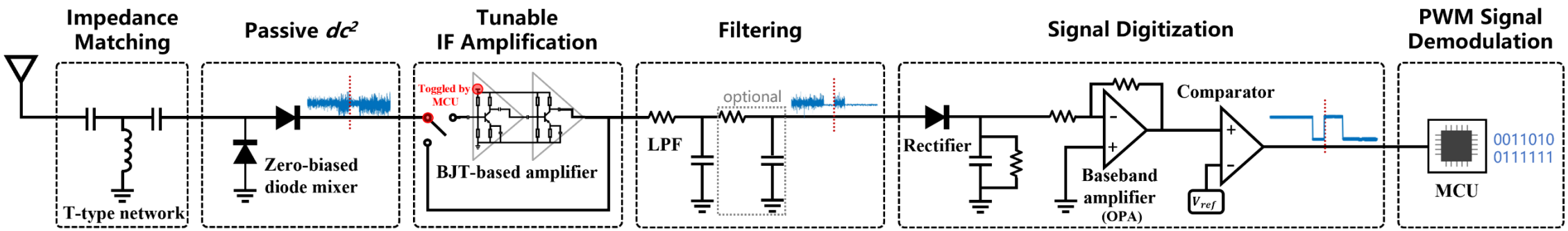
Modify CF and compensate its variation to amplify the shifting frequency to avoid overlapping between the two mirror copies.

Solution:

Modify CF and compensate its variation in the shifting frequency

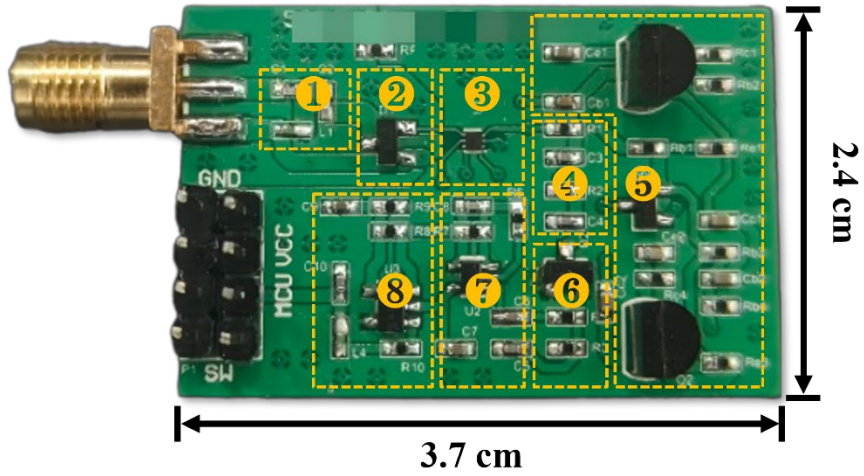


Implementation



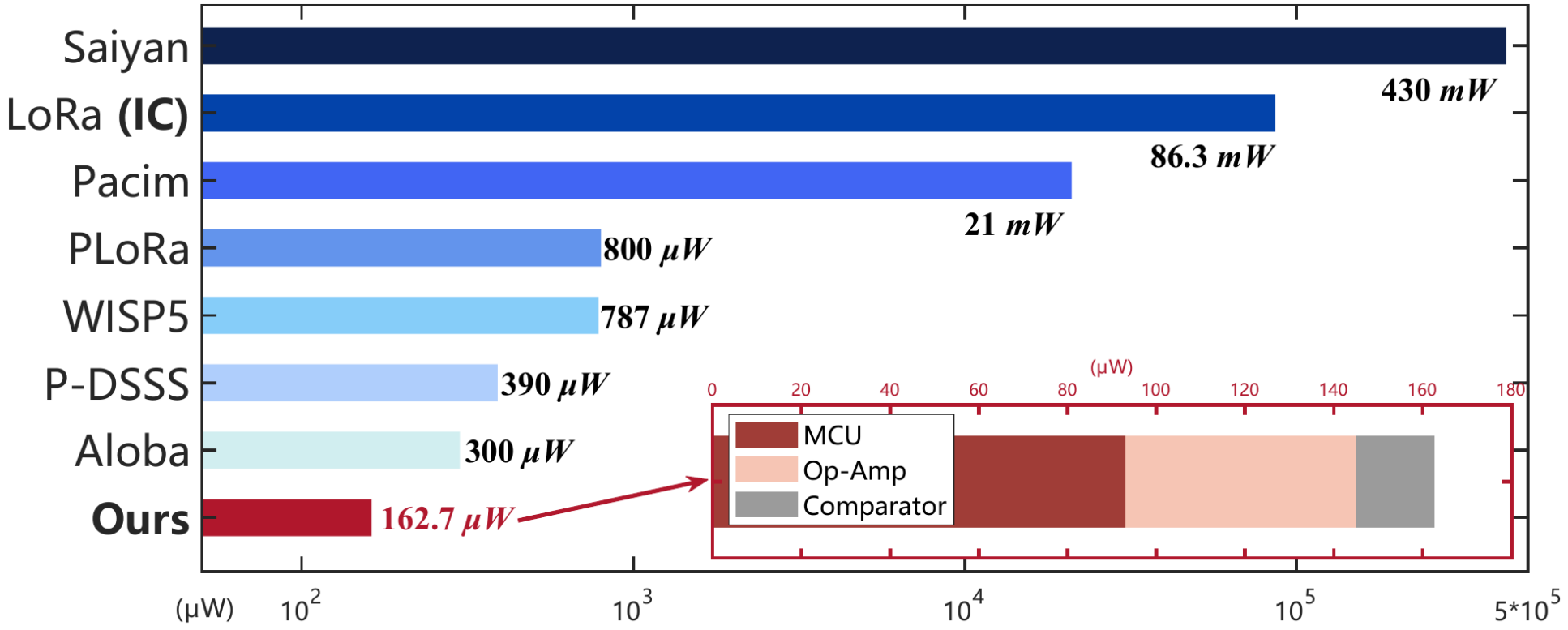
1. Matching Network
2. Passive Mixer
3. SPDT
4. RC Filters
5. IF Amplifier
6. Rectifier
7. OP Amplifier
8. Discriminator

Prototype



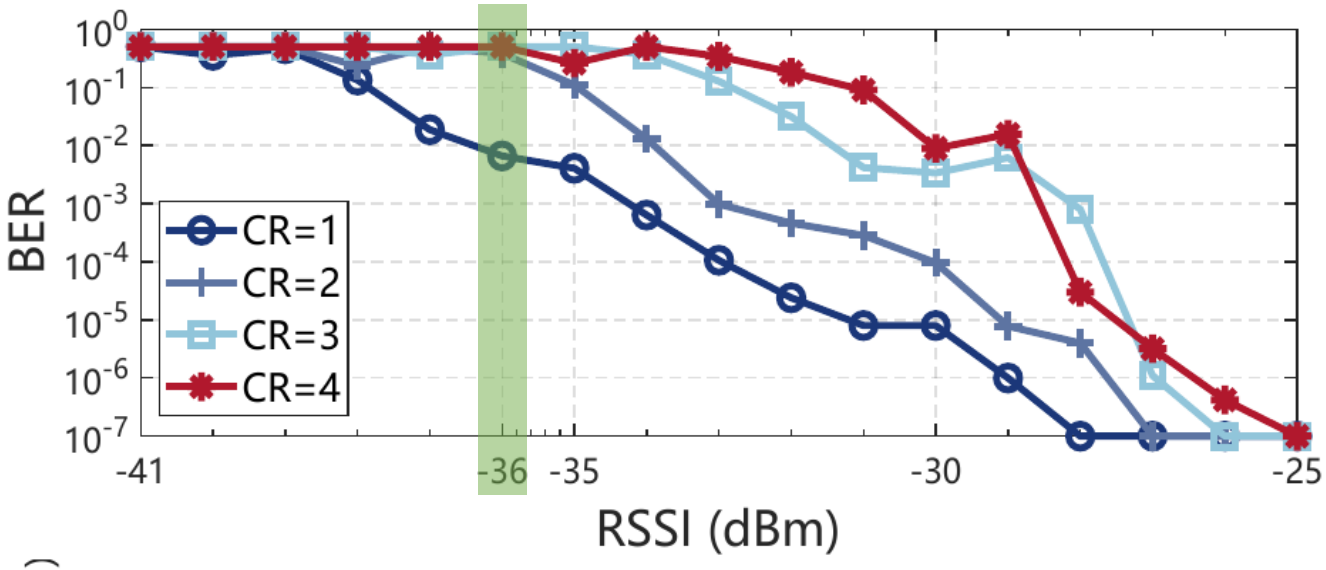
- 37mm×24mm 4-layer FR4 PCB
- 2 versions:
  - Sisyphus+: IF amplifier ON
  - Sisyphus: IF amplifier OFF

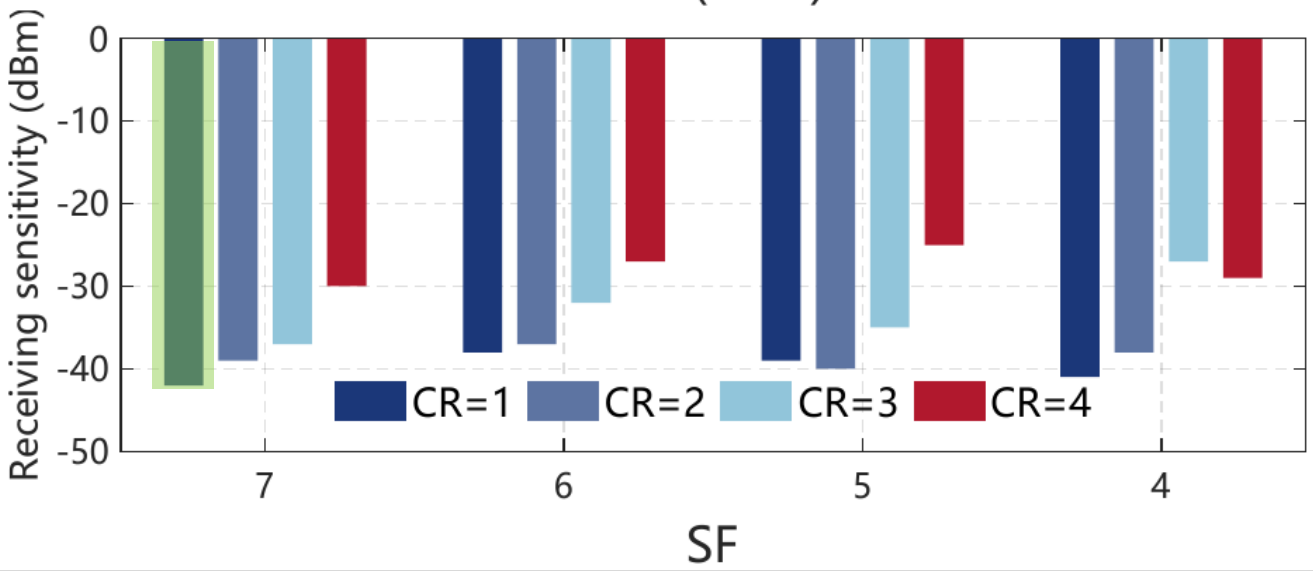
Evaluation > power breakdown



- ✓ **530**× reduction compared to IC-based legacy LoRa receiver
- ✓ **4.9**×, **1.8**×, **129**× reduction compared to demodulation-disable LoRa-based backscatter systems' downlink
- ✓ Power of IF amplifier: **286 μW**

Evaluation > receiving sensitivity





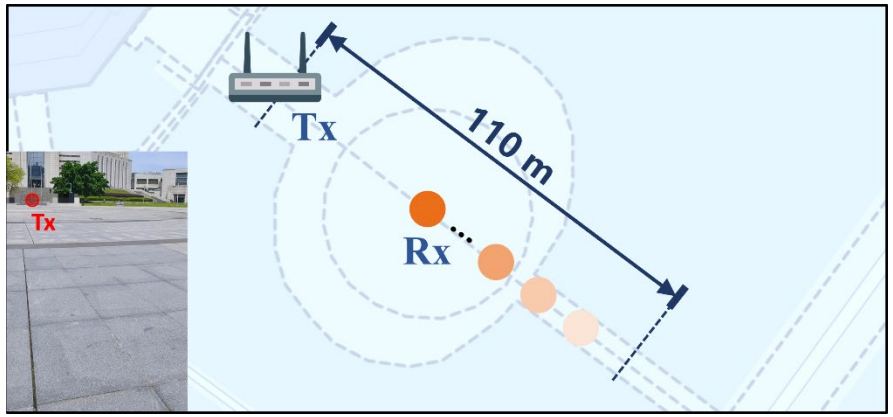
Sisyphus

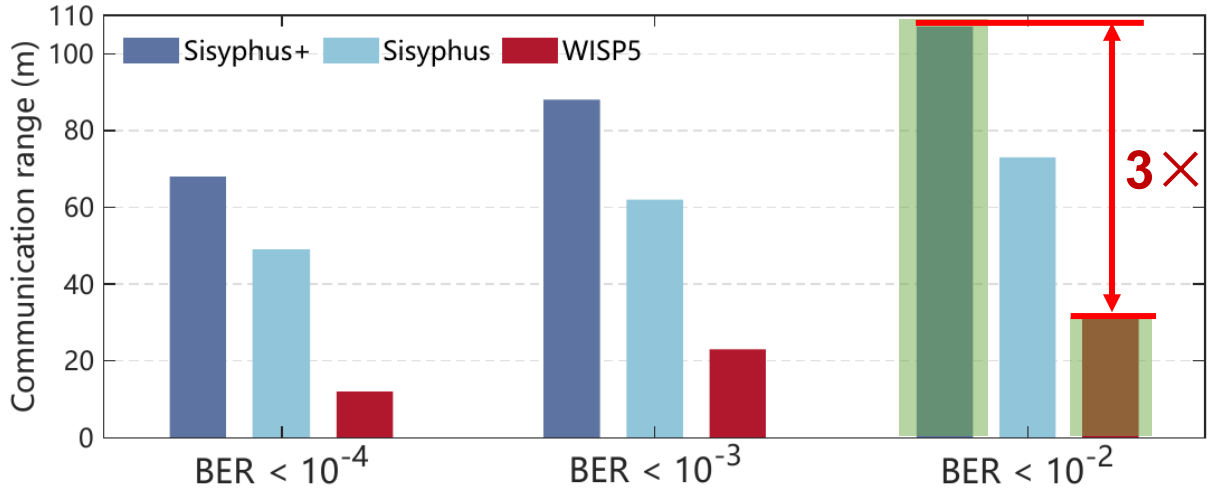
Sensitivity: **-36dBm**

6dB gain
with IF amplifier ON

Experimental setup:

- Transmission power: 20dBm;
- LOS Tx antenna gain: 6dBi, Rx antenna gain:3dBi.

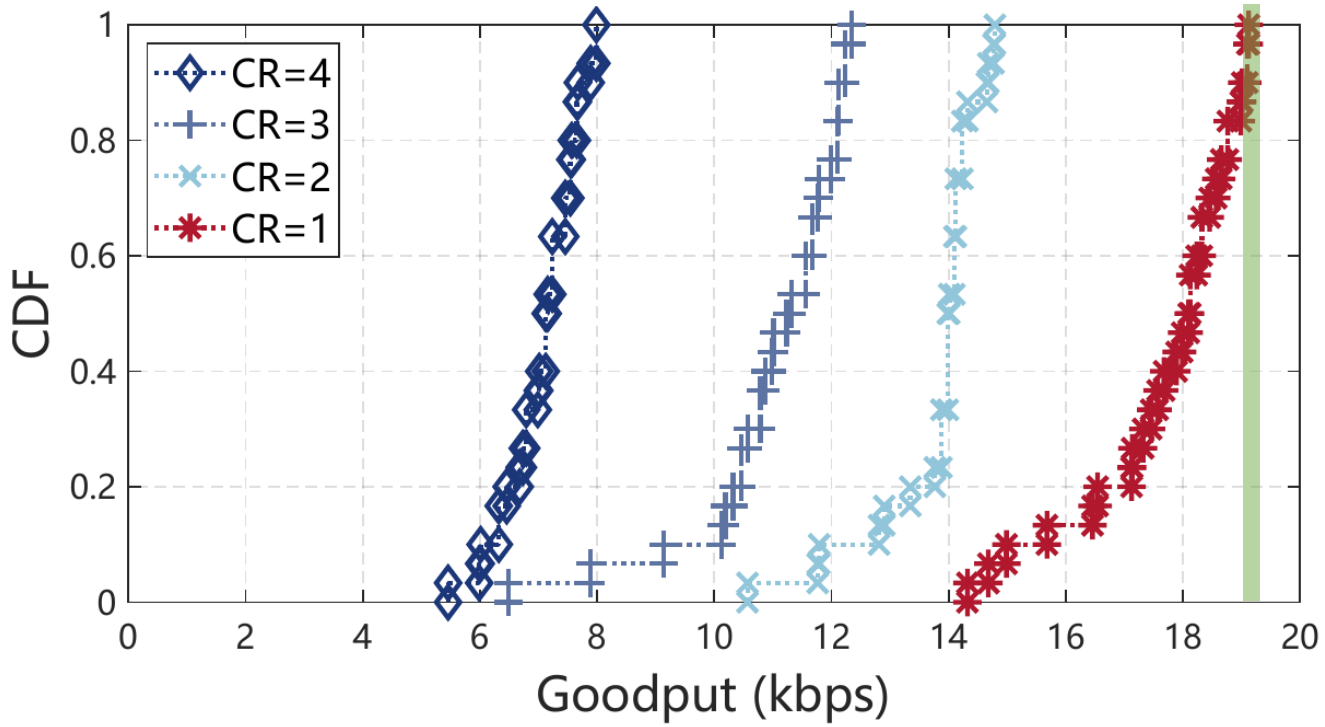




3× improvement range
compared to ED-based receiver

Goodput

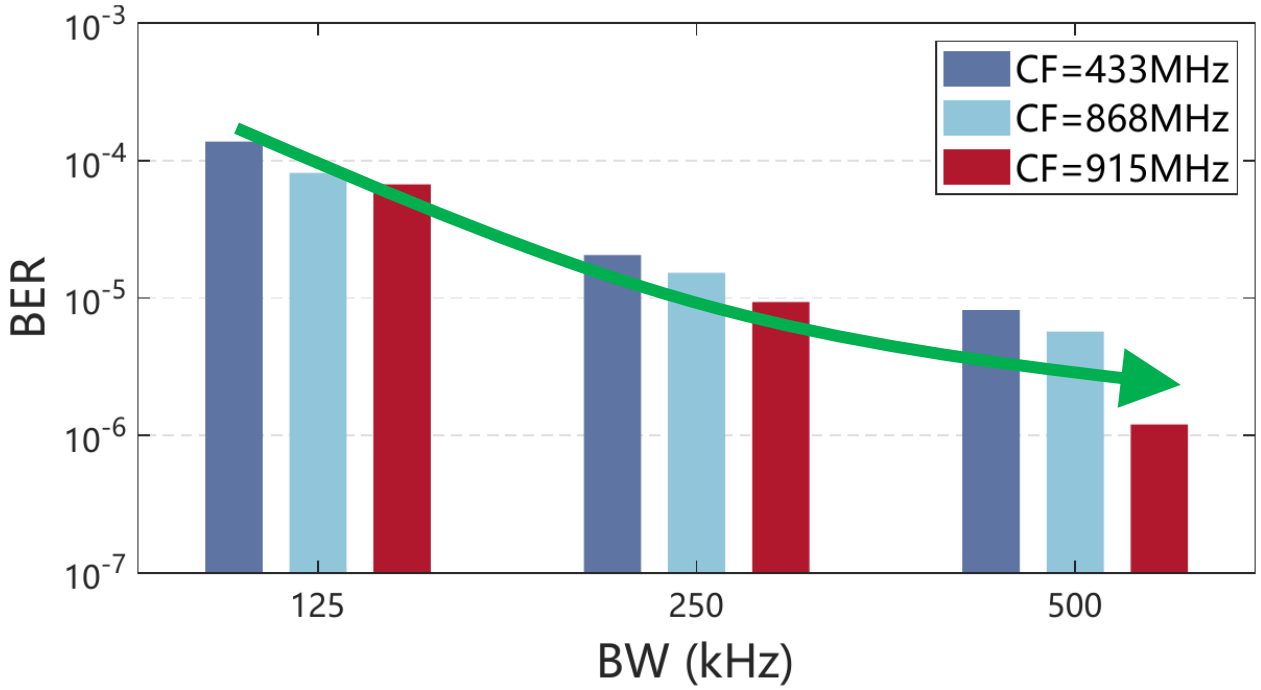
Indicating the BER in different time and locations



Comparative goodput with legacy receiver

Why?

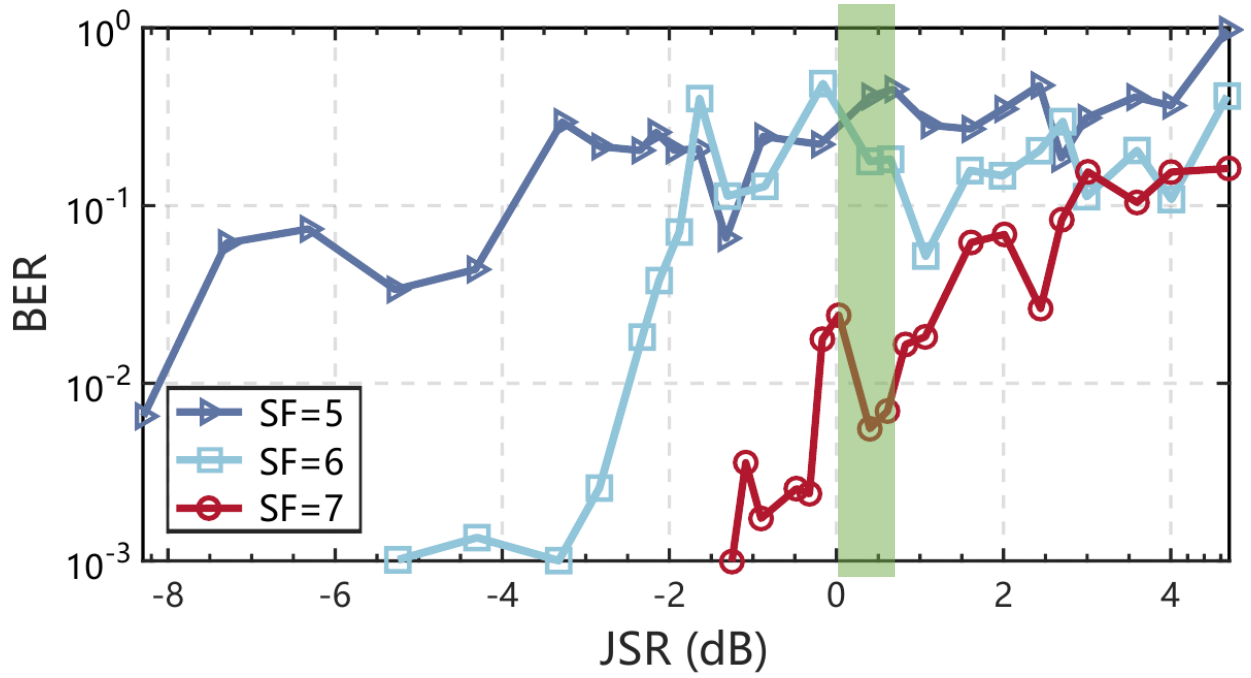
More BW, more distinguishable sub-symbols;
And CF will impact the conversion loss of diode in our circuit.



BW↑ and CF↑, performance↑

Setup:

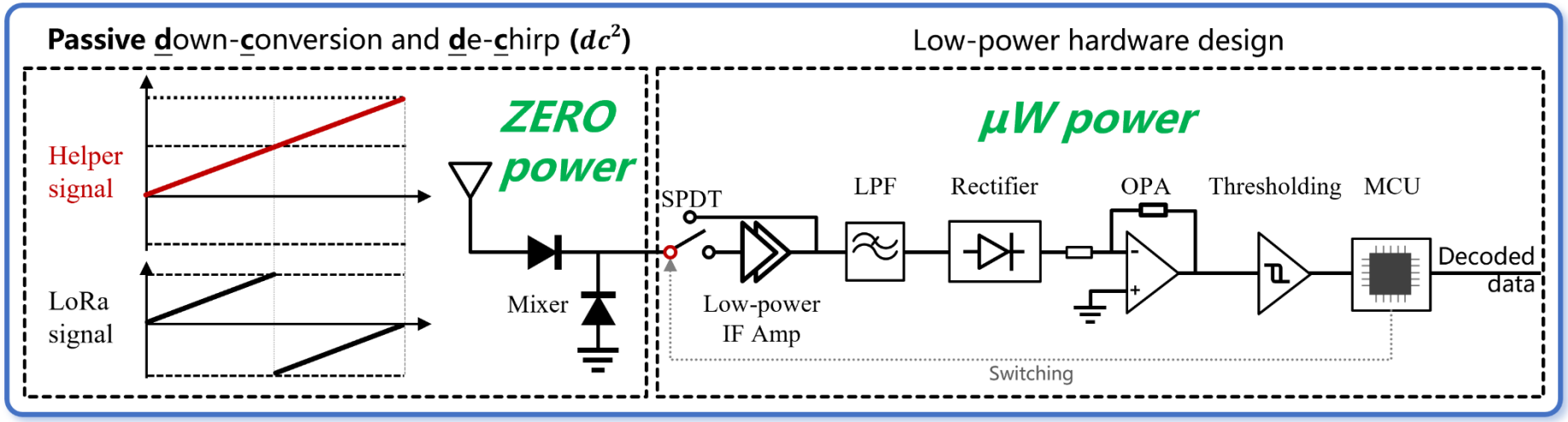
Send helper+data along with in-band jamming signals within an RF cable



Sisyphus can achieve accurate communication with 0.8dB JSR

Takeaway

- ✓ The low-power promise of LoRa can only be delivered in Class A and B, in other words, **LoRa is NOT always low power!**
- ✓ Sisyphus enables the first **ultra-low-power LoRa receiver design with de-chirping ability**
- ✓ Sisyphus can be **compatible with legacy LoRa**



Sisyphus: Redefining Low Power for LoRa Receiver

Thanks for your attention! 🥰

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Q&A