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

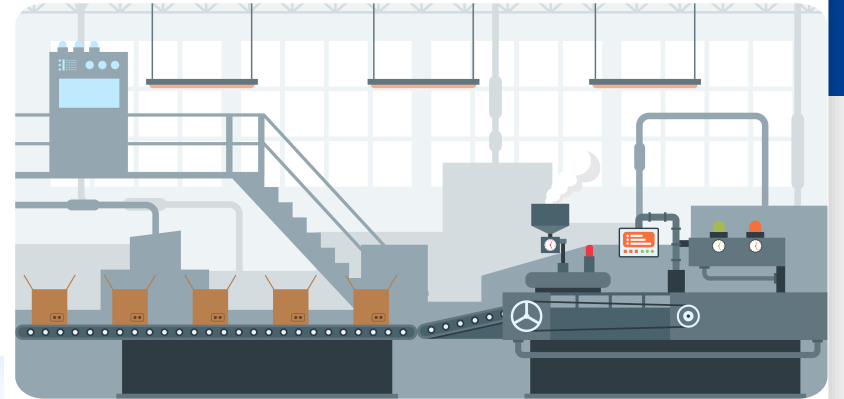**LoRa** – *a key cog to enable the ubiquitously connected world* 🤗

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

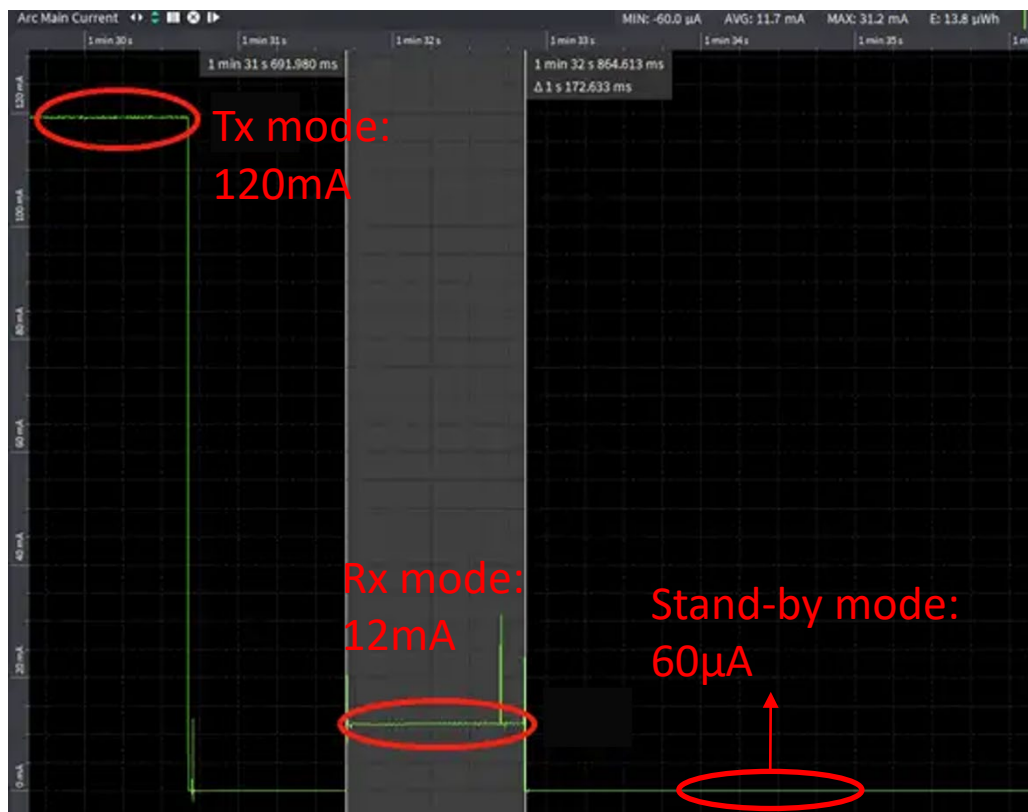**Long-range**

Low-power

Anti-interference

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

LoRa — always low power? 🤔

LoRa – _**always** low power?_

Empirical testing reveals that:

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

  ~ 1500 mAh   ~ 225 mAh
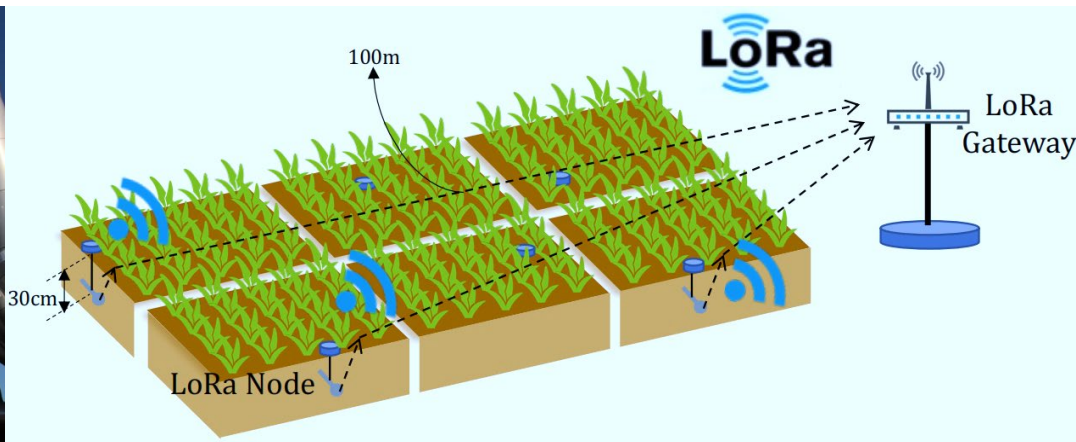
  battery life > 5 years 😊

- **Class C?** 🤔

LoRaWAN – *Class C mode*

Forest fire-alarm   Toxic material monitoring   Sensor-less sensing in the wild
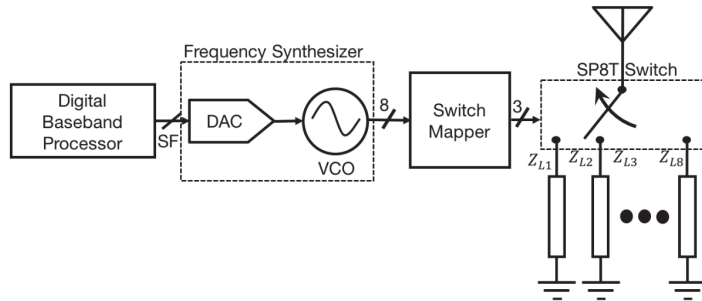
Necessitate **long-term** and **around-the-clock** operation !
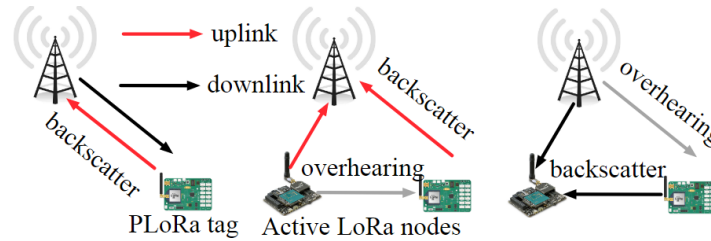
Utility power is not always **available**

If powered by a battery, it will only sustain **a matter of hours to days** 😭
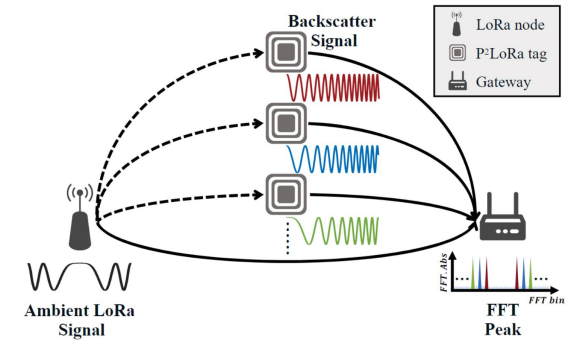
Reducing the <u>runtime</u> power of **LoRa**

LoRa Backscatter
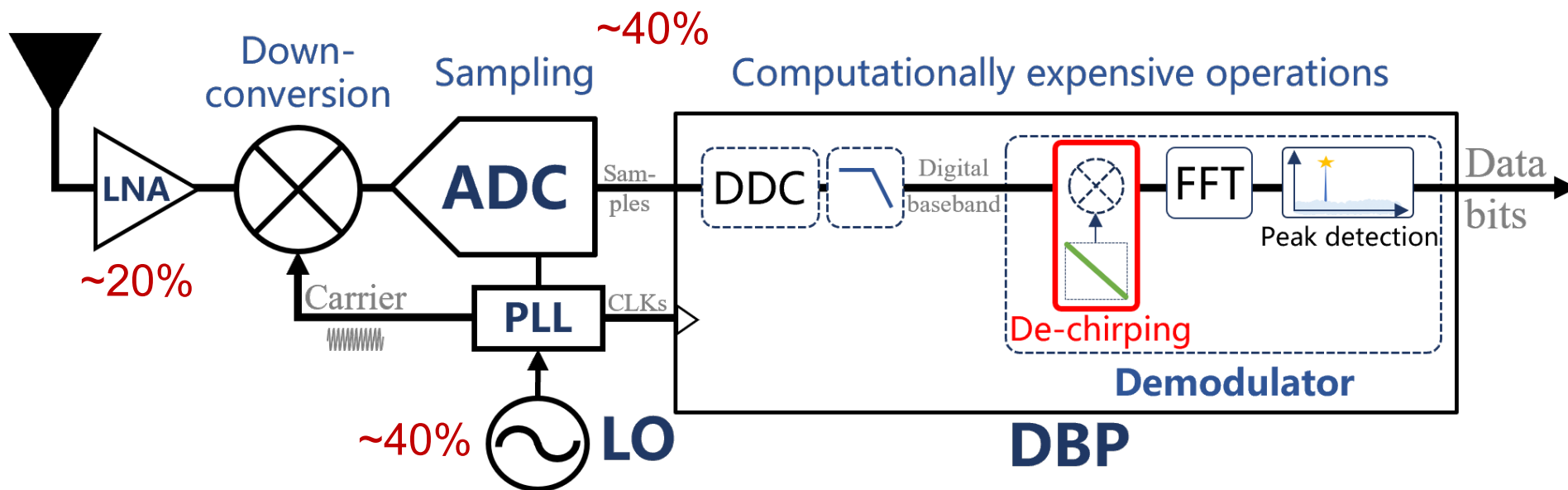[UbiComp '17]

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 🥺
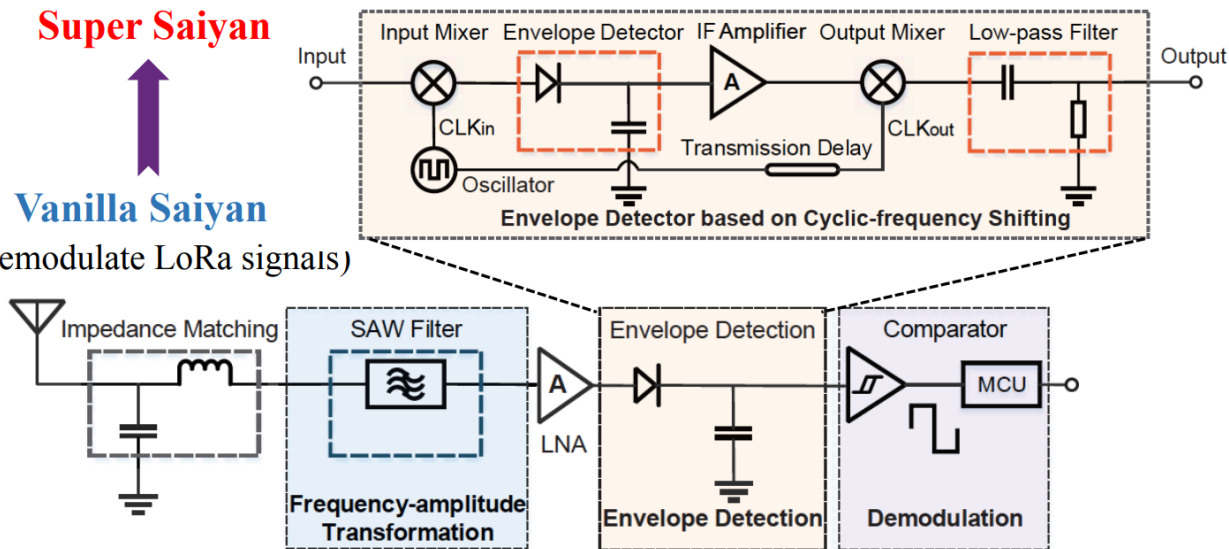
Addressing the _downlink_ runtime power issue of LoRa

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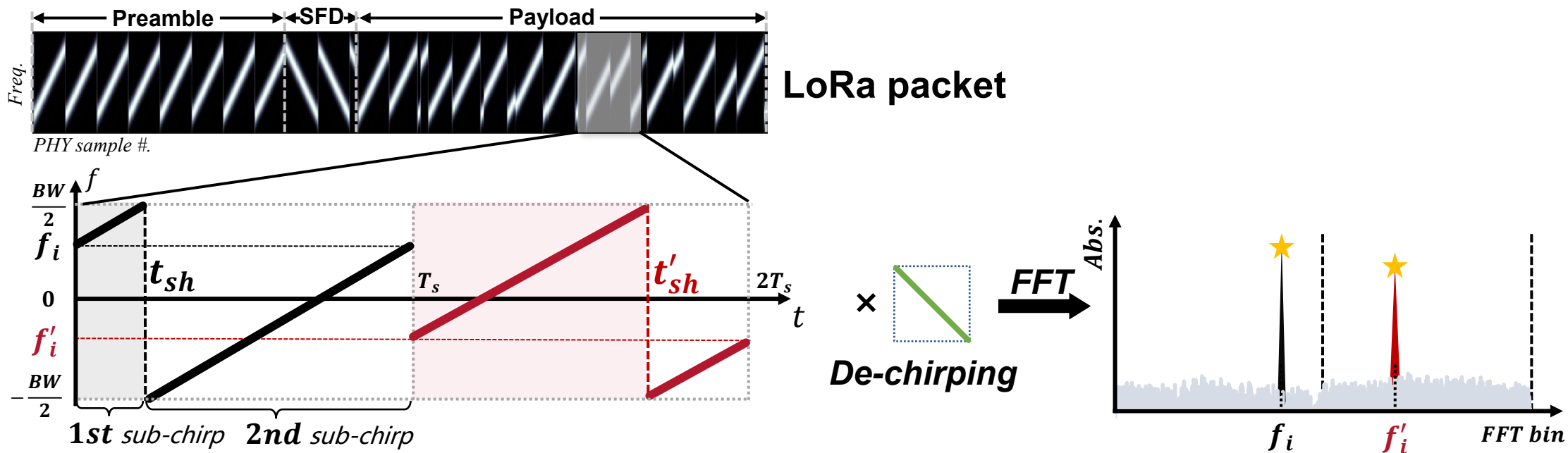

😭 No de-chirping

🙁 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).
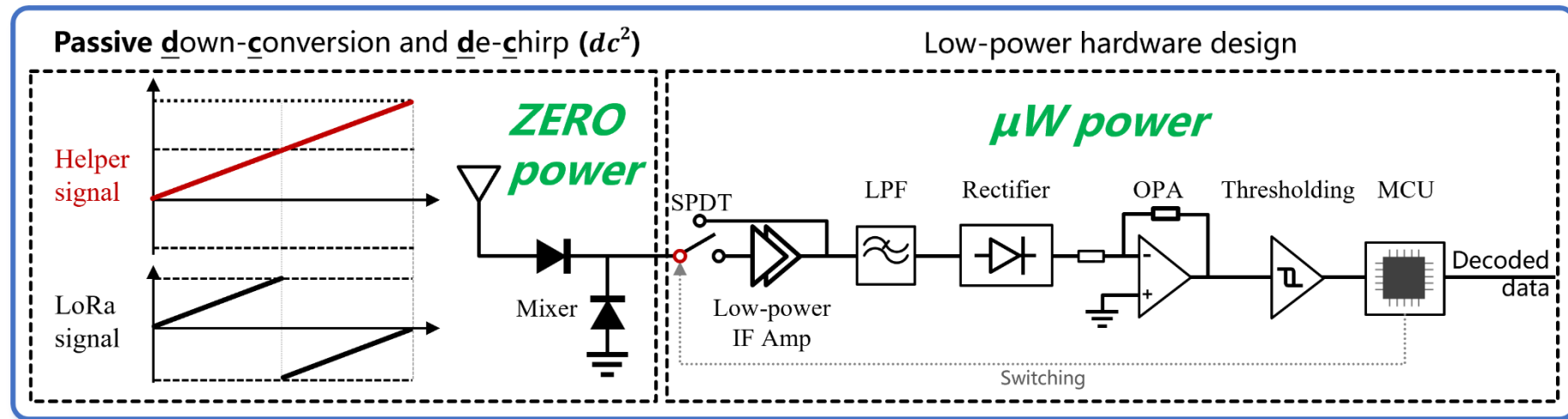
LoRa **– Can it low-power** 🤔
while retaining de-chirping?

LoRa *Primer 2 – chirp spread spectrum (CSS) technology*

LoRa packet

De-chirping

FFT

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 <u>downlink</u> LoRa power issue while retaining de-chirping ability
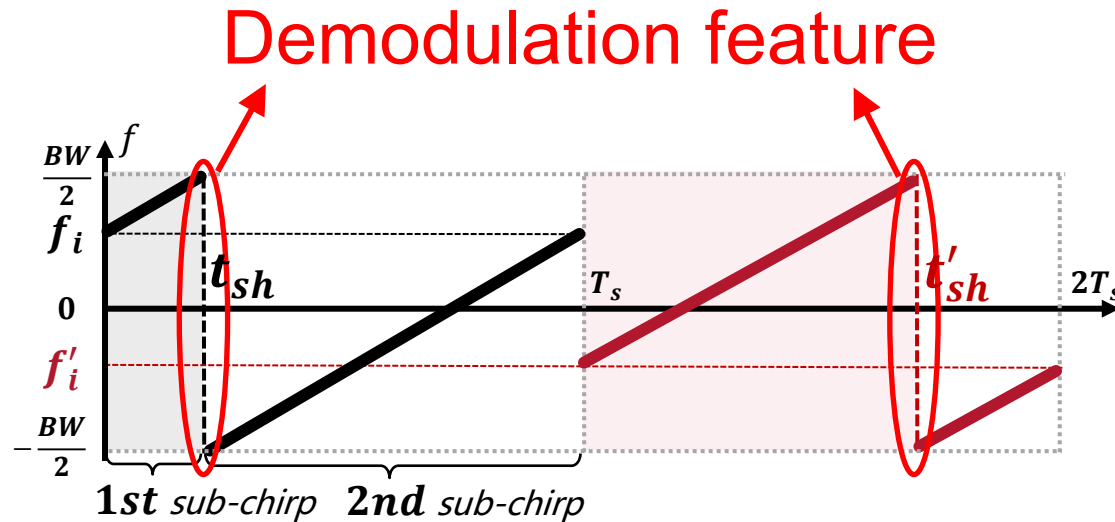

Passive d̲own-c̲onversion and d̲e-c̲hirp (dc^2) — Low-power hardware design

ZERO power — **µW power**

Helper signal / LoRa signal / Mixer / SPDT / Low-power IF Amp / LPF / Rectifier / OPA / Thresholding / MCU / Decoded data / Switching

Insight: time localization LoRa demodulation

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

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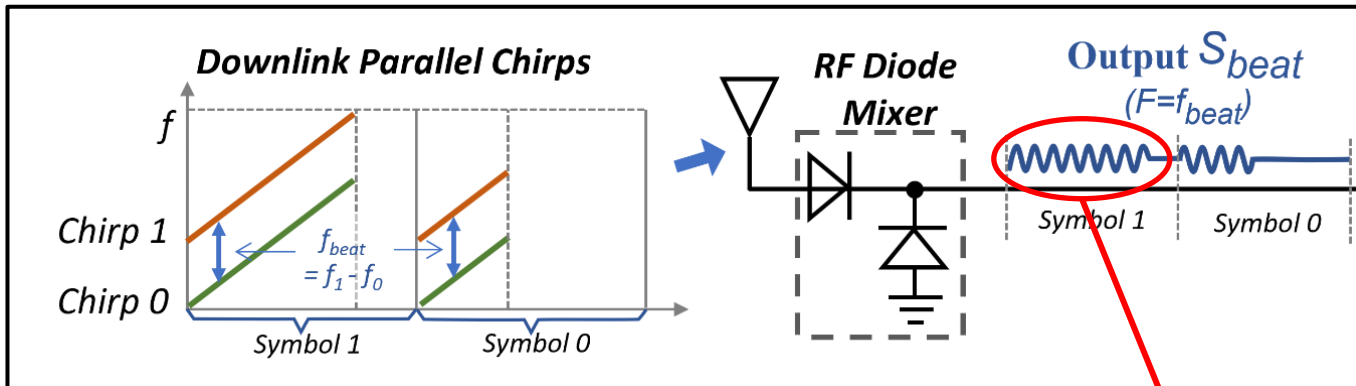
Passive one-shot **d**own-**c**onversion and **d**e-**c**hirping (dc^2) while reserving the demodulation feature for LoRa demodulation
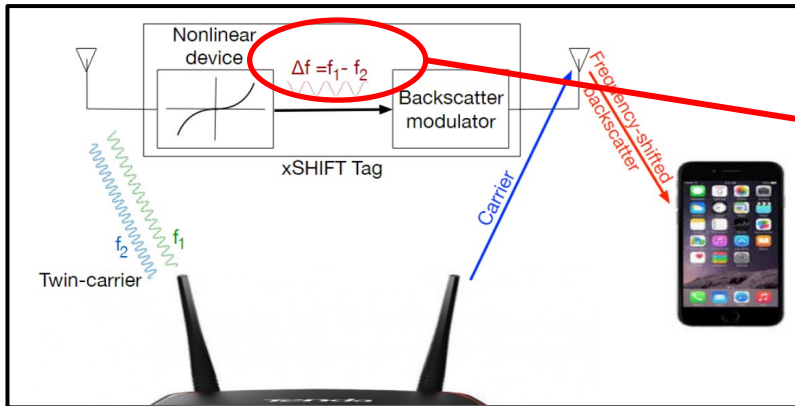

Demodulation feature

Problem:

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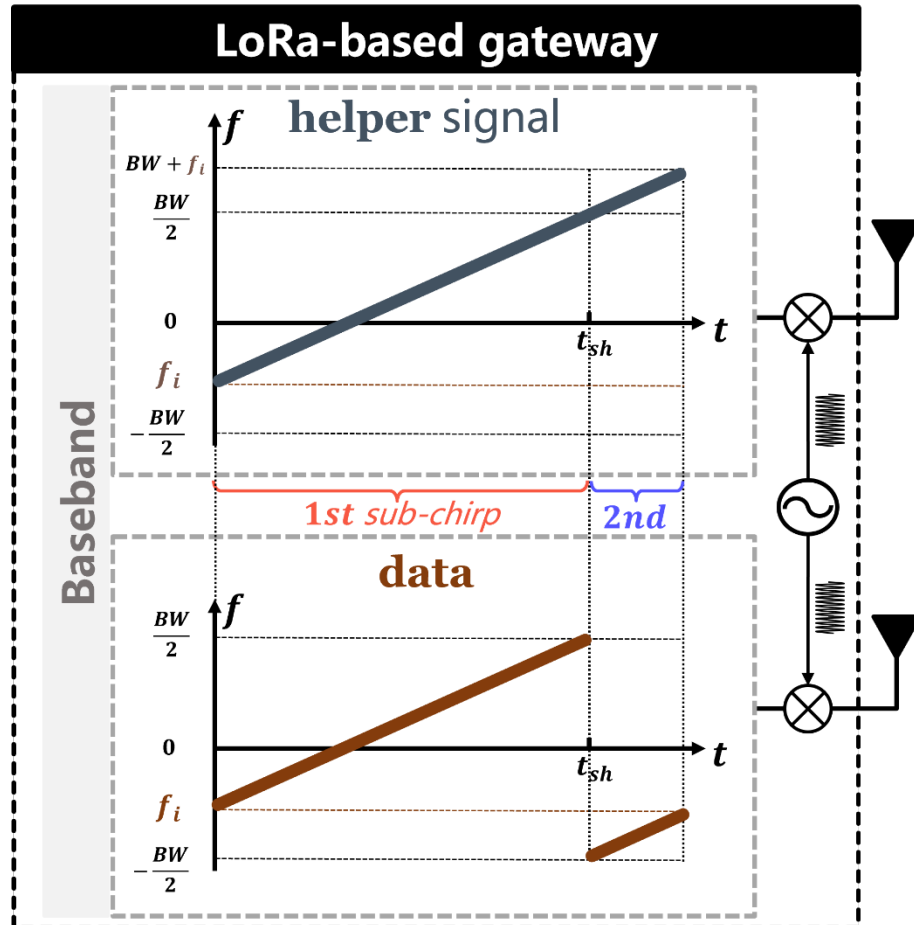

μMote
NSDI '23

XSHIFT
MobiCom '21

Single-tone
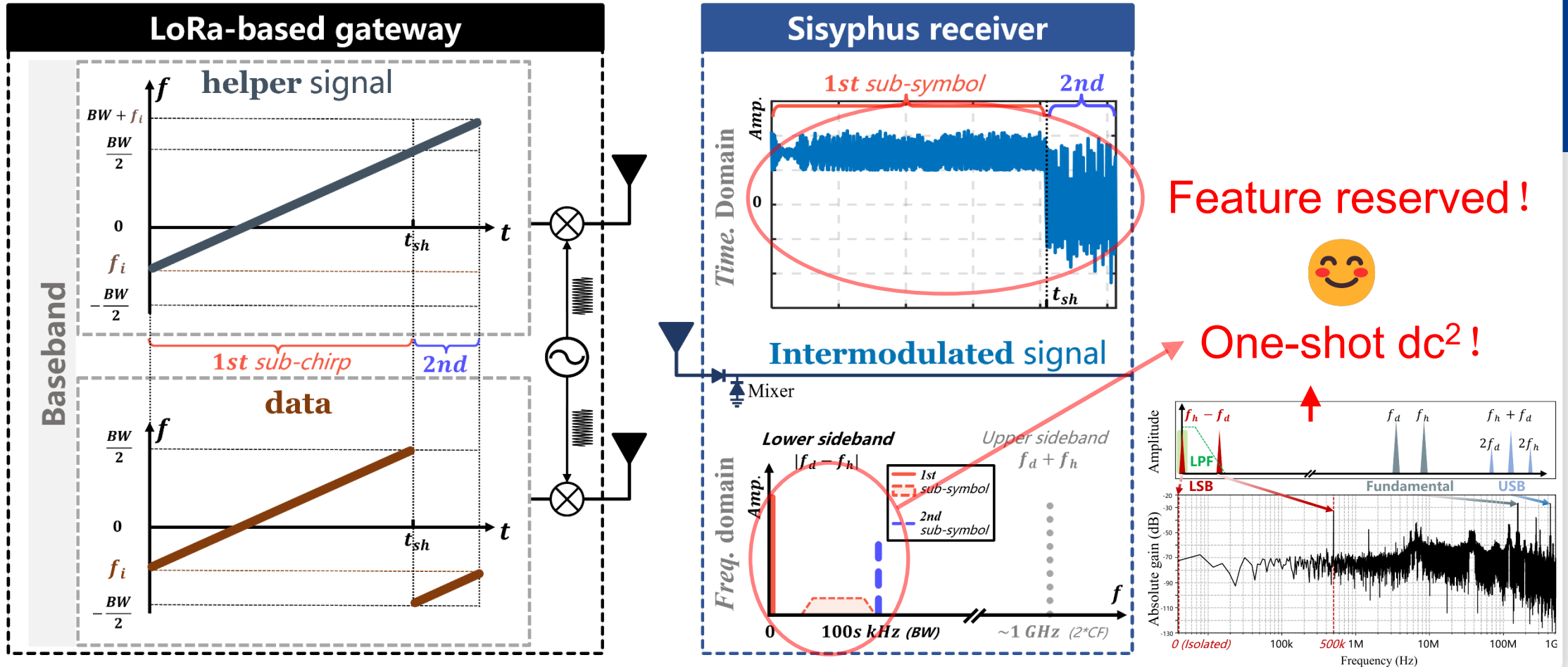
Destroy the demodulation feature

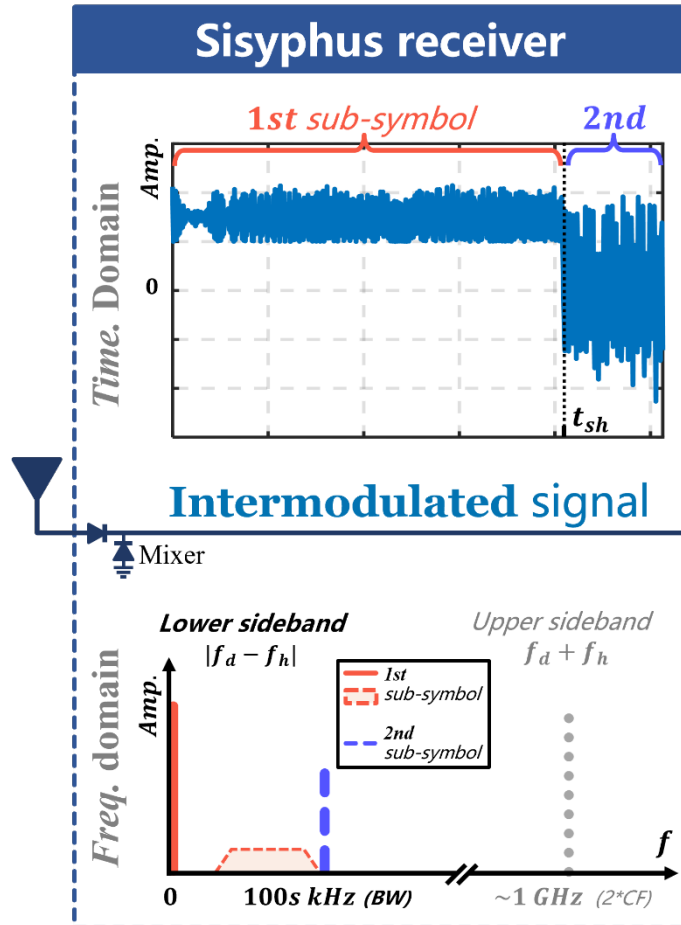## Solution:

Collaborative helper signal waveform design

Solution:

Collaborative helper signal waveform design

Feature reserved !

😊

One-shot dc^2 !

Problem:

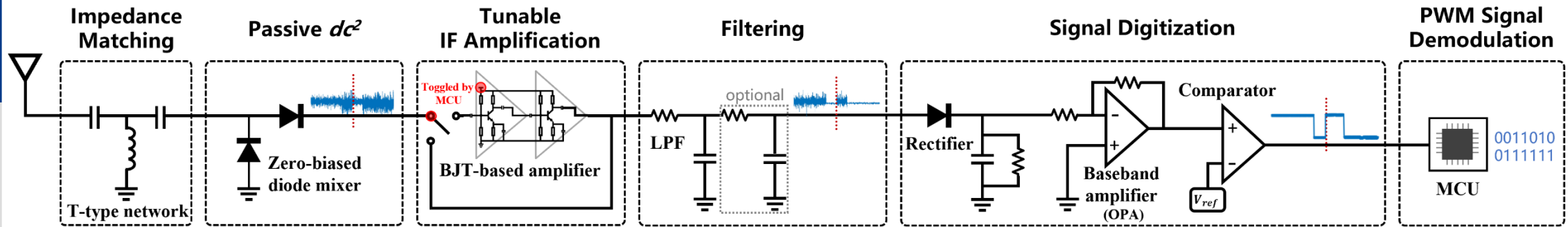How to demodulate post-dc^2 signals with negligible power consumption

Through digital signal processing? 🤔
(*e.g.,* wavelet transform, STFT and etc.)

🫨
**Power-consuming
and defeat our original purpose**
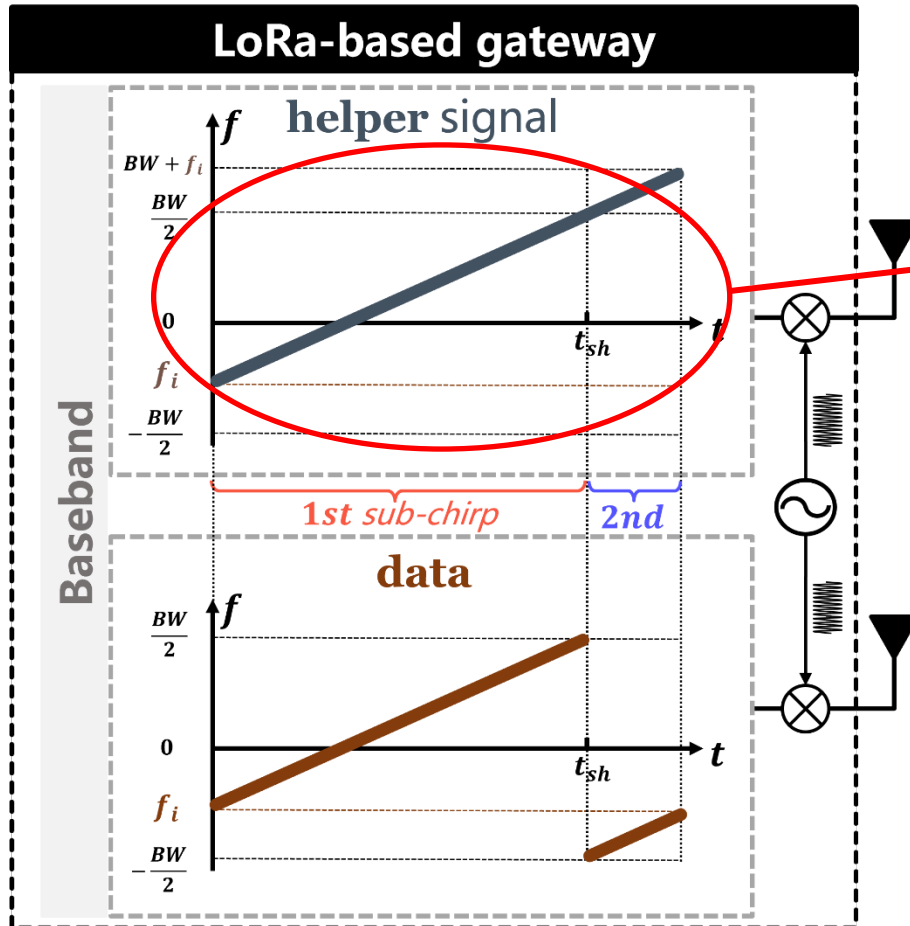
Solution:

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:
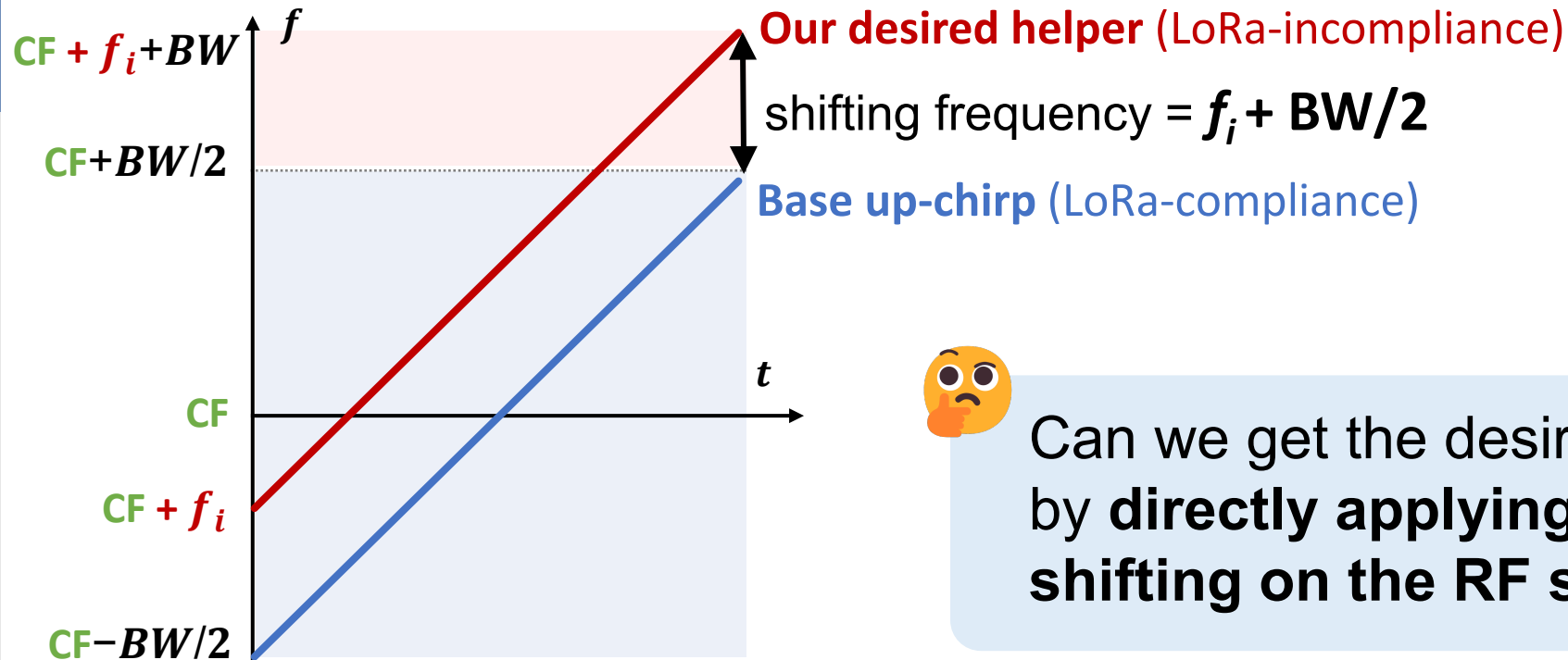
Backward compatible with COTS LoRa

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:
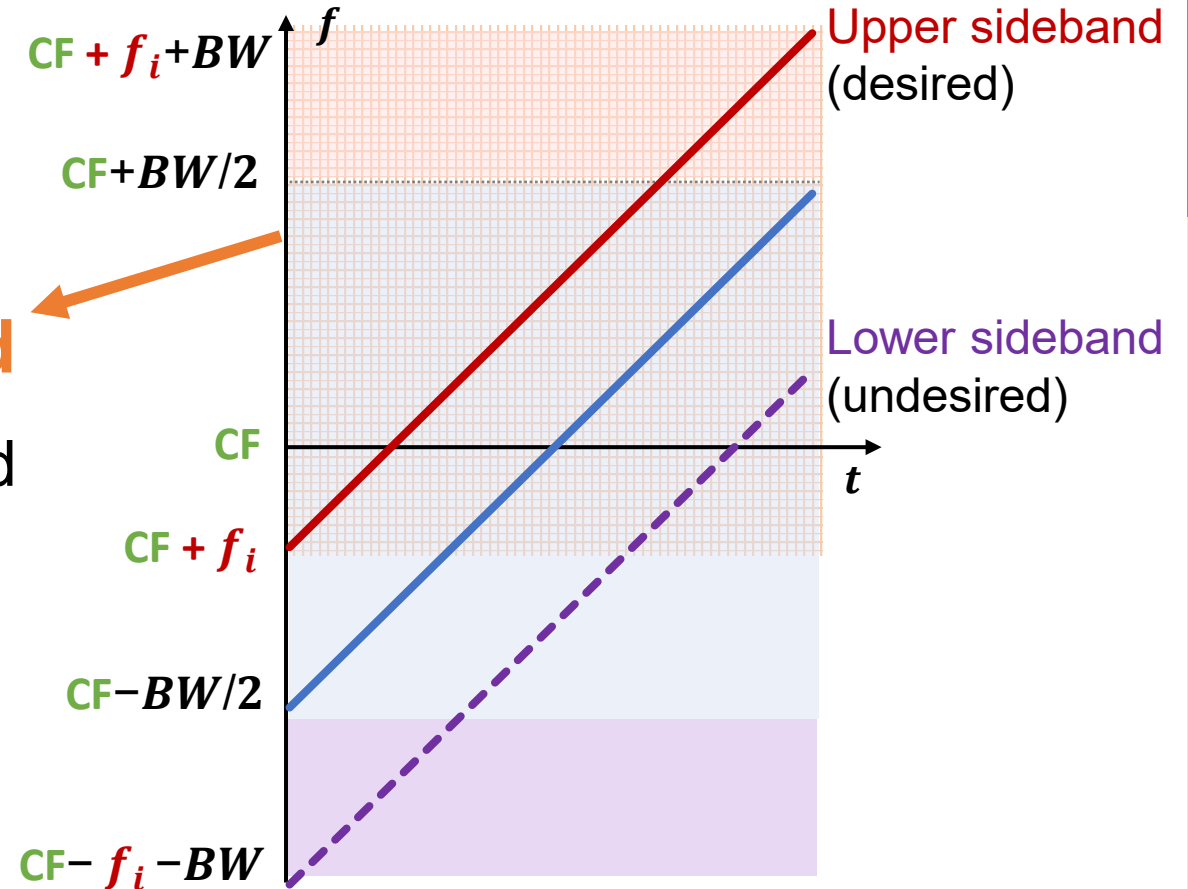Double sideband overlapping

Overlapped

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

CF + f_i + BW

CF + BW/2

CF

CF + f_i

CF − BW/2

CF − f_i − BW

f

Upper sideband
(desired)

Lower sideband
(undesired)

t

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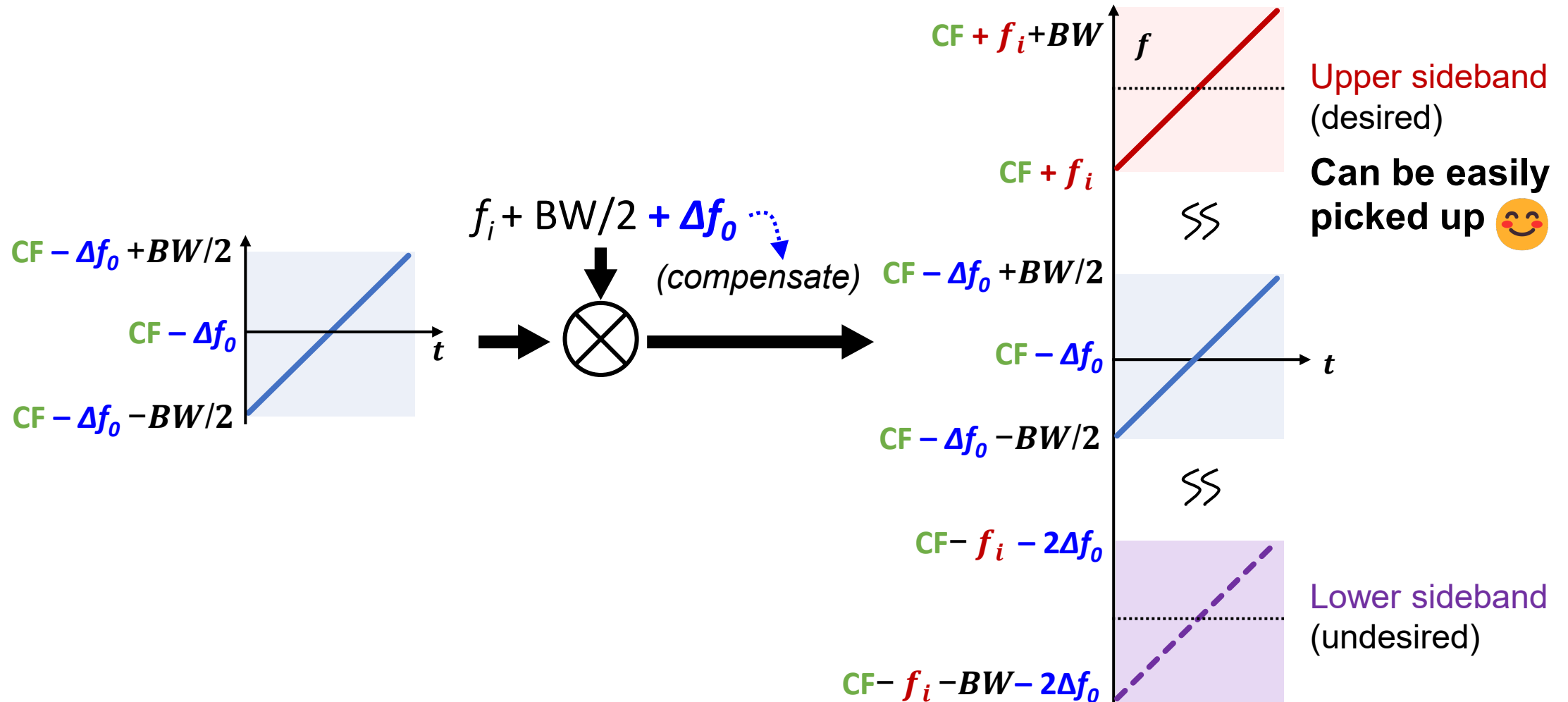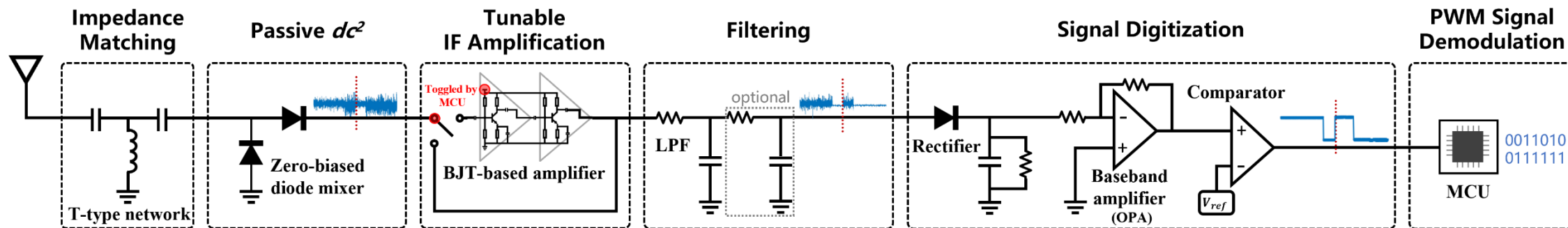
$$F_{RF} = F_{STEP} \times Frf(23,0)$$

Solution:

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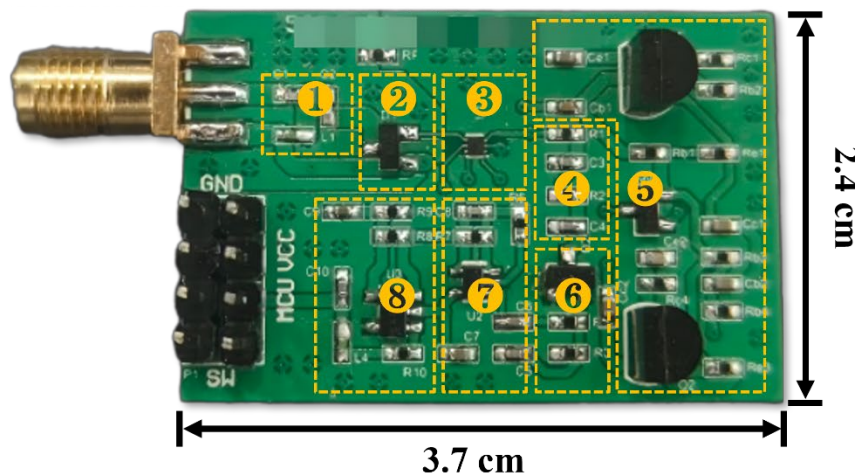
Solution:

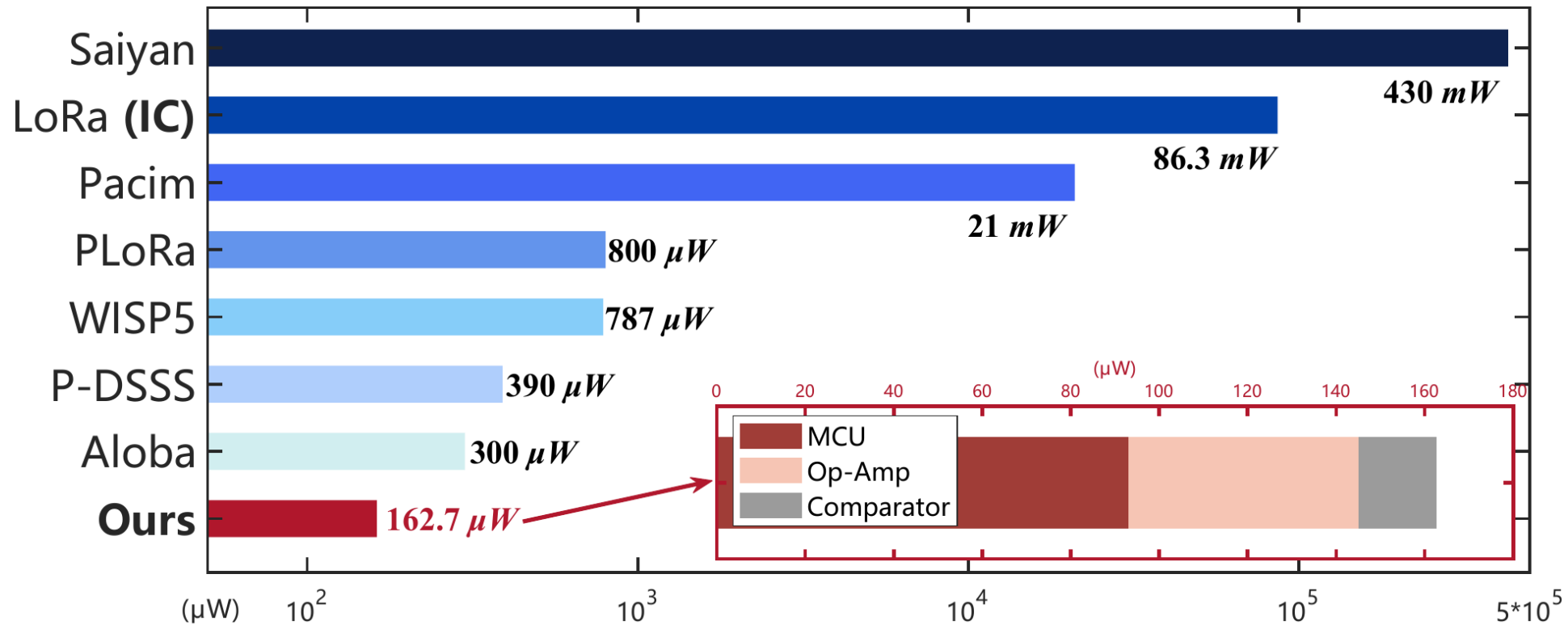Modify CF and compensate its variation in the shifting frequency

f_i + BW/2 **+ Δf₀**

(compensate)

CF **+ f_i + BW**

CF **+ f_i**

Upper sideband
(desired)

**Can be easily
picked up** 😊

CF **− Δf₀ + BW/2**

CF **− Δf₀**

CF **− Δf₀ − BW/2**

CF **− Δf₀ + BW/2**

CF **− Δf₀**

CF **− Δf₀ − BW/2**

CF **− f_i − 2Δf₀**

CF **− f_i − BW − 2Δf₀**

Lower sideband
(undesired)

Impedance Matching · Passive dc^2 · Tunable IF Amplification · Filtering · Signal Digitization · PWM Signal Demodulation

T-type network · Zero-biased diode mixer · Toggled by MCU · BJT-based amplifier · LPF · optional · Rectifier · Baseband amplifier (OPA) · Comparator · V_{ref} · MCU · 0011010 0111111

Prototype

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

2.4 cm

3.7 cm

- 37mm×24mm 4-layer FR4 PCB

- 2 versions:
  - ☐ Sisyphus+: IF amplifier ON
  - ☐ Sisyphus: IF amplifier OFF
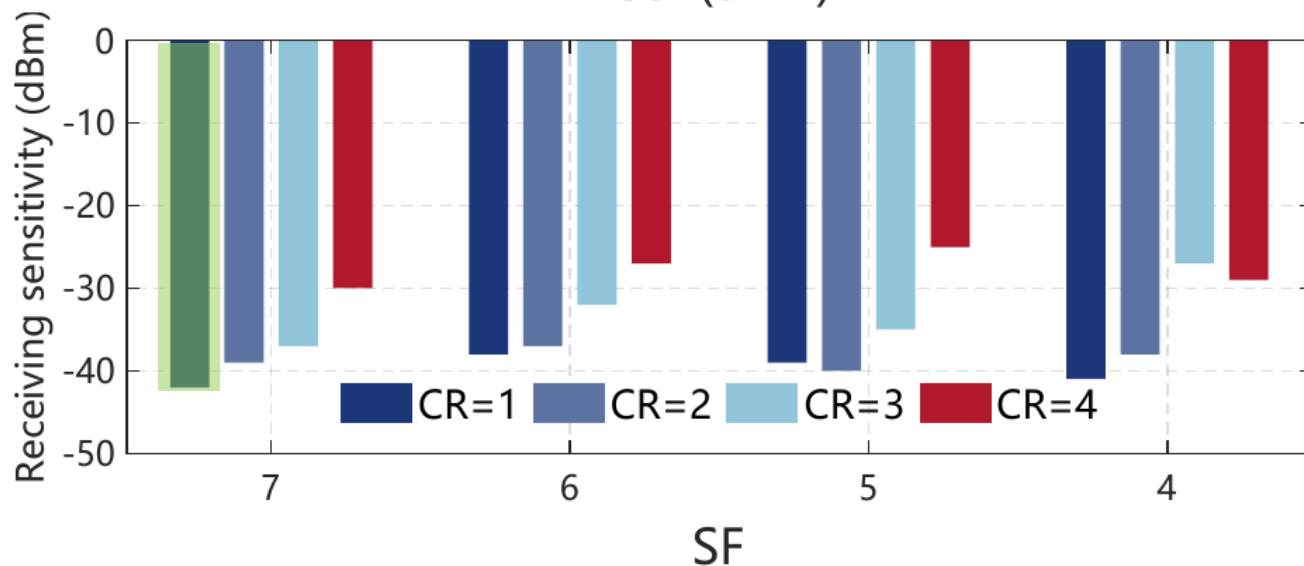
- ✓ **530×** reduction compared to IC-based legacy LoRa receiver

- ✓ **4.9×, 1.8×, 129×** reduction compared to demodulation-disable LoRa-based backscatter systems' downlink

- ✓ Power of IF amplifier: **286 μW**

Sisyphus

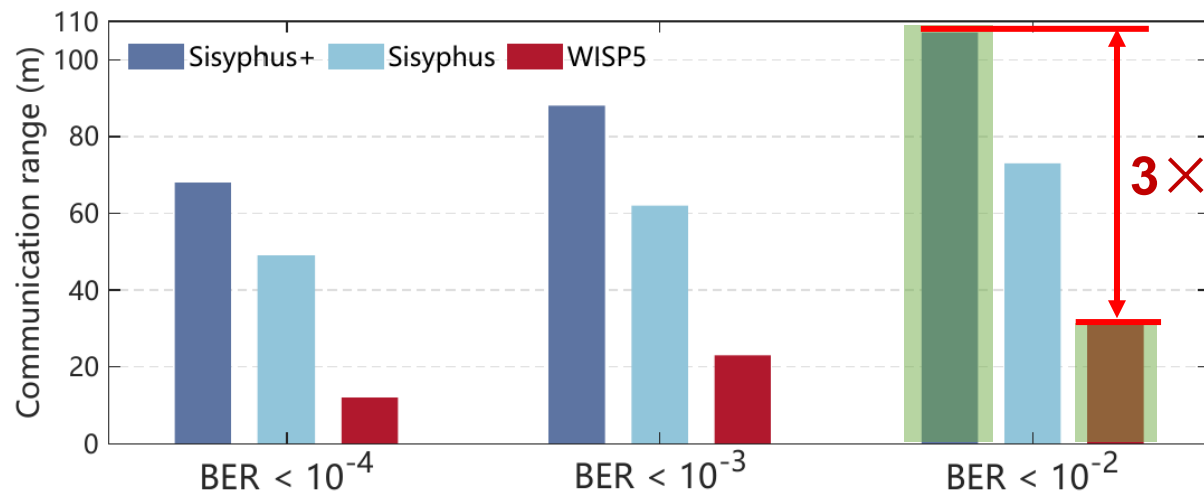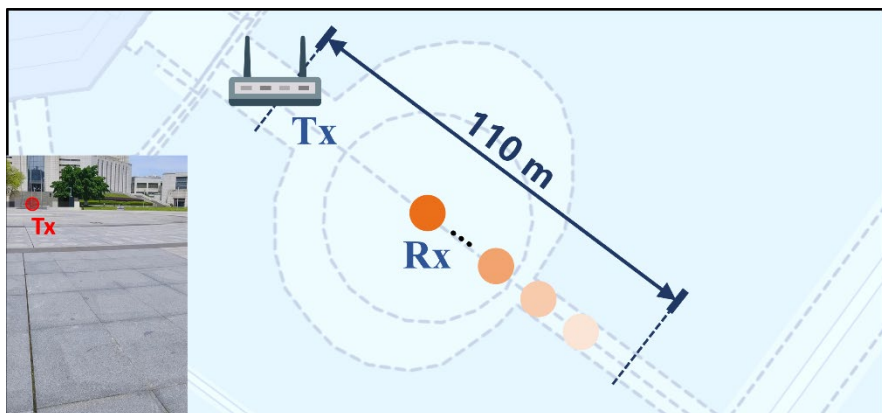Sensitivity: **-36dBm**

6dB gain
with IF amplifier ON
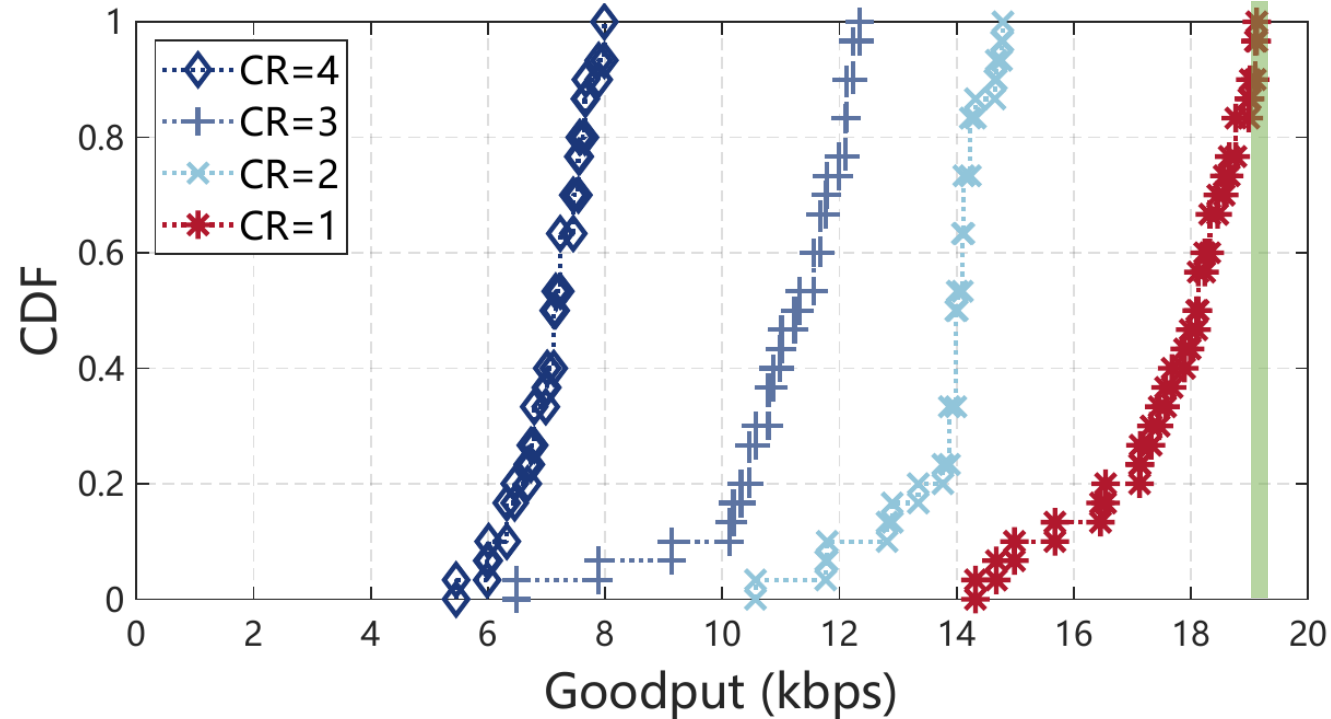
Experimental setup:

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

3× improvement range
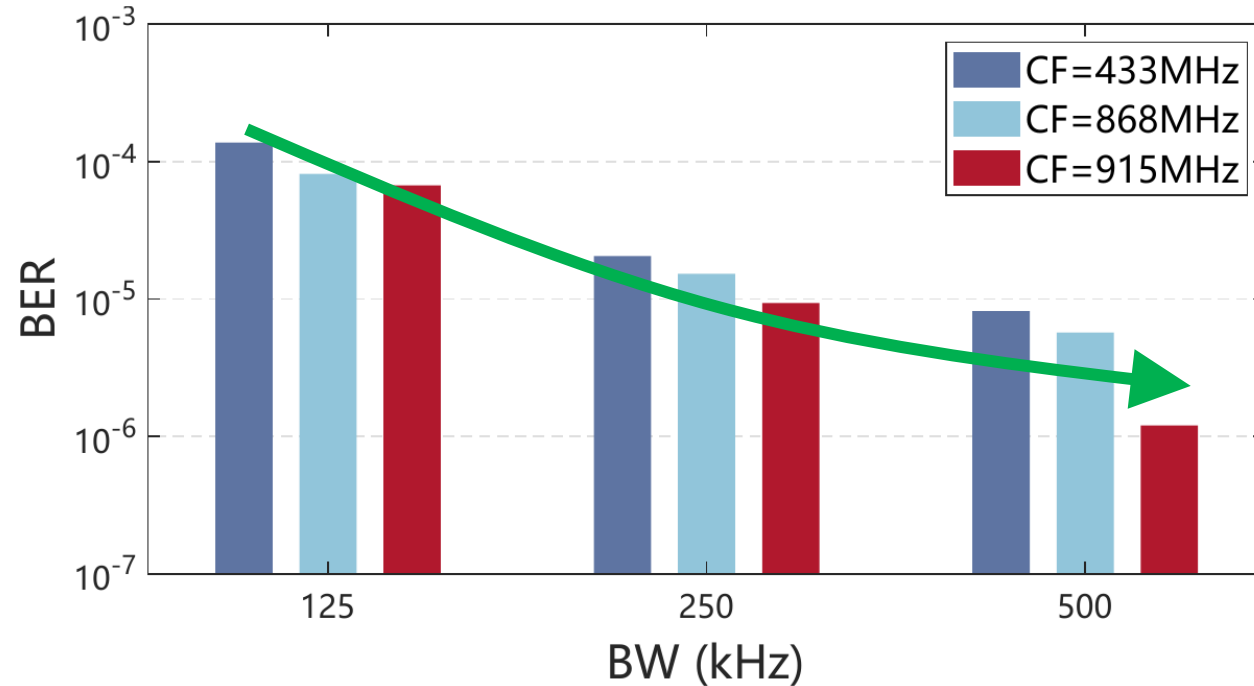compared to ED-based receiver

Goodput

Indicating the BER in different time and locations

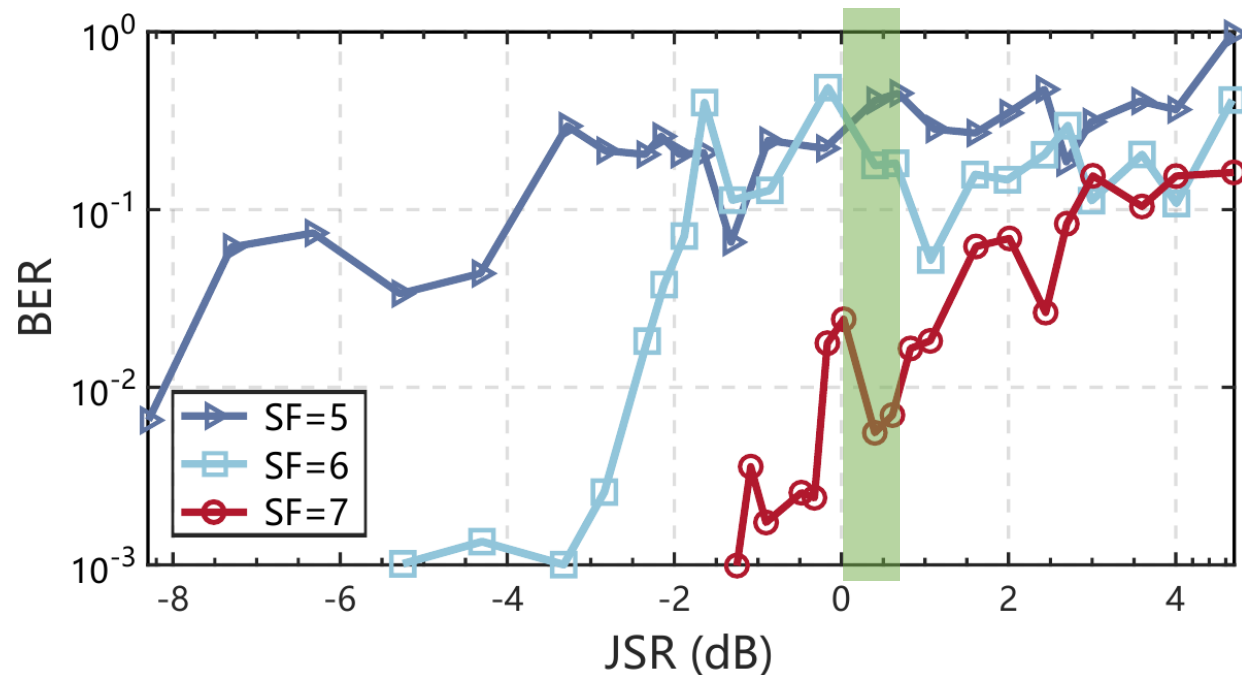**Comparative goodput with legacy receiver**

Why?

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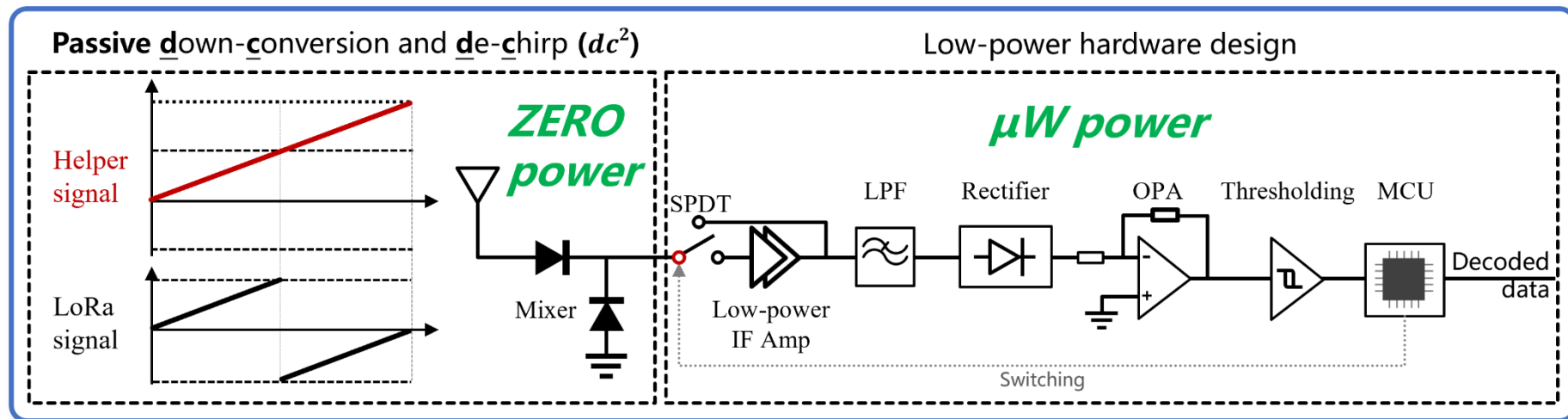

BW↑ and CF↑, performance↑

Setup:

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

Sisyphus can achieve accurate communication with 0.8dB JSR

✓ 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**

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Sisyphus: Redefining Low Power for LoRa Receiver

Thanks for your attention! 🥰

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Q&A