Saiyan: Design and Implementation of a Low-power Demodulator for LoRa Backscatter Systems

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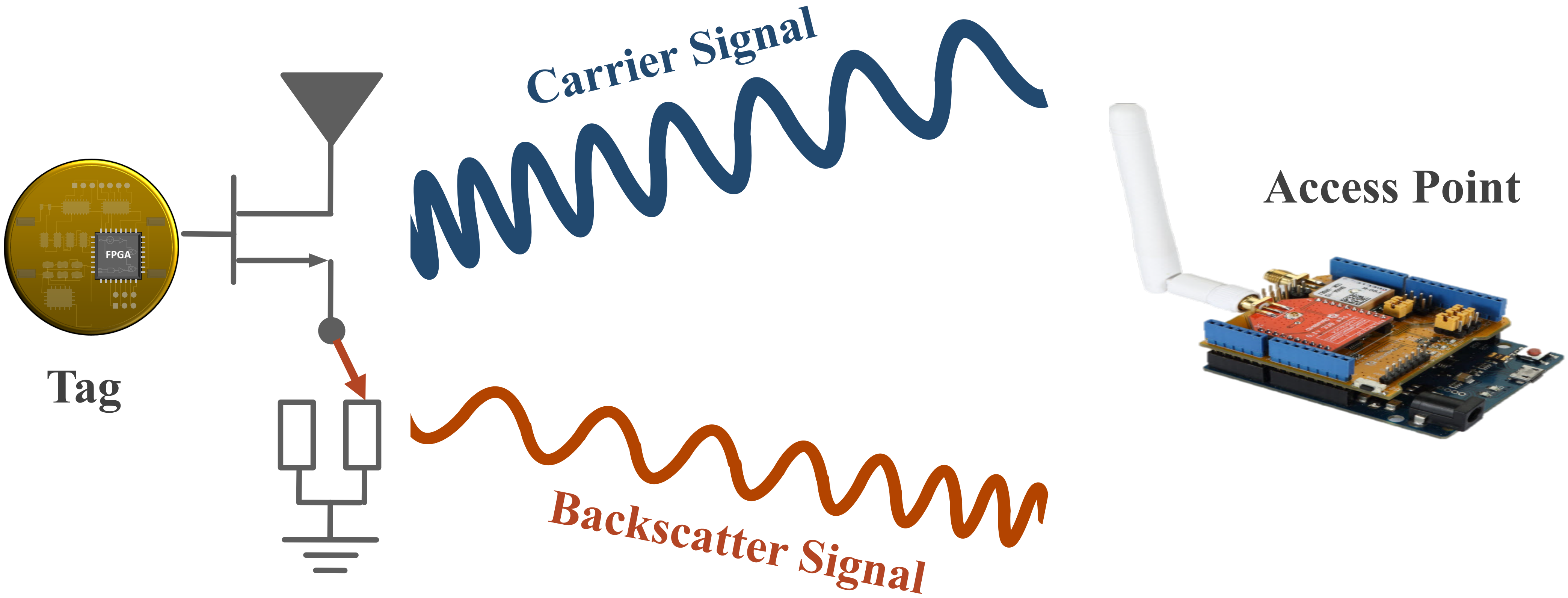
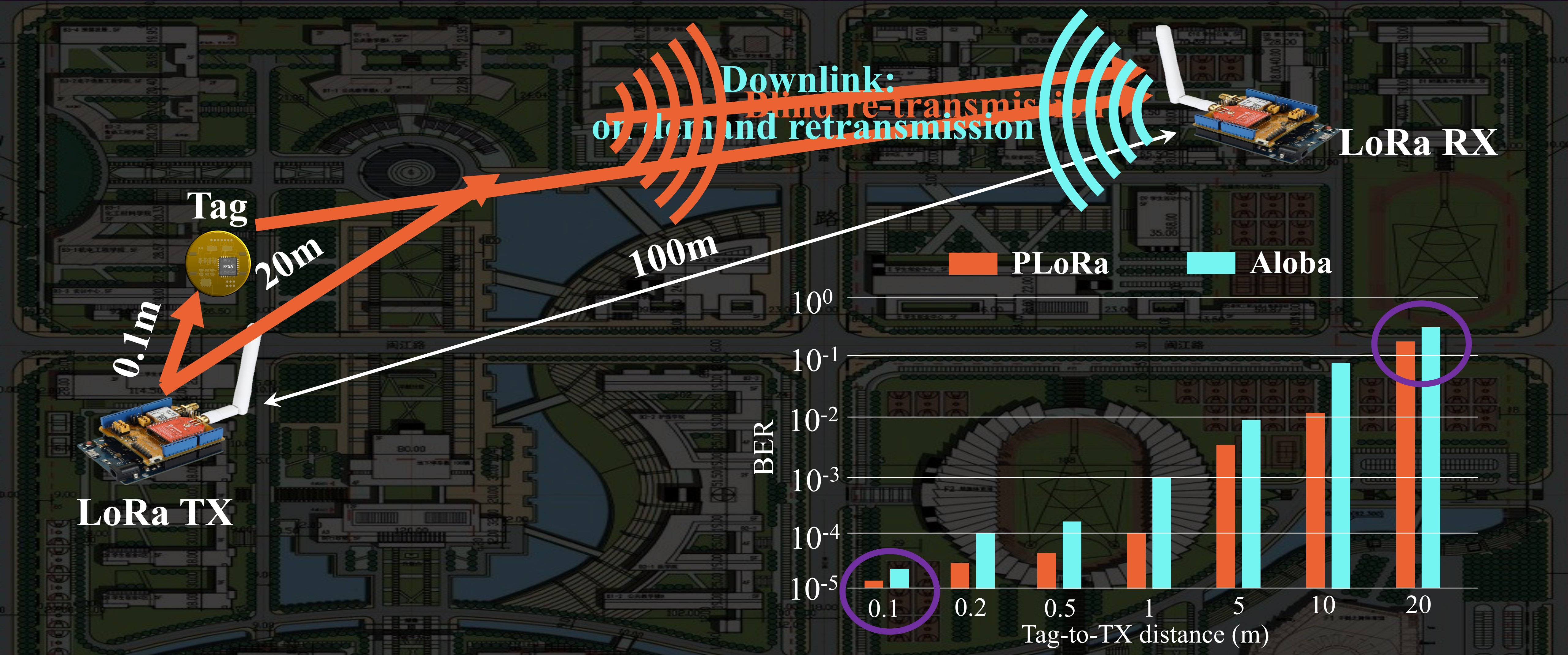
Backscatter Provides Ubiquitous Wireless Connectivity

LoRa Backscatter Primer



[1] **PLoRa**: A passive long-range data network from ambient LoRa transmissions. SIGCOMM, 2018
[2] **Aloba**: Rethinking on-off keying modulation for ambient LoRa backscatter. SenSys, 2020.

Challenge on Packet Delivery



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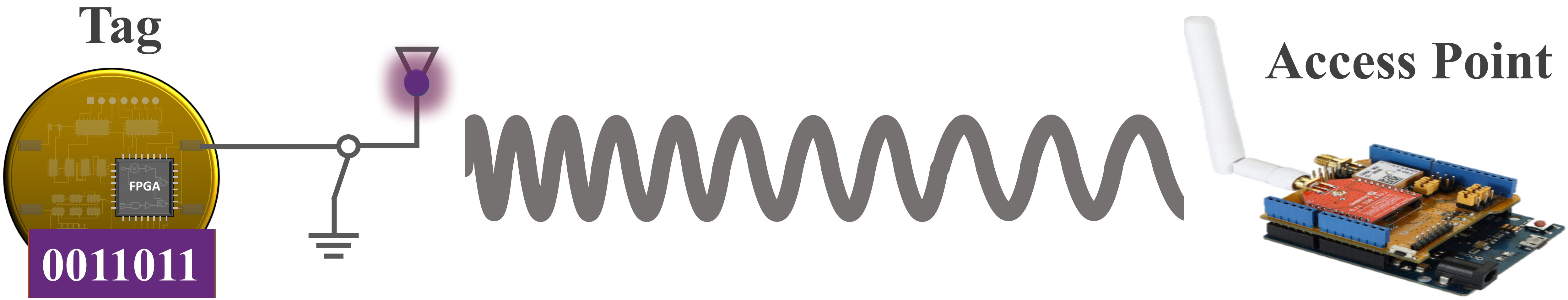
Downlink Demodulation



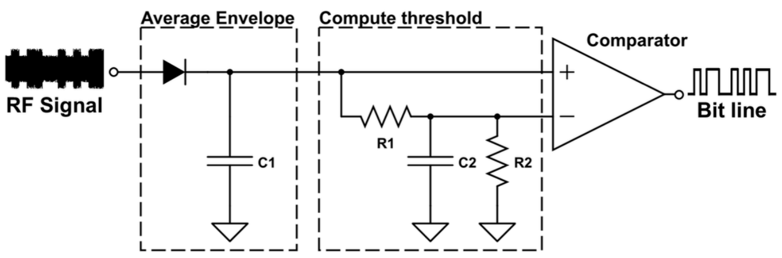
Making on-demand re-transmissions

Allocating commands and scheduling channels

Adapting data rate to link condition

Existing Works for Downlink Demodulation

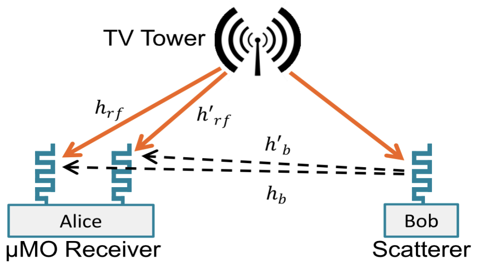
Leveraging the envelope detector



- RFID systems
- Ambient backscatter [SIGCOMM'12]
- Passive WiFi [NSDI'18]
- Netscatter [NSDI'16]

For amplitude-modulated signals

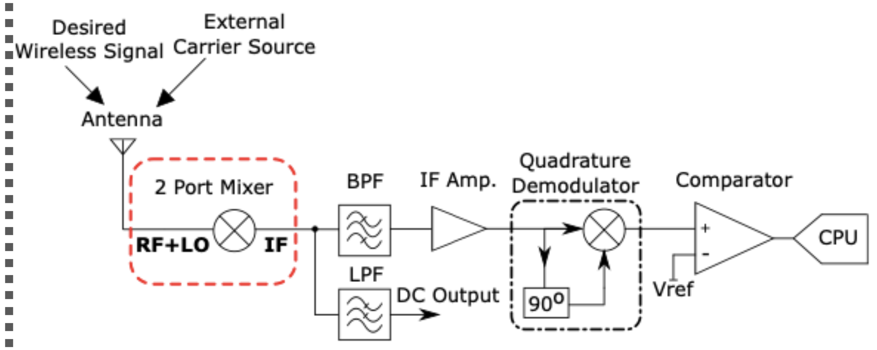
Leveraging a multi-antenna cancellation circuit



- Turbocharging [SIGCOMM 2014]
- Full-duplex LoRa backscatter [NSDI 2021]

Power-intensive and complex

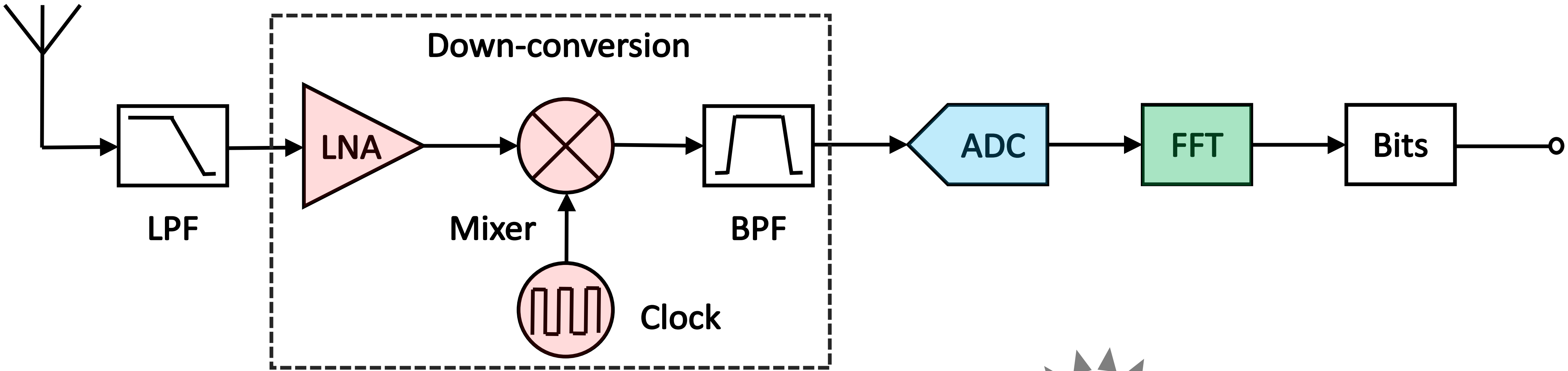
Offloading power-intensive functions to external devices



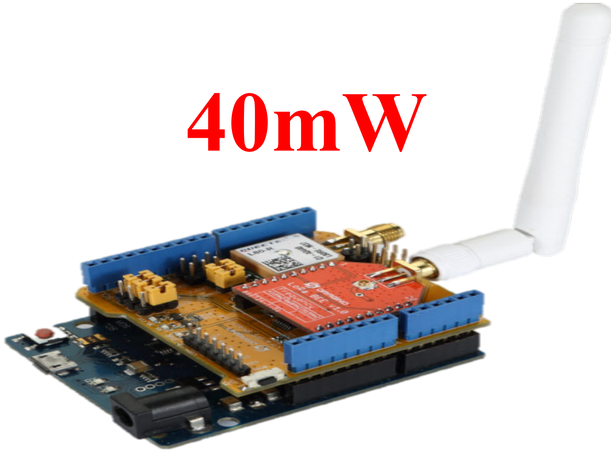
- Low-power BLE receiver [RFID 2017]
- Low-power ZigBee receiver [IPSN 2018]

Limited demodulation range

How to demodulate LoRa Symbols?

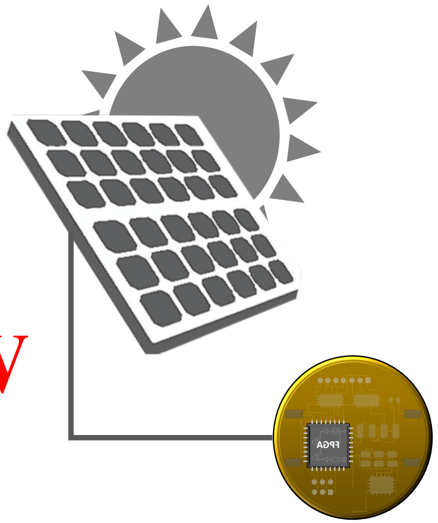


40mW



A commercial LoRa receiver

1mW

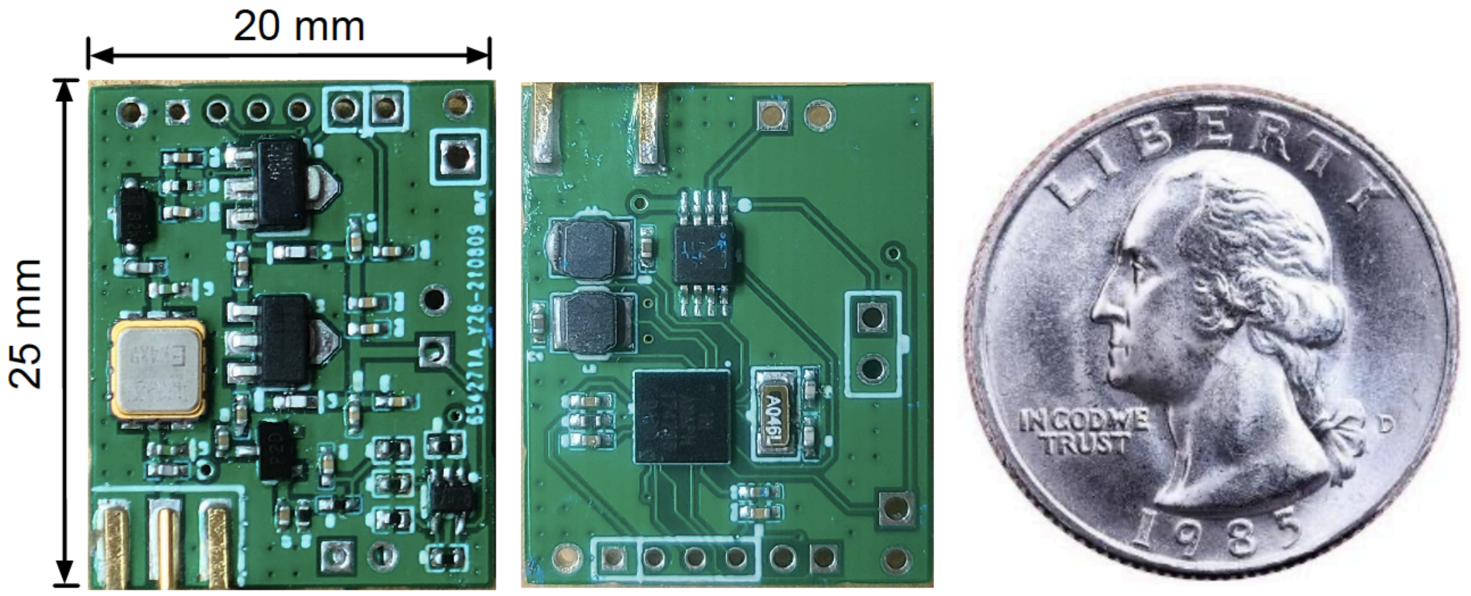


Tag

Can we enable a low-power demodulator for long-range LoRa backscatter systems?

Saiyan: a Low-power Demodulator

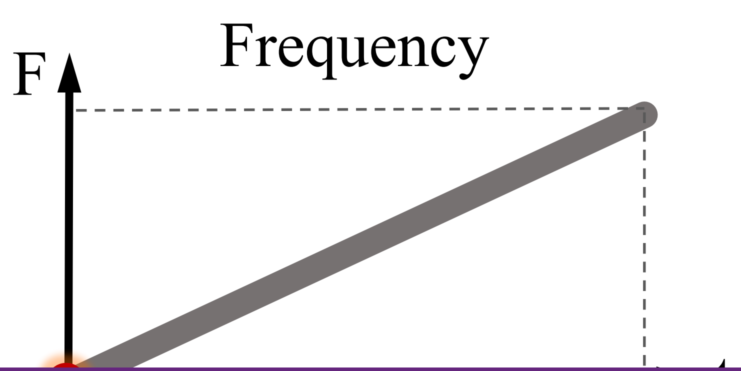
- **The first-of-its-kind low-power LoRa demodulator**
  - **Power consumption of 369.4uW**
  - **Demodulation range of 180m**

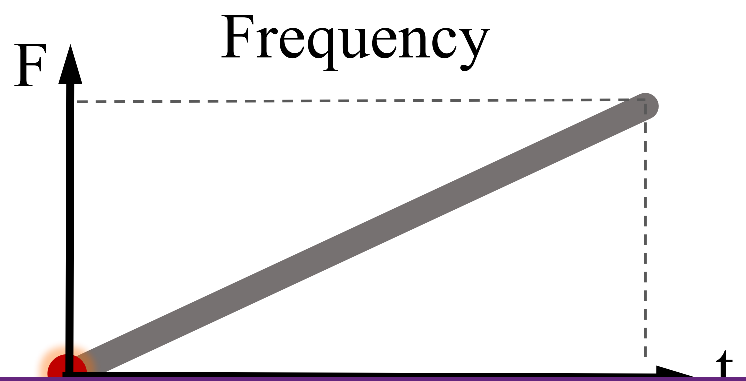


(a) Front (b) Back (c) Quarter

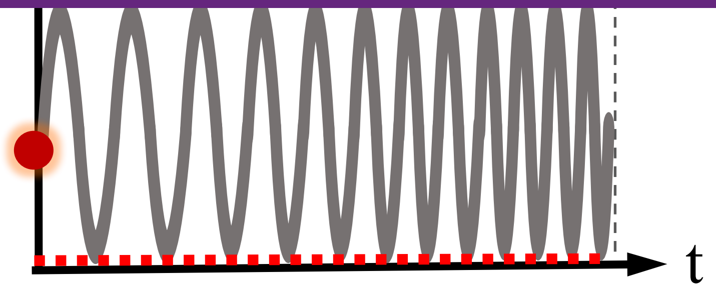
Code and hardware schematics can be found at: https://github.com/ZangJac/Saiyan

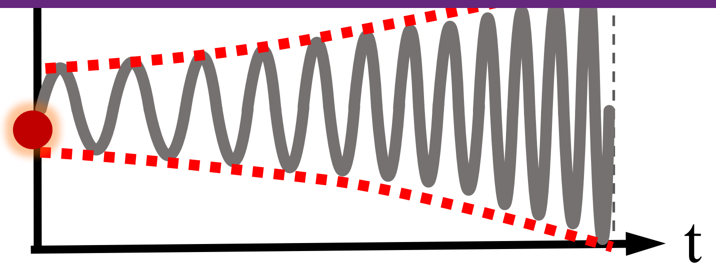
Key Observation





The frequency-modulated chirp signal can be transformed into the amplitude-modulated signal using a differential circuit.





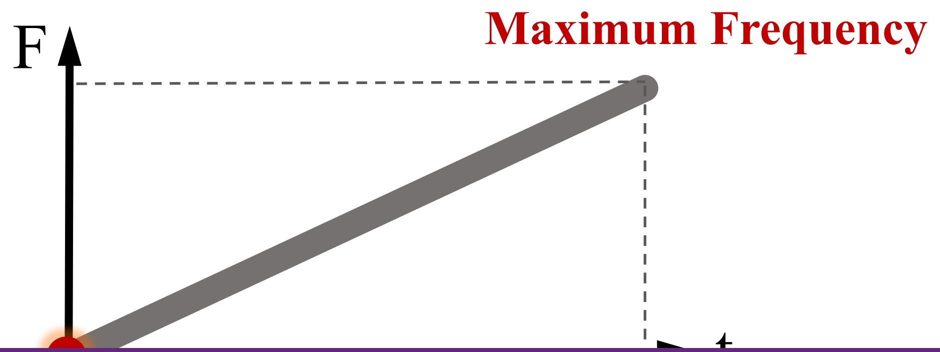
$$s(t) = A sin(2\pi f(t)t)$$

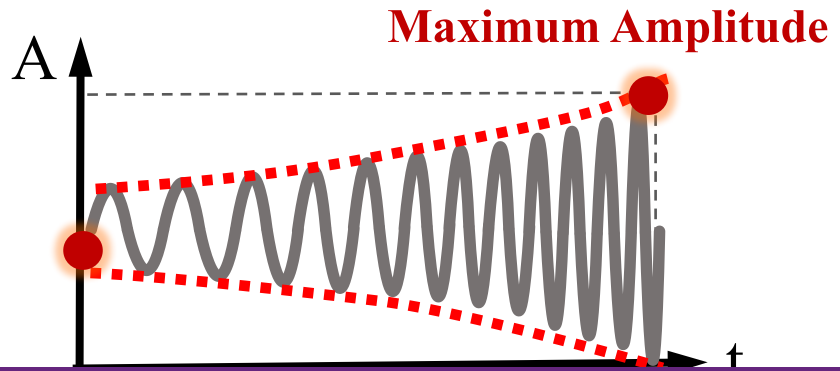
$$f(t) = F_0 + kt$$

$$s'(t) = \frac{ds(t)}{dt} = A cos(2\pi f(t)t)[2\pi \frac{df(t)}{dt} t + 2\pi f(t)]$$

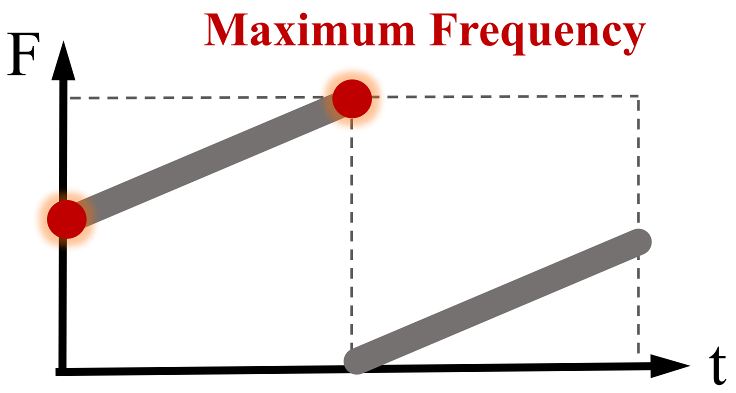
$$= \underbrace{2\pi A(F_0 + 2kt)}_{Amplitude} cos(2\pi f(t)t)$$

Key Observation

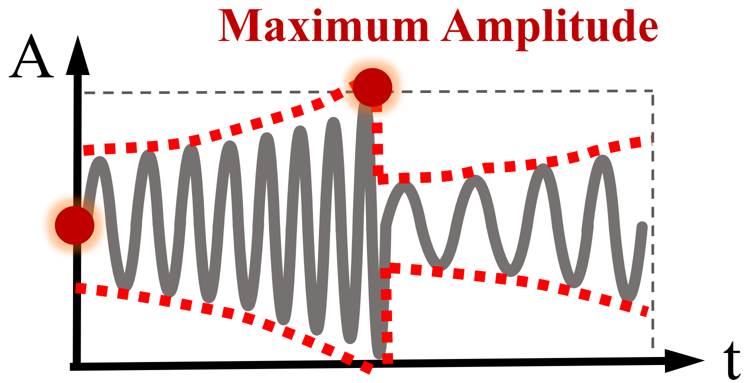




Demodulate the frequency-modulated LoRa signal by tracking the peak amplitude on its transformed counterpart.

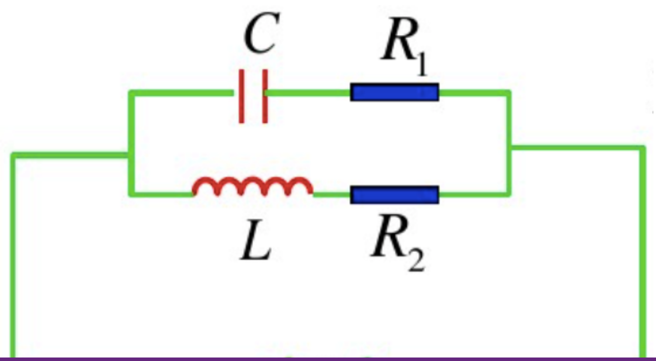


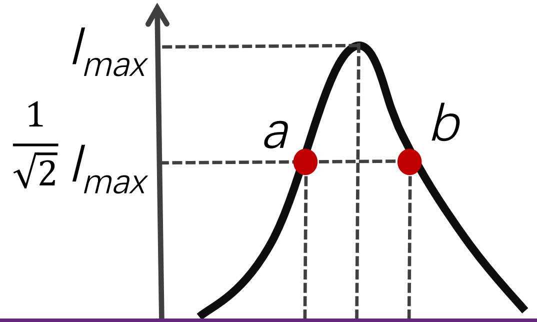
Symbol “10”



Symbol “10”

Frequency-amplitude Transformation





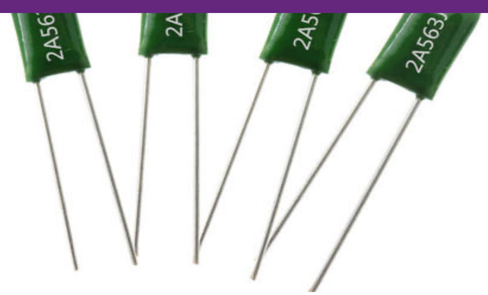
Upper bound capacitance

$$C = \frac{1}{Q\,\omega_0 R} = \frac{\Delta\omega}{\omega_0^2 R} = \frac{500KHz}{(433MHz)^2 * 50}$$

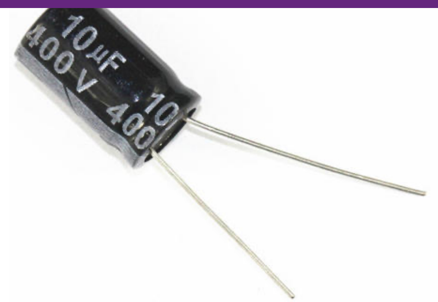
Building a narrow-bandwidth RLC differential circuit is impractical for LoRa signals!

5pF

100pF



1000pF

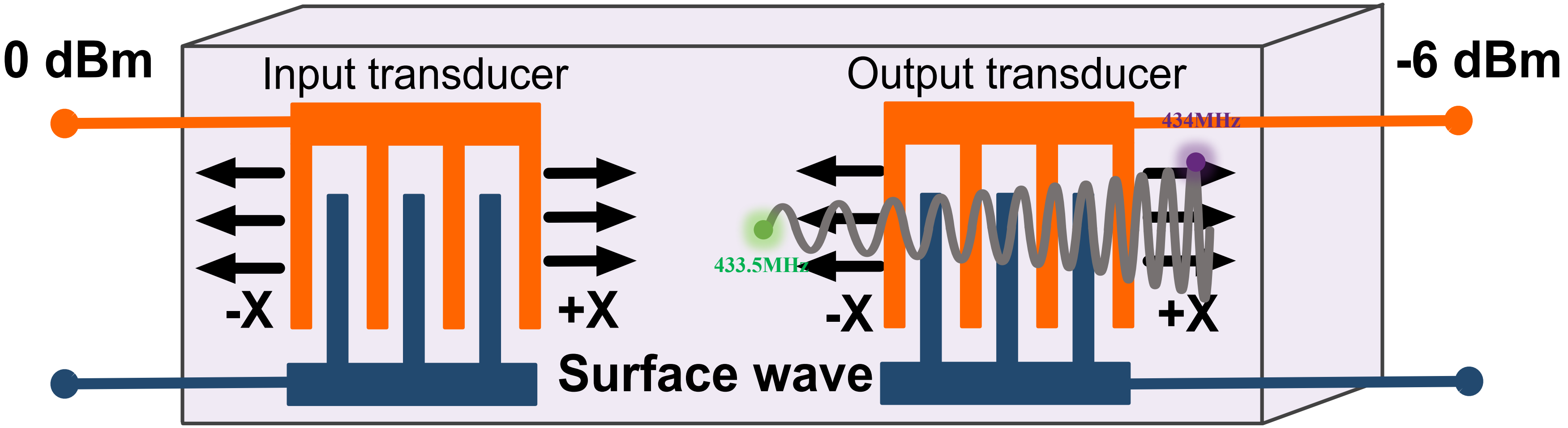


0.1uF

Very difficult!

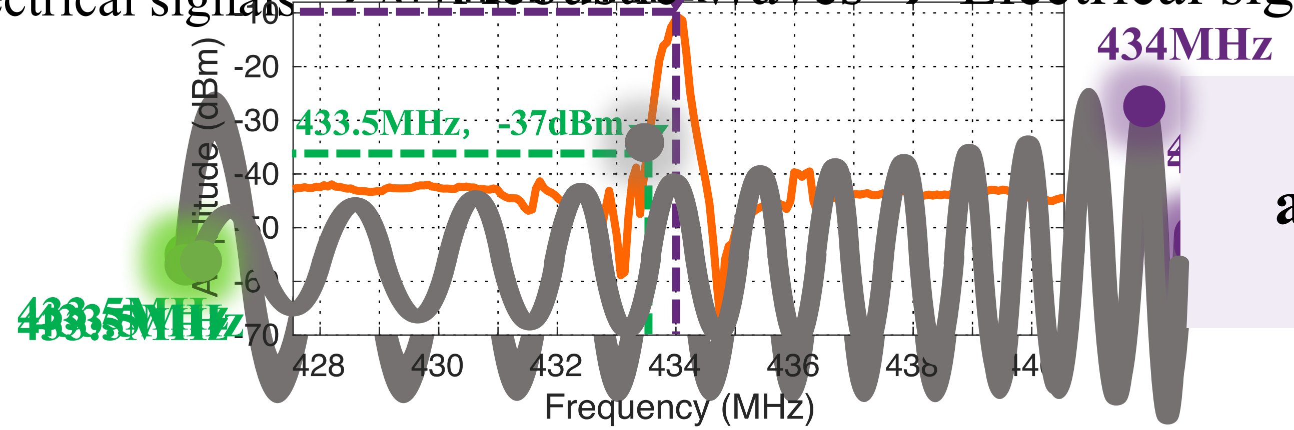
Surface Acoustic Wave (SAW) Filter

Passive SAW Filter



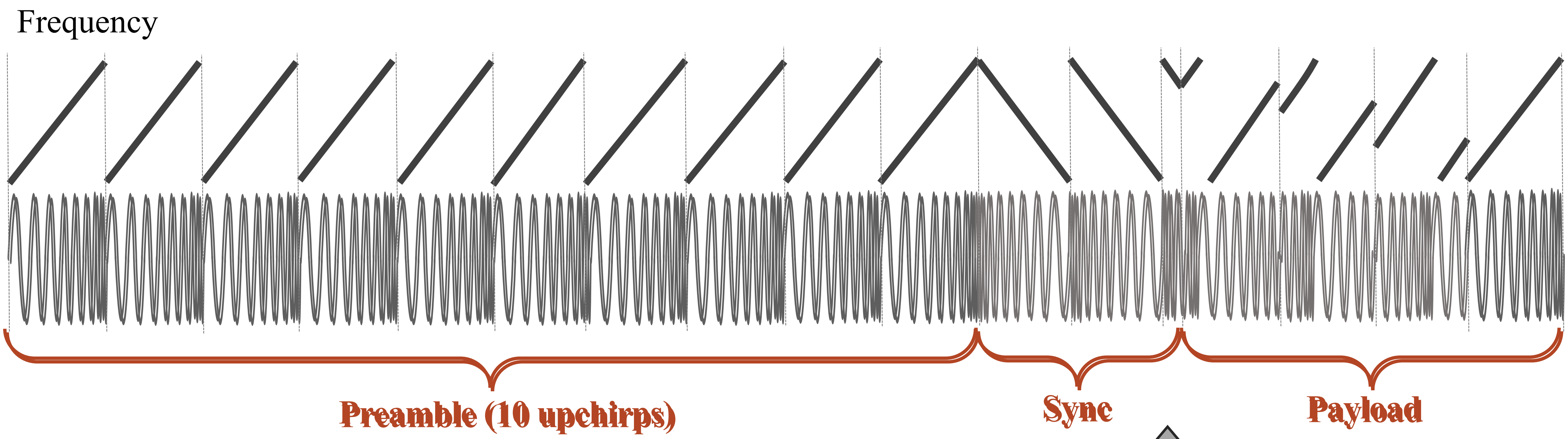
Electrical signals → Acoustic Waves

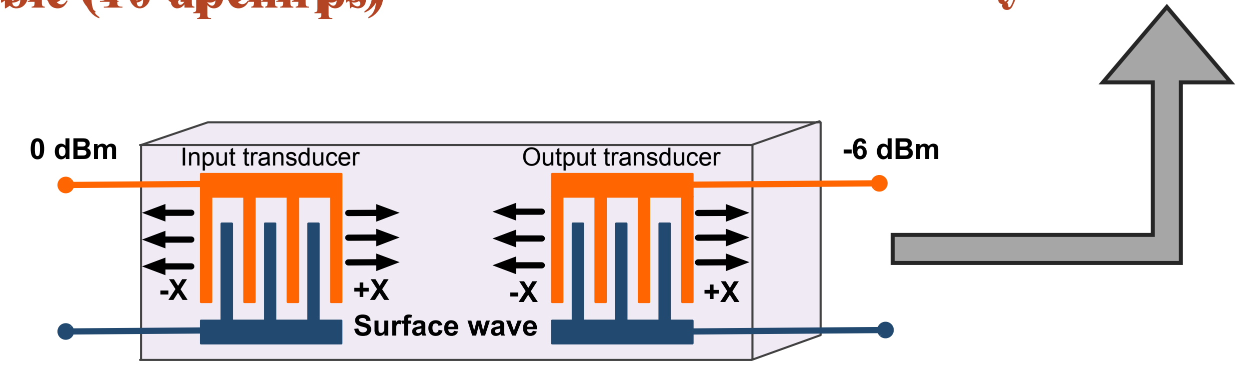
Acoustic Waves → Electrical signals



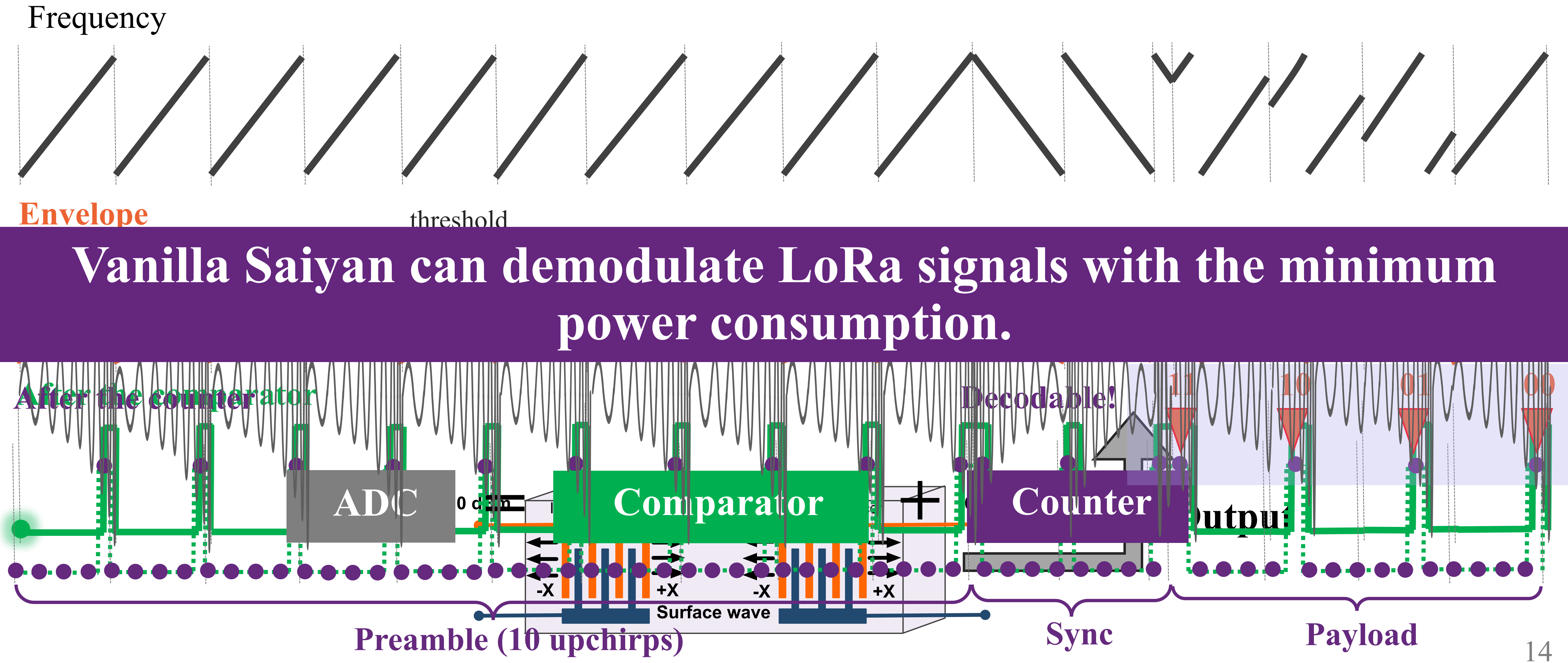
Sharp amplitude-frequency response

Vanilla Saiyan



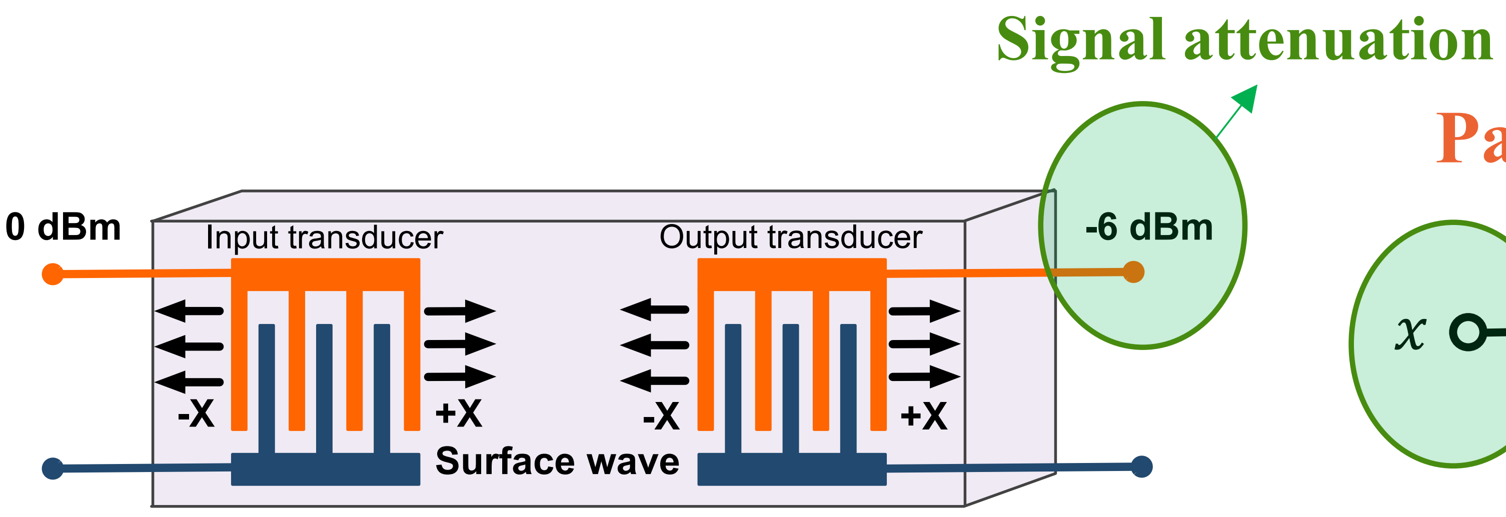


Vanilla Saiyan

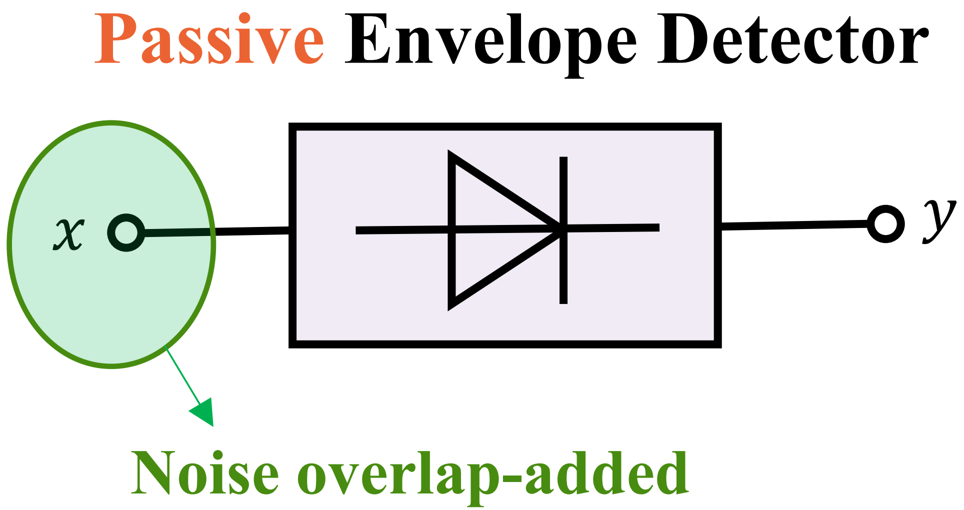


Vanilla Saiyan can demodulate LoRa signals with the minimum power consumption.

Demodulation Sensitivity of Vanilla Saiyan



Passive SAW Filter

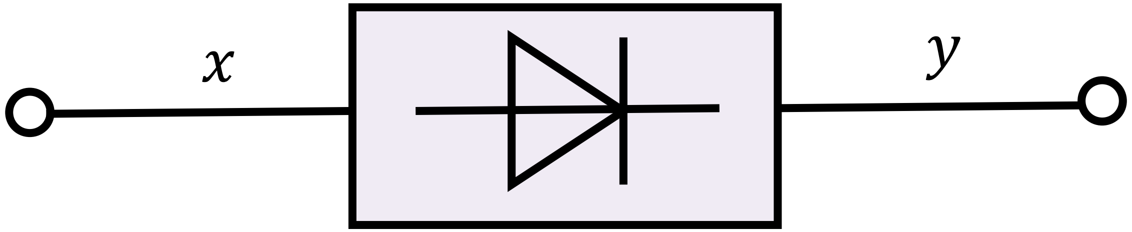


Super Saiyan

Improving the Demodulation Sensitivity

Non-linearity

$$y = kx^2$$



Envelope Detector

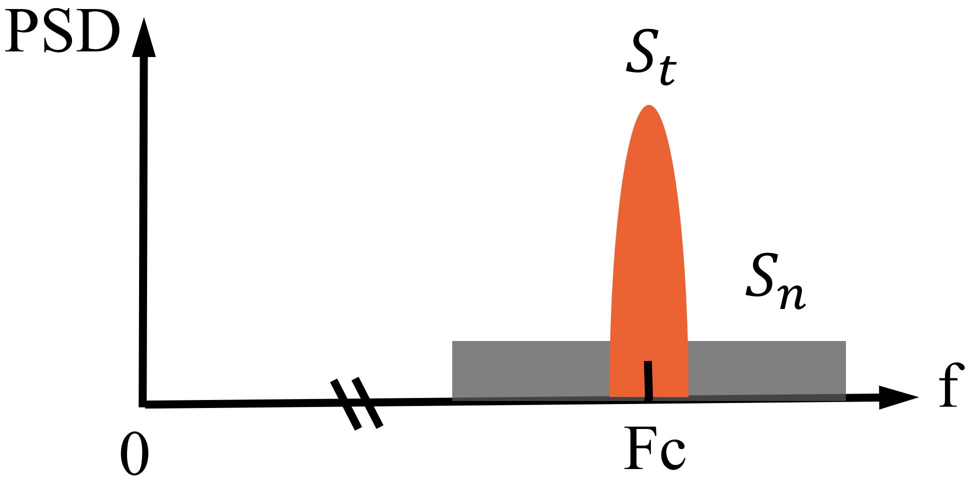
$$S_{out} = kS_{in}^2 = k(S_t + S_n)^2$$

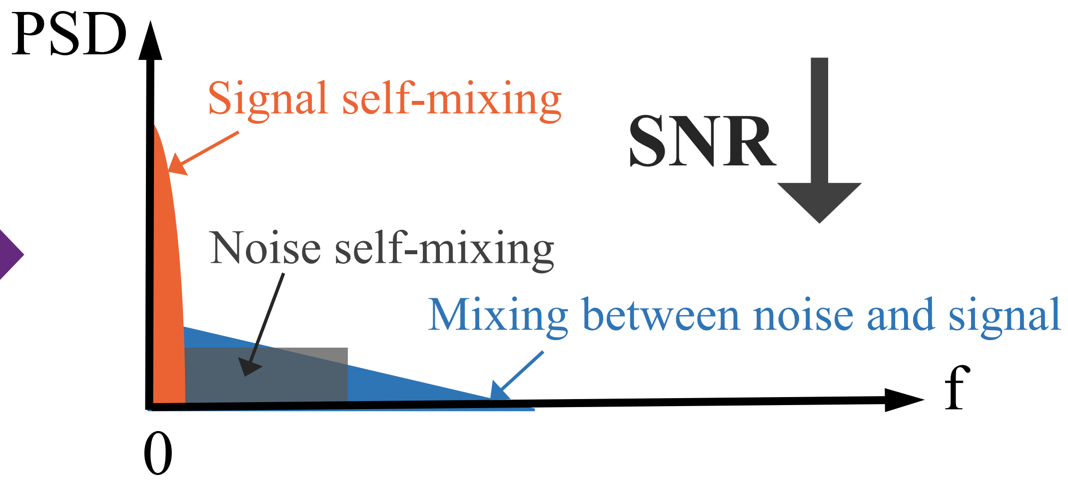
$$= kS_t^2 + 2kS_tS_n + kS_n^2$$

Noise self-mixing

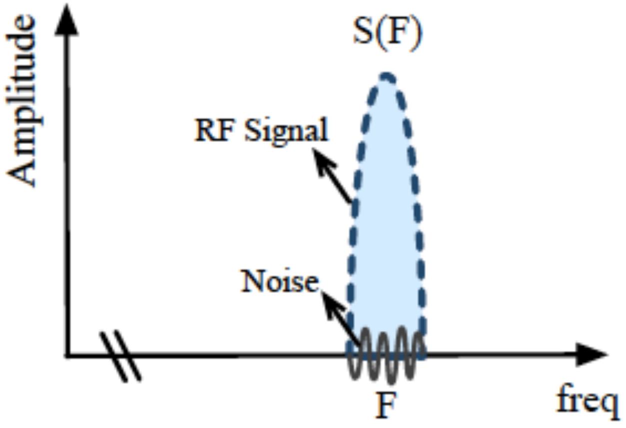
Signal self-mixing

Mixing between noise and signal



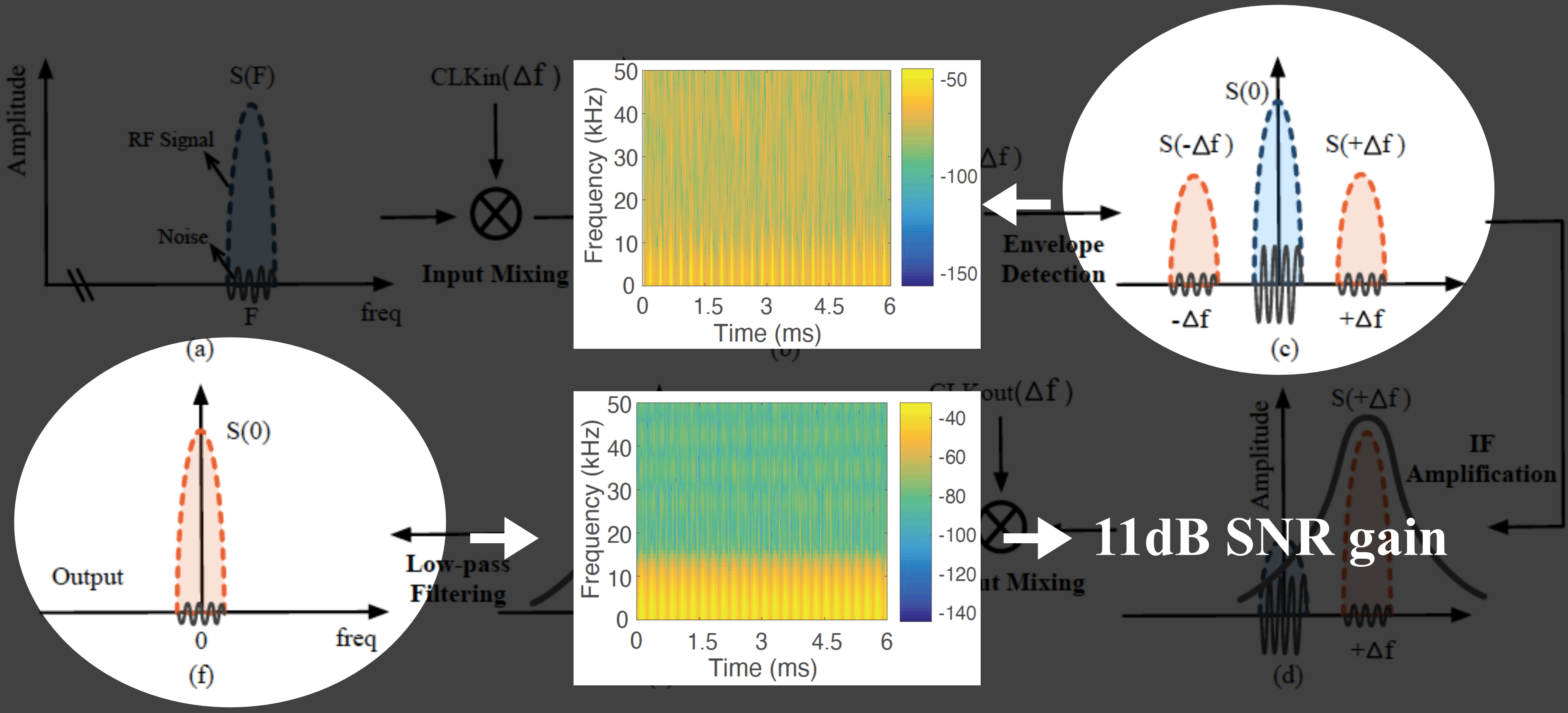


Cyclic-frequency Shifting



(a)

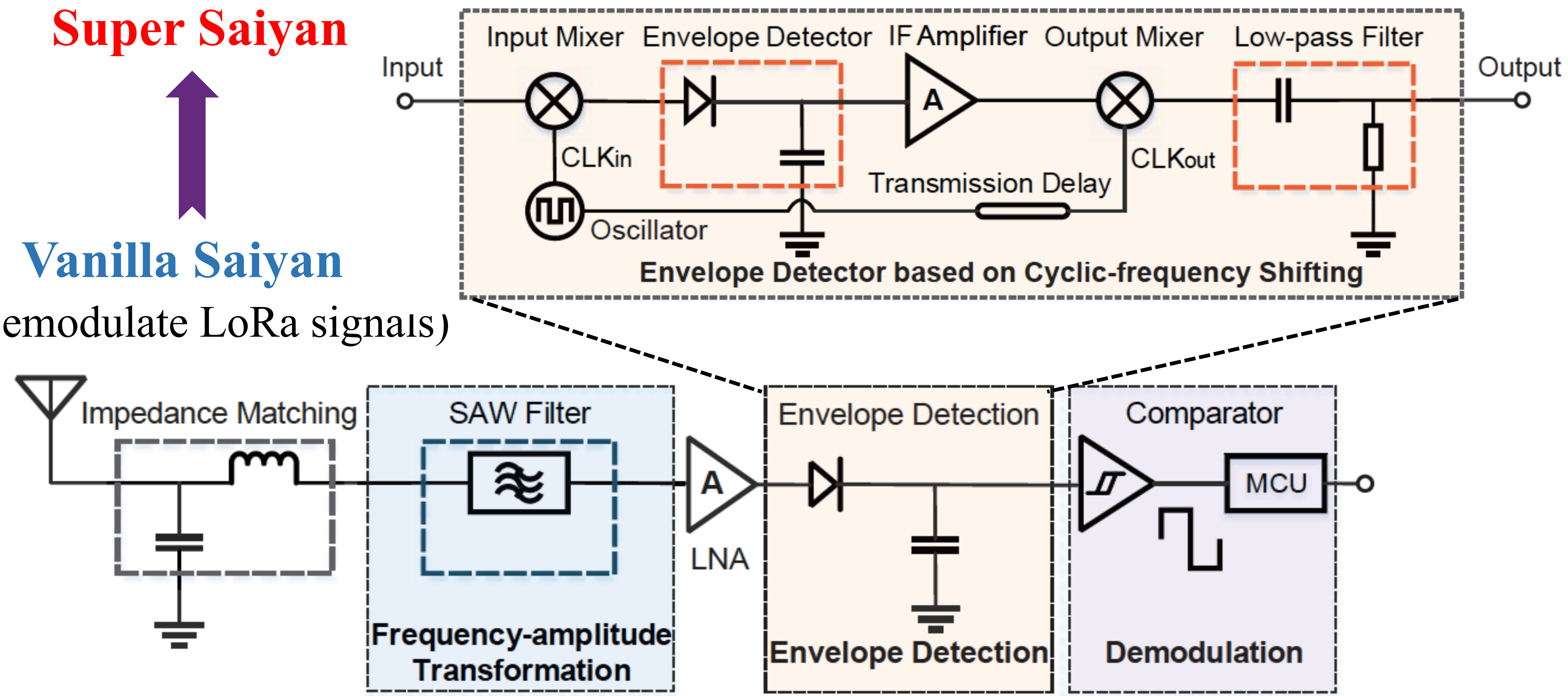
Cyclic-frequency Shifting



11dB SNR gain

High-level Circuit Schematic

(Improve demodulation sensitivity)

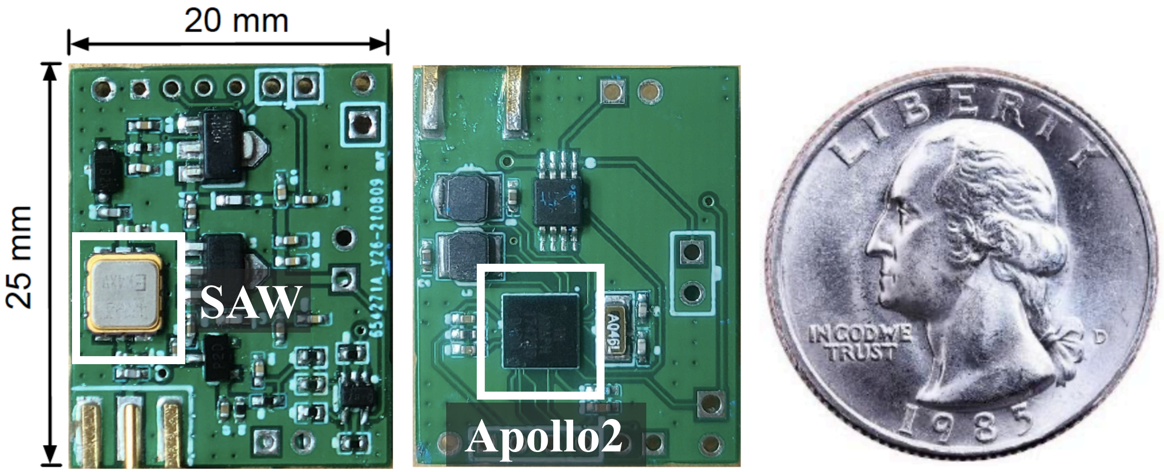


(Demodulate LoRa signals)

Implementation & Evaluation

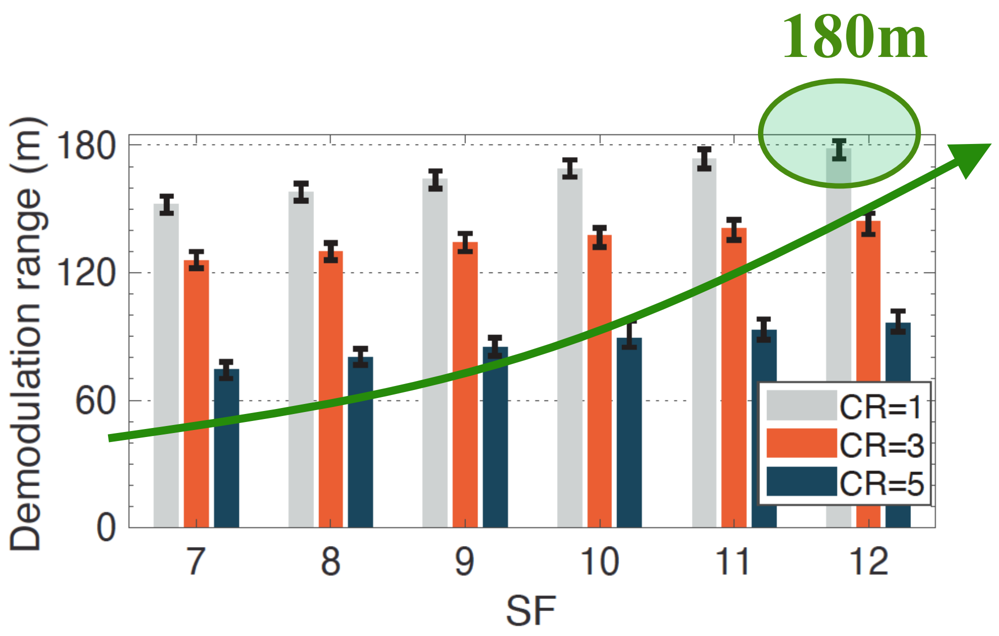
Implementation

- Backscatter Tag
  - ➢ 25mm * 20mm two-layer PCB
  - ➢ Passive SAW chip B39431B3790Z810
  - ➢ Ultra-low power Apollo2 (10 µA/MHz) MCU
- **Plug-and-play**
- Power management: palm-sized photovoltaic panel + DC/DC converter LTC3105

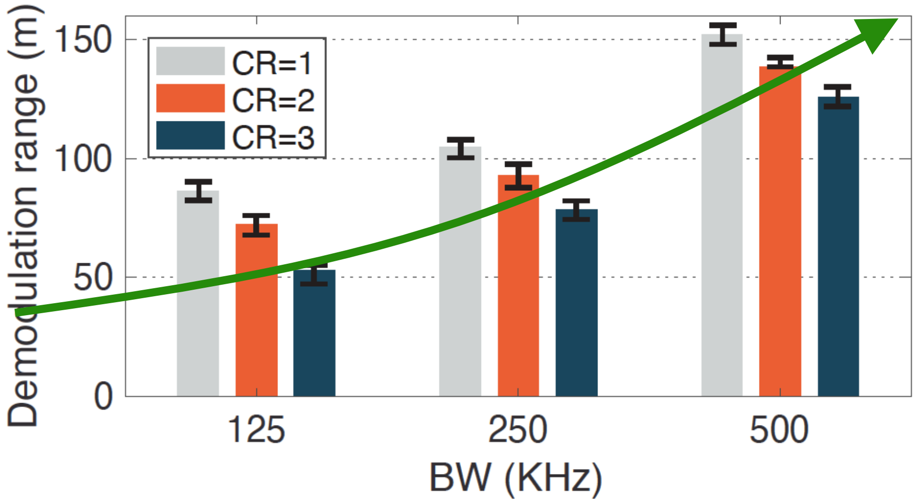


(a) Front (b) Back (c) Quarter

Demodulation Range



Spreading Factor

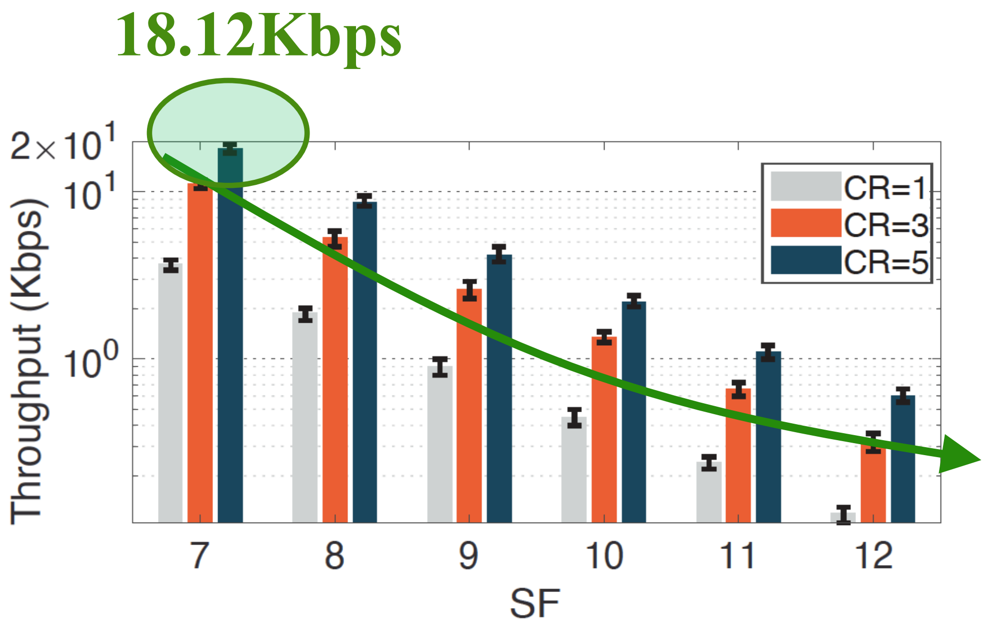


Bandwidth

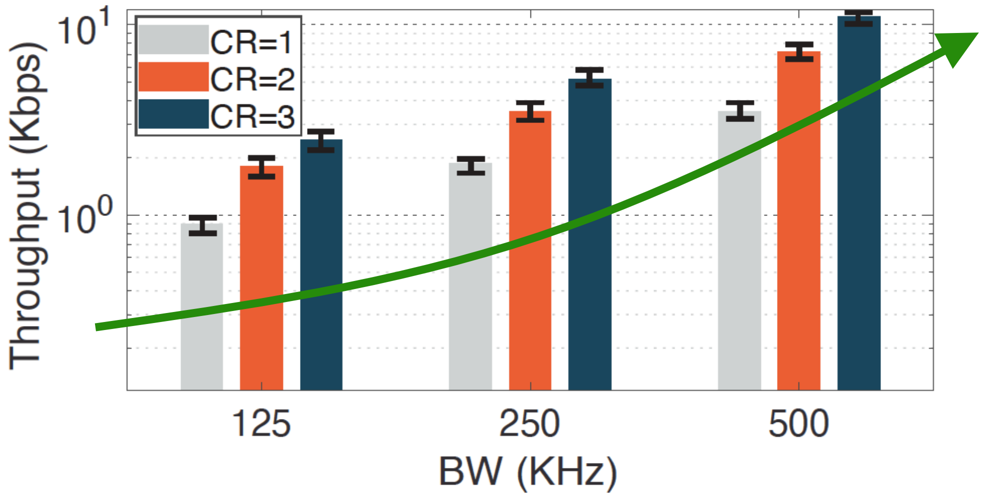
The demodulation range grows with the increasing SF and BW.

The maximum demodulation range can be up to 180m.

Throughput



Spreading Factor



Bandwidth

The throughput declines with SF and grows with BW.

The maximum throughput can be up to 18.12Kbps.

Power Consumption & System Cost

Component	SAW Filter	LNA	OSC Clock	Envelope Detector	Comparator	MCU	Total
Energy (μW)	0	248.5	86.8	0	14.45	19.6	369.4
Cost ($)	3.87	4.15	1.25	1.20	1.26	15.43	27.2

Passive

Low-power

The power and cost can be reduced sharply after ASIC fabrication

Take Away

- **The advancement of downlink (TX→Tag), a fundamental but missing piece, will promote the development of the backscatter technology.**
- **Replacing active components with their passive counterparts (e.g. SAW filter) can significantly reduce the power consumption.**
- **Reducing the inherent non-linear distortion of the analog device is a key step to improve the SNR.**

Conclusion

- **Simplify the standard LoRa demodulation from energy perspective and propose the first-of-its-kind low-power LoRa demodulator.**

- **Design a set of simple but effective circuits and algorithms, prototyping them on PCB board for system evaluation.**

- **Conduct extensive experiments and demonstrate Saiyan’s performance on power consumption, communication range, and throughput.**

THANK YOU

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Yuan He

Nan Jing

Jiacheng Zhang

Haotian Jiang

Yunhao Liu

Code and hardware schematics can be found at: https://github.com/ZangJac/Saiyan

Visit http://tns.thss.tsinghua.edu.cn/sun/ for details