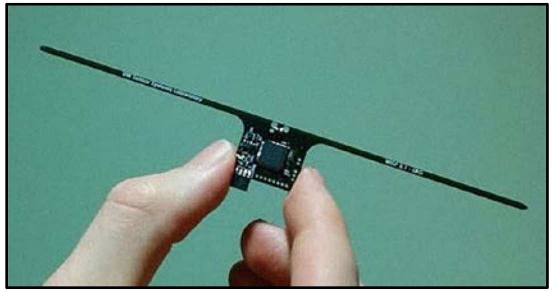
μMote: Enabling Passive Chirp De-spreading and μW-level Long-Range Downlink for backscatter Devices

Yihang Song[1], Li Lu[1], Jiliang Wang[2], Chong Zhang[1], Hui Zheng[1], Shen Yang[1], Jinsong Han[3], and Jian Li[1]

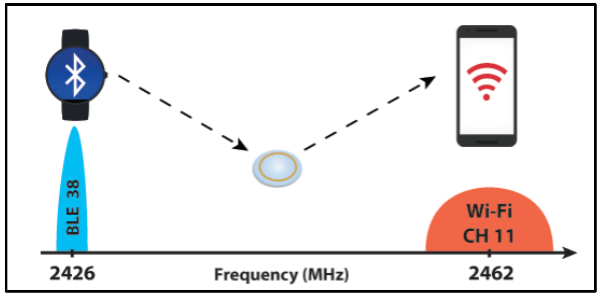
[1]University of Electronic Science and Technology of China
[2]Tsinghua University
[3]Zhejiang University

Conventional Backscatter Devices



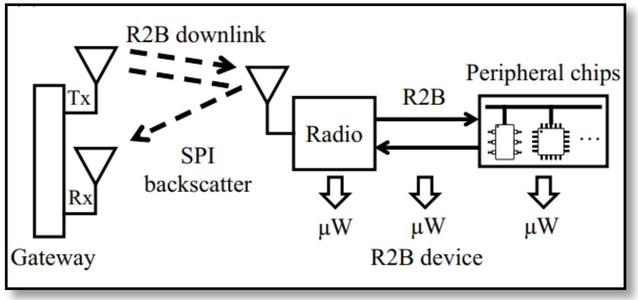
WISP Platform

IEEE TIM (2008)



Inter-Technology Backscatter

SIGCOMM 2016



Internet-of-Microchips

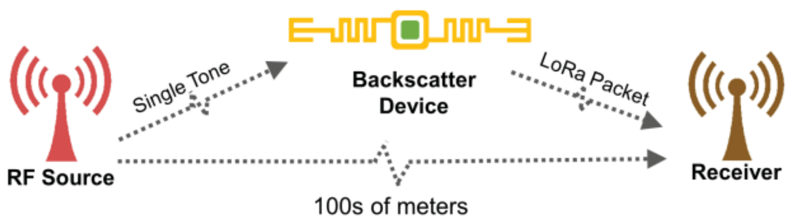
MobiCom 2020

😄 μW-level low-power communication

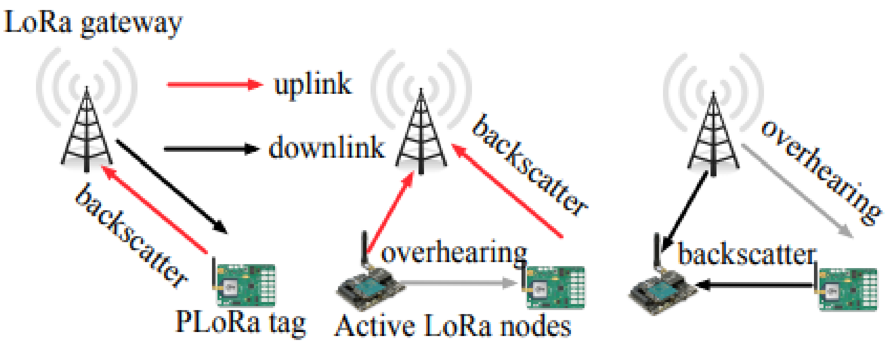
😭 Short range (<20 meters)

CSS-based Long-range Backscatter

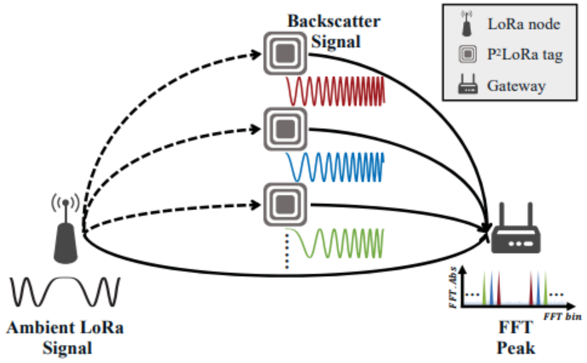
CSS=Chirp Spread Spectrum



LoRa Backscatter



PLoRa



P^2loRa

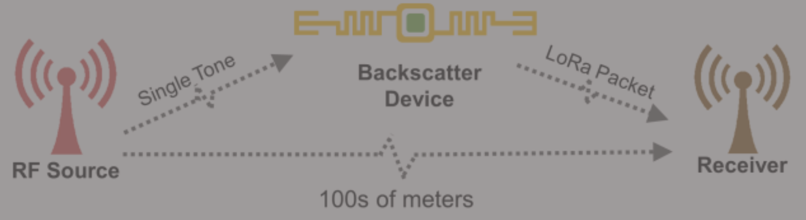
	LoRa Backscatter	PLoRa	P^2loRa
Power:	9.25µW	220µW	320µW
Uplink:	2.8km	1.1km	2.2km
Downlink:	5m	<1m	<1m

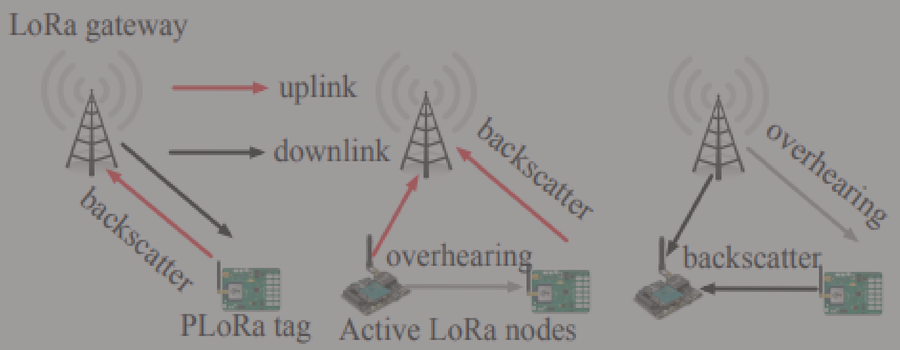
😄CSS significantly increases the uplink range with µW-level power

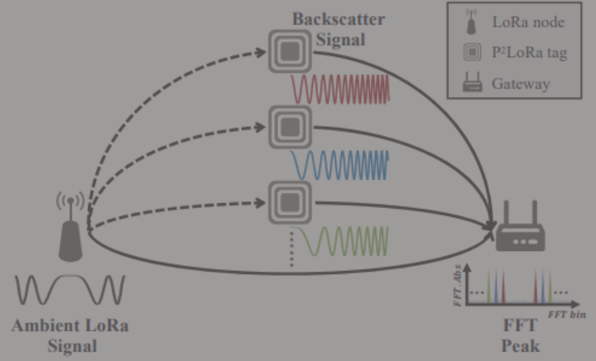
😭 The downlink range remains limited

CSS-based Long-range Backscatter

CSS=Chirp Spread Spectrum







Can we achieve CSS on the downlink to extend the receiving range of low-power backscatter devices?

Downlink: 5m

Downlink: <1m

Downlink: <1m

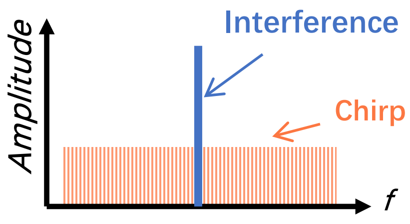
😄CSS significantly increases the uplink range with μW-level power

😭 The downlink range remains limited

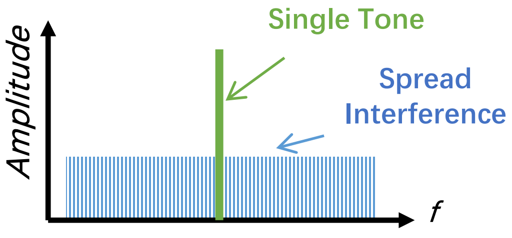
CSS communication principle

Basic idea of CSS

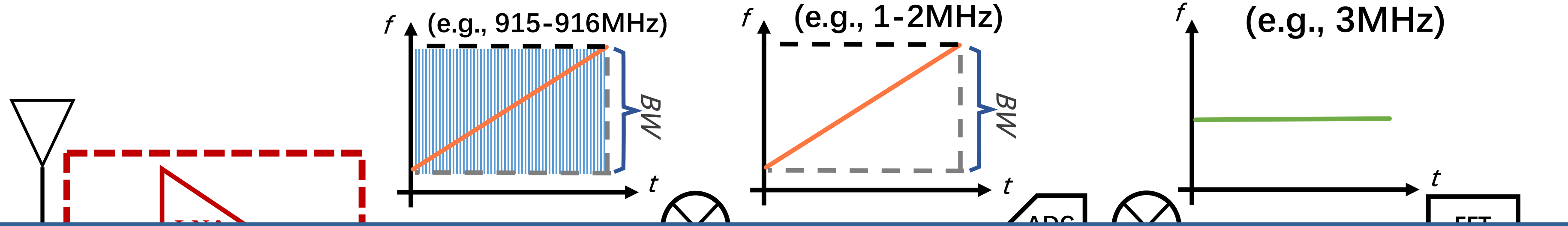
Before De-spreading



After De-spreading



De-spreading procedures



Chirp de-spreading and RF signal amplification consumes unaffordable **Milliwatts of Power**

mWs

Two challenges

Challenge 1:

How to de-spread chirp to combat interference with extremely low power?

Challenge 2:

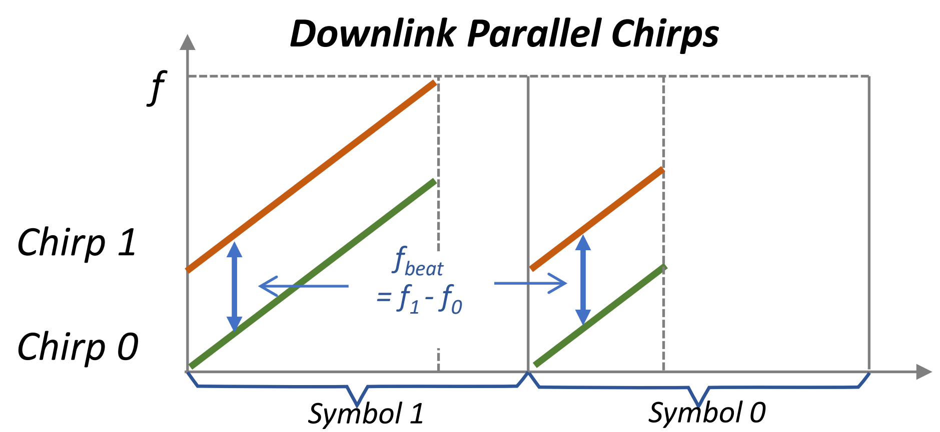
How to raise the signal amplitude with extremely low power?

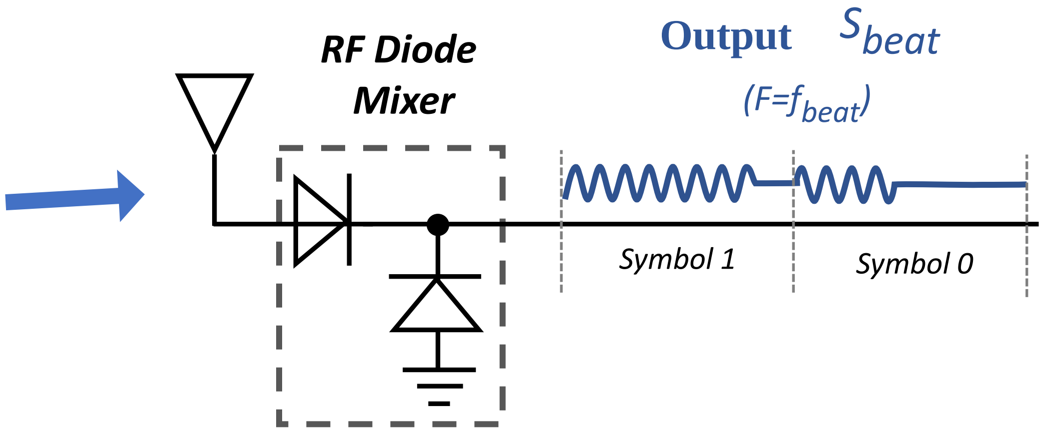
Challenge 3

(will be discussed later)

Passive Chirp De-spreading Method

Basic idea: **upload** the power consuming carrier generation function





Chirp 0： the chirp signal to be de-spread
Chirp 1： plays the role of carrier signal + de-spreading signal (similar to the down-chirp signal)

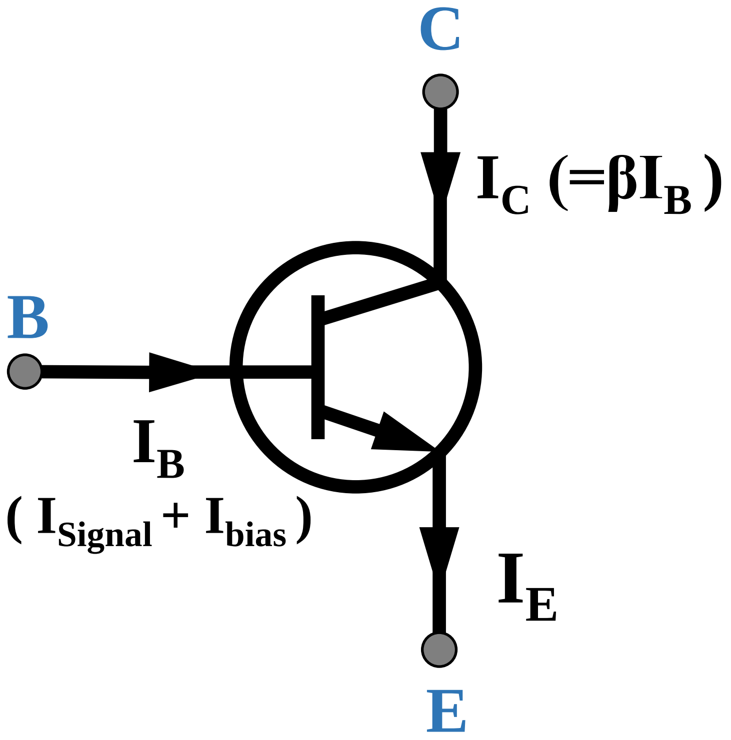
Using RF diode as mixer for circuit simplicity

Solution to Challenge 2

Magnify Signals by Accumulating Energy

LNA principle analysis

Commercial LNA IC



$I_E = I_C + I_B$

$I_B = I_{Bias} + I_{Signal}$
(100s of μA) (1-10μA)

$I_E \approx \beta I_B\ (\beta \gg 1)$
$= \beta I_{Bias} + \beta I_{Signal}$
(10s of mA) (10s of μA)
(Unused) (with data)

Unused βI_{Bias} can waste 99% of power → Power Consumption: mW-level

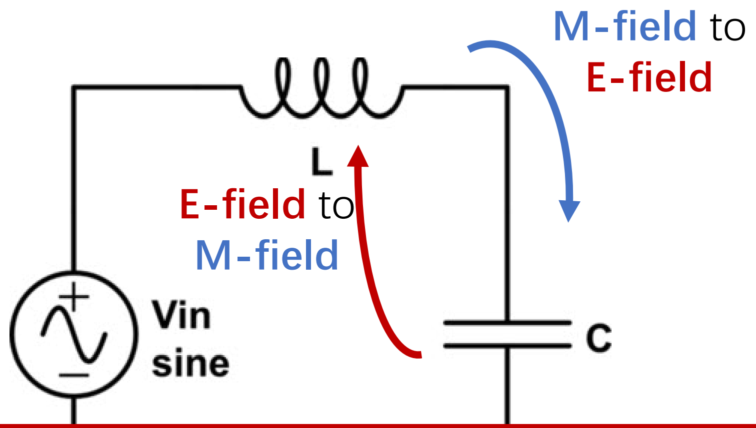
Magnify Signals by Accumulating Energy

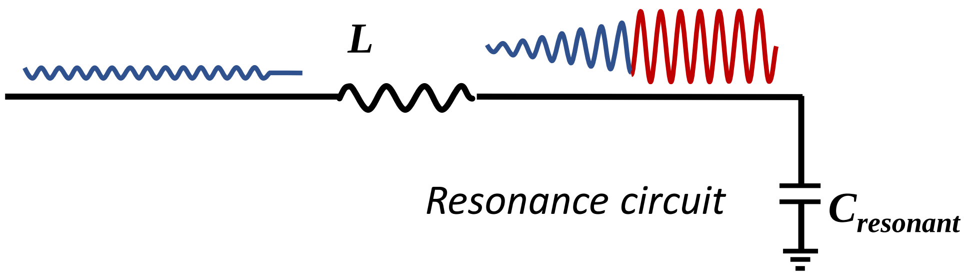
Our Solution: LC resonance circuit

① **Energy periodically transitions between E and M fields, creating resonance**

② **Signal energy can be accumulated in the form of resonance,**

③ **And Hence the signal amplitude is magnified**

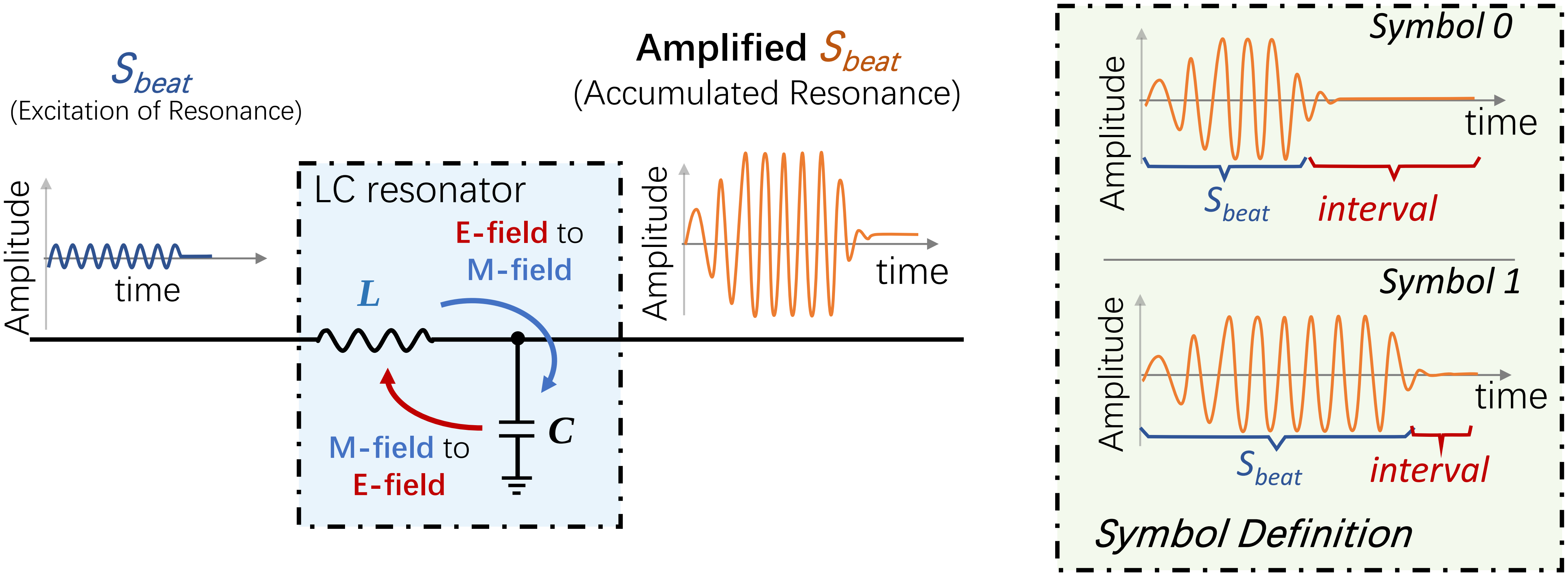




Signal characteristics (e.g. frequency, phase, amplitude) are distorted.
How can the signal information be preserved during the accumulation?

Magnify Signals by Accumulating Energy

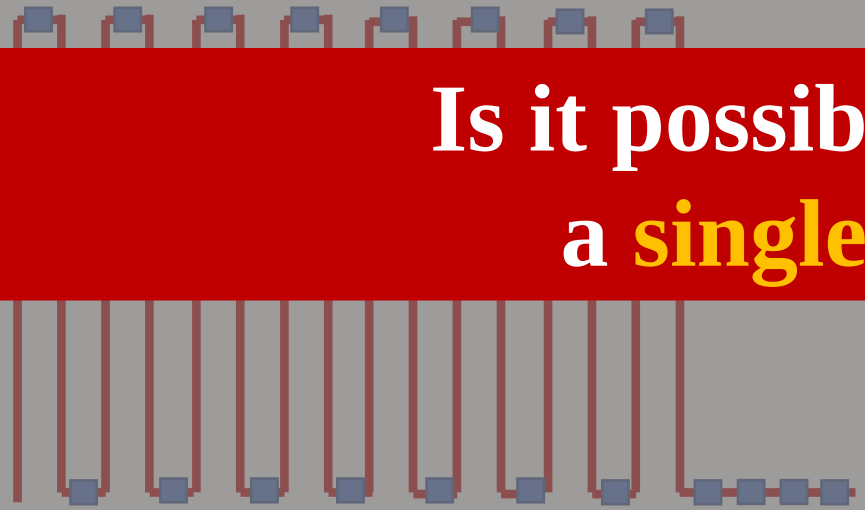
Encoding data with the duration of resonance



Challenge 3
How to decode the symbol with low power?

Conventional solution: ADC-based sampling

A symbol to be decoded
(Blue dots represent sampling points)



- **Sampling rate** → obey Nyquist's theorem
- Sapling operation **numbers for each symbol： 80-120**

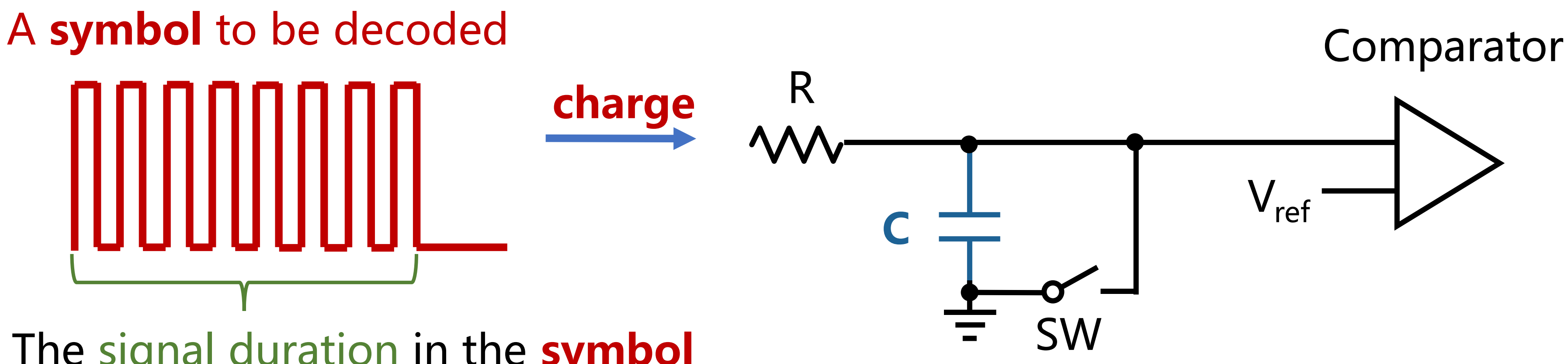
Is it possible to decode a symbol with a single integration operation?

  - Quantization （using inverse **integration** ）
  - Digital Output

Typical power of ADC sampling： 100s of μW

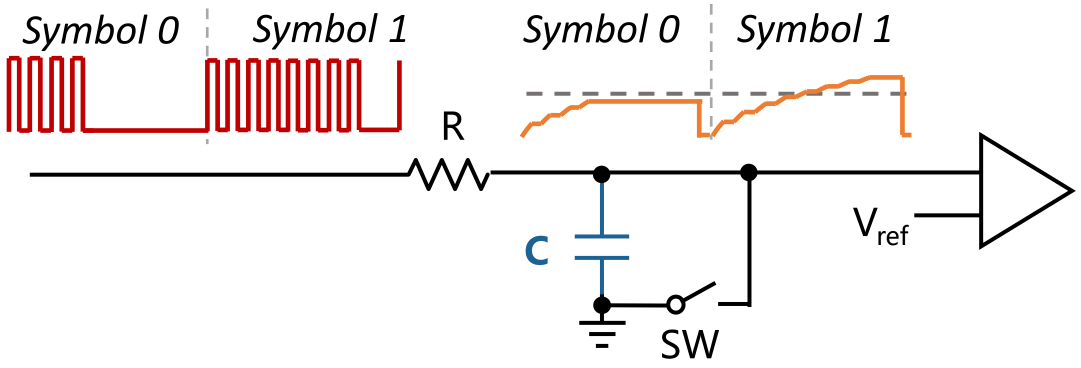
Low-power Decoding with a single integration

Basic idea



The signal duration in the **symbol**

will determine the peak voltage in **Capacitor C**



if Peak voltage in C > V_{ref}:

decoding result =1

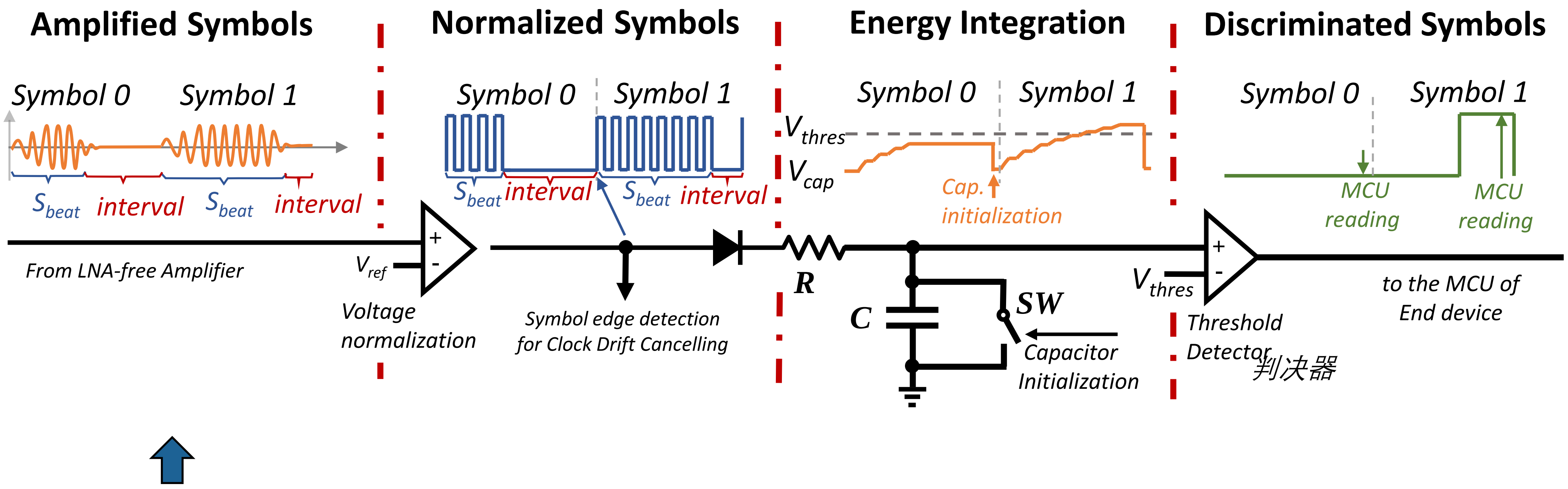
if Peak voltage in C < V_{ref}:

decoding result =0

Solution to Challenge 3

Low-power Decoding with a single integration

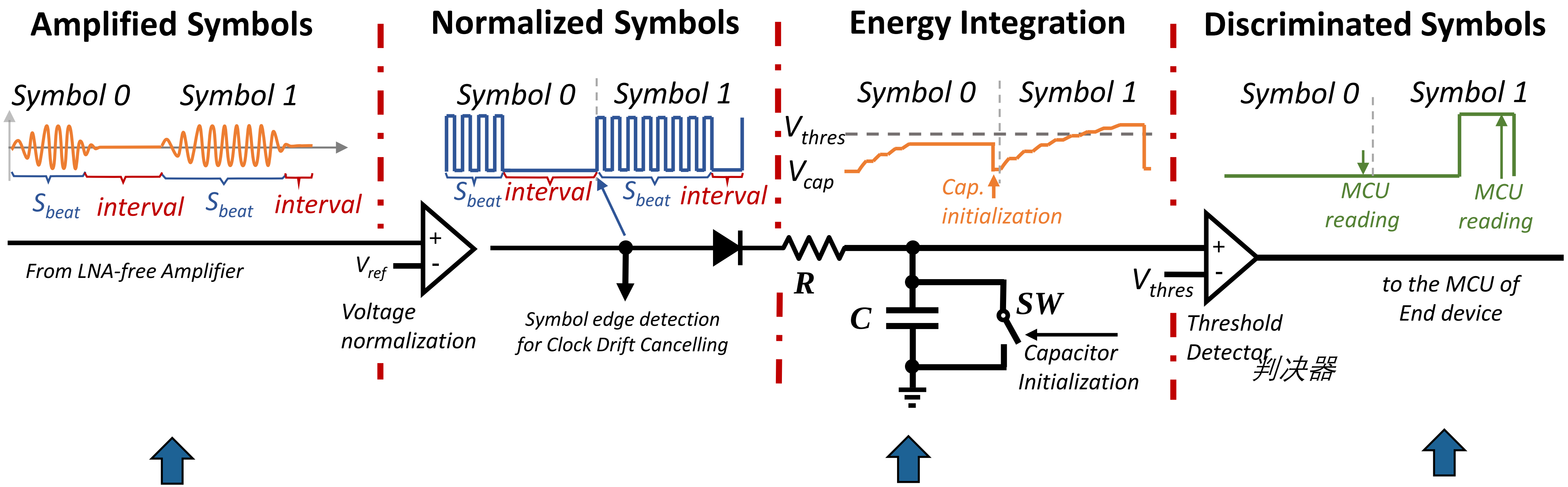
A more detailed circuit design



Dynamic signal strength Problem

Low-power Decoding with a single integration

A more detailed circuit design



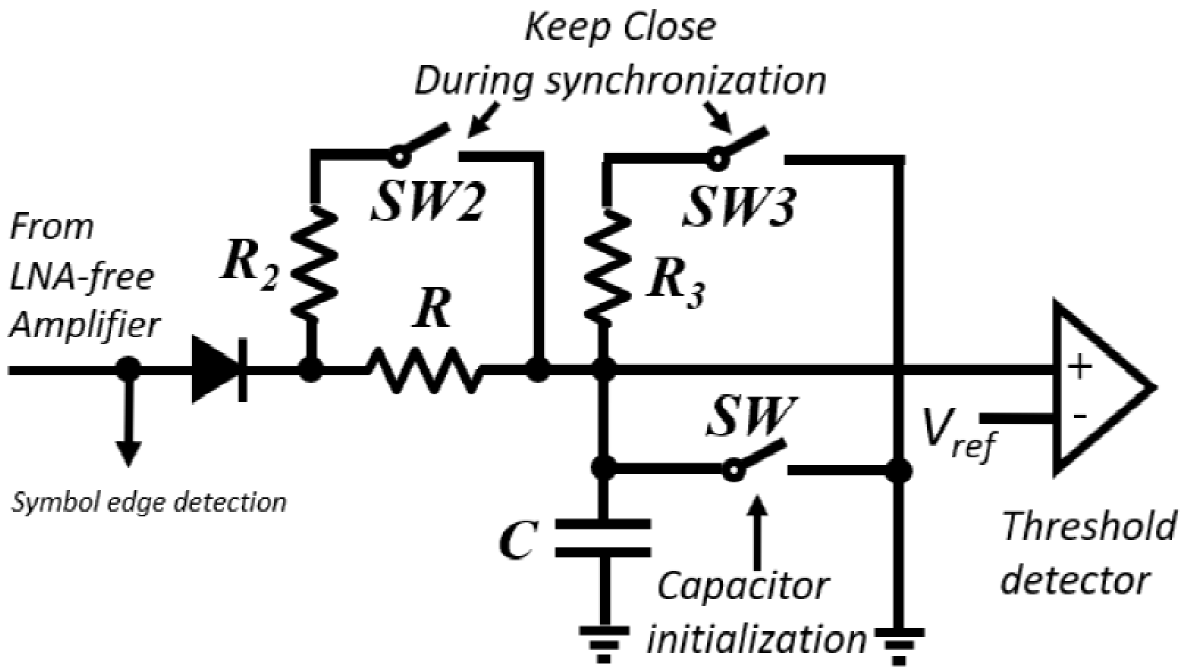
Dynamic signal strength Problem

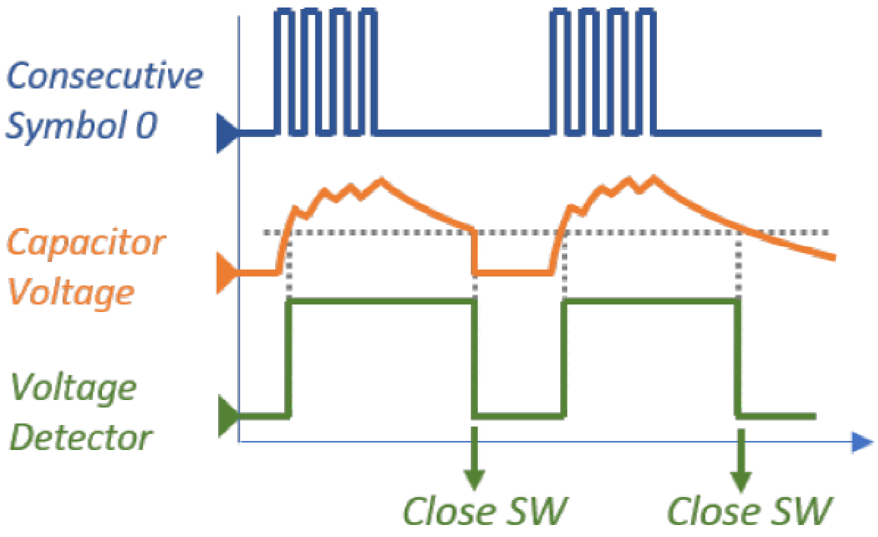
Capacitor initialization Problem

Synchronization Problem

Low-power Decoding with a single integration

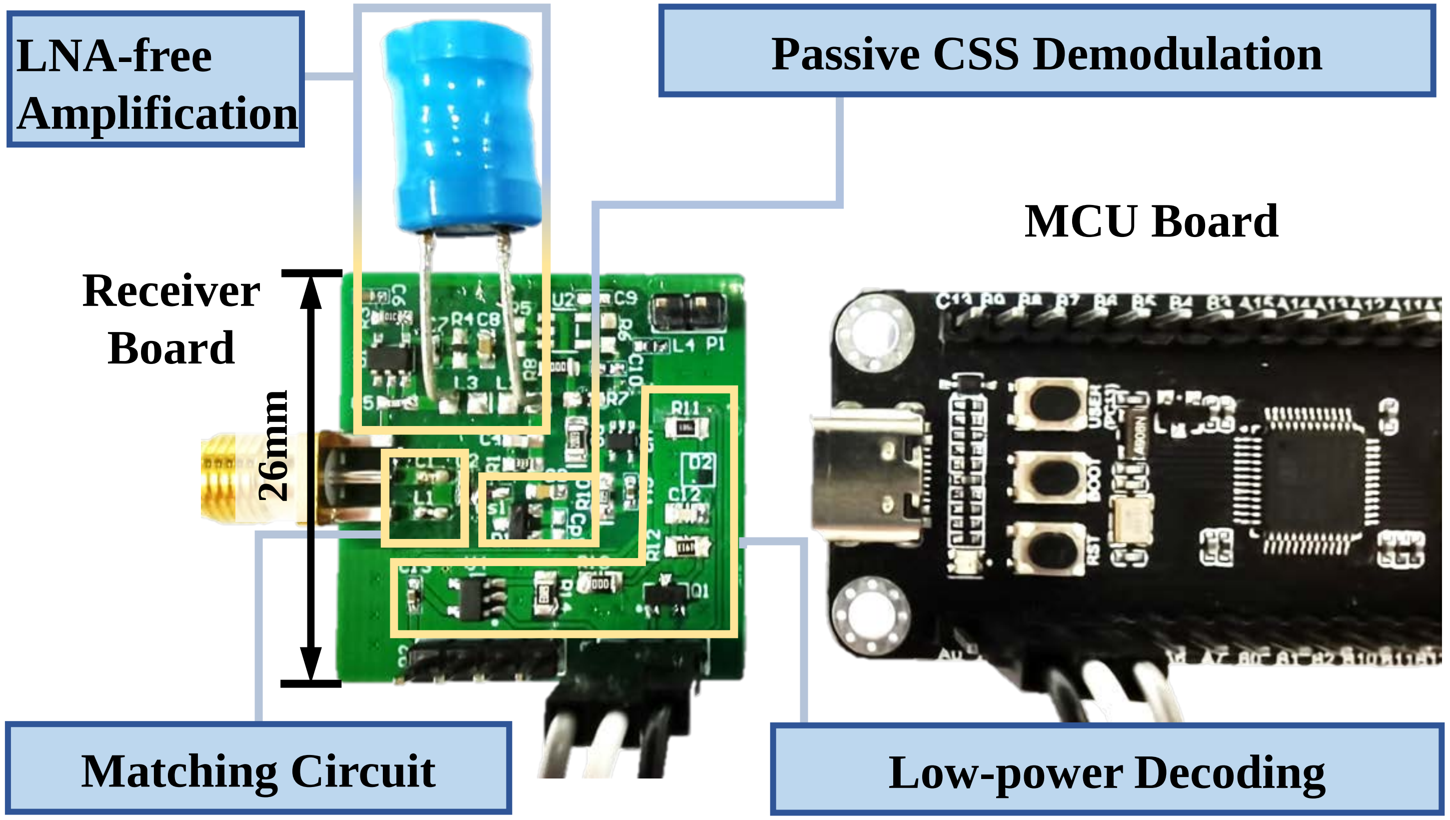
Solution to Synchronization Problem





Change the RC value of the circuit in the synchronization period,
making the synchronization symbols (which are actually symbol 0) be able to detected

Implementation



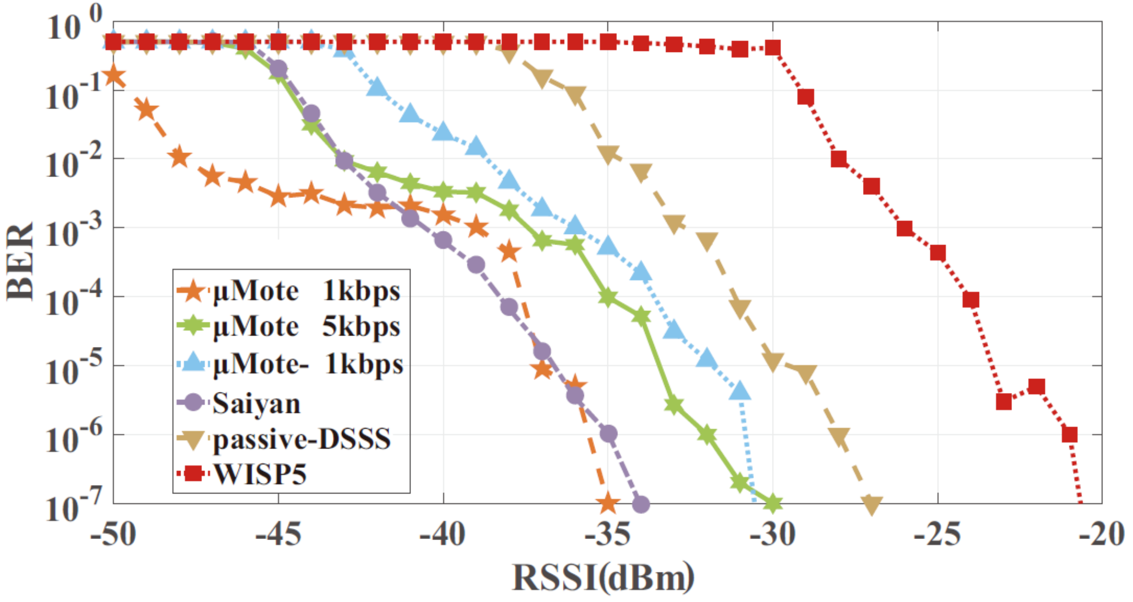
- 26mm × 24mm PCB
- Power Consumption
  - “μMote” : 62.07μW
  - “μMote –” : 28.9μW
- Communication rate:

  1/2/5kbps

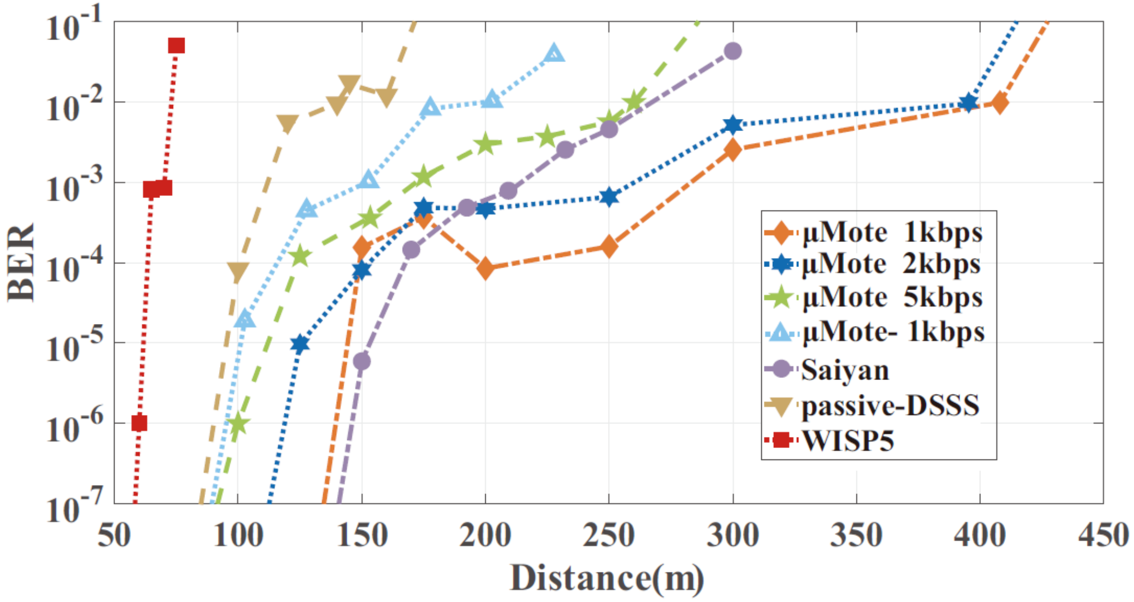
“μMote –” is a μMote prototype which removes the operational amplifier

Evaluation

Receiving Sensitivity
(Calibrated by Agilent E4418b RF power meter)



LOS Receiving Range



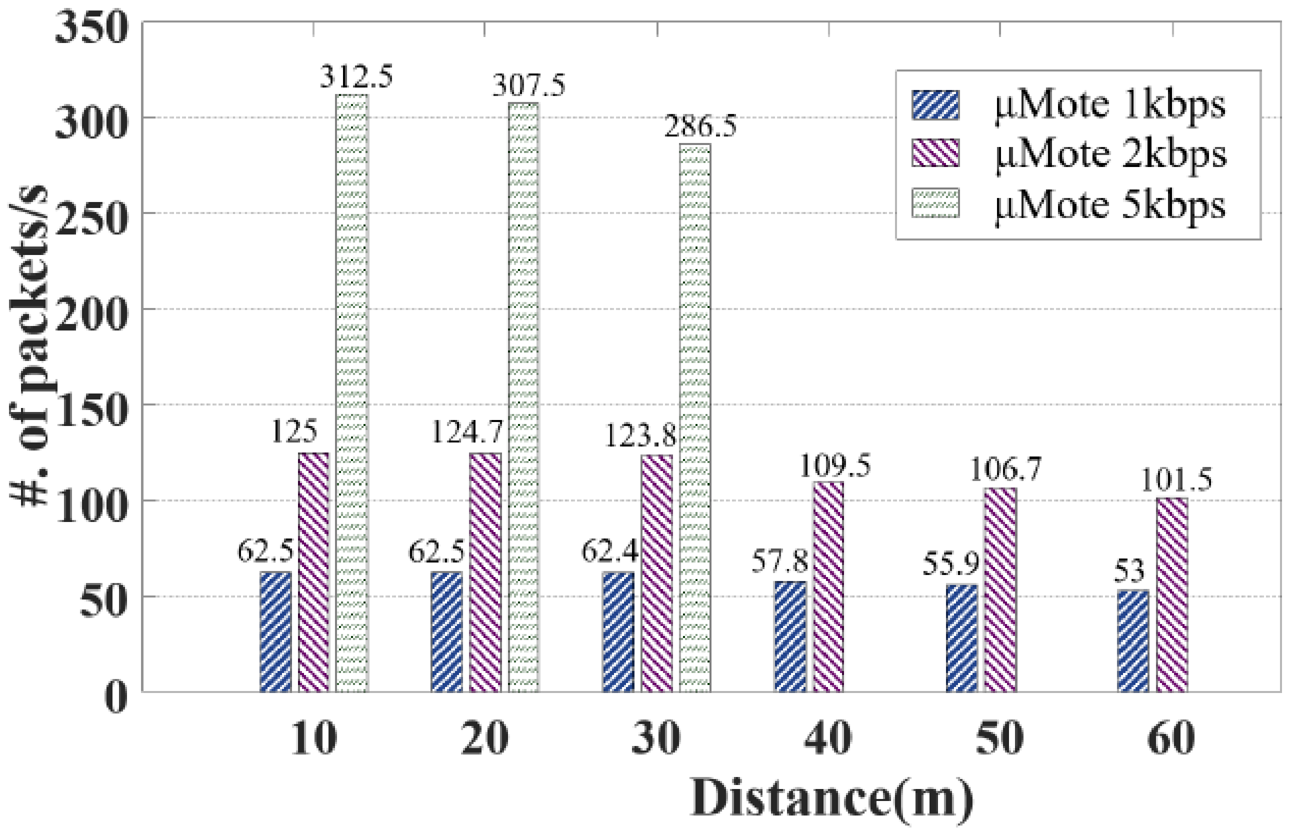
Benchmarks:
Saiyan[1], passive-DSSS[2], and WISP5[3] (with battery)

[1]Saiyan: Design and implementation of a low-power demodulator for LoRa backscatter systems
[2] Passive DSSS: Empowering the downlink communication for backscatter systems
[3] WISP5: https://github.com/wisp/wisp5-hw

Evaluation

NLOS throughput: signal penetrates one wall

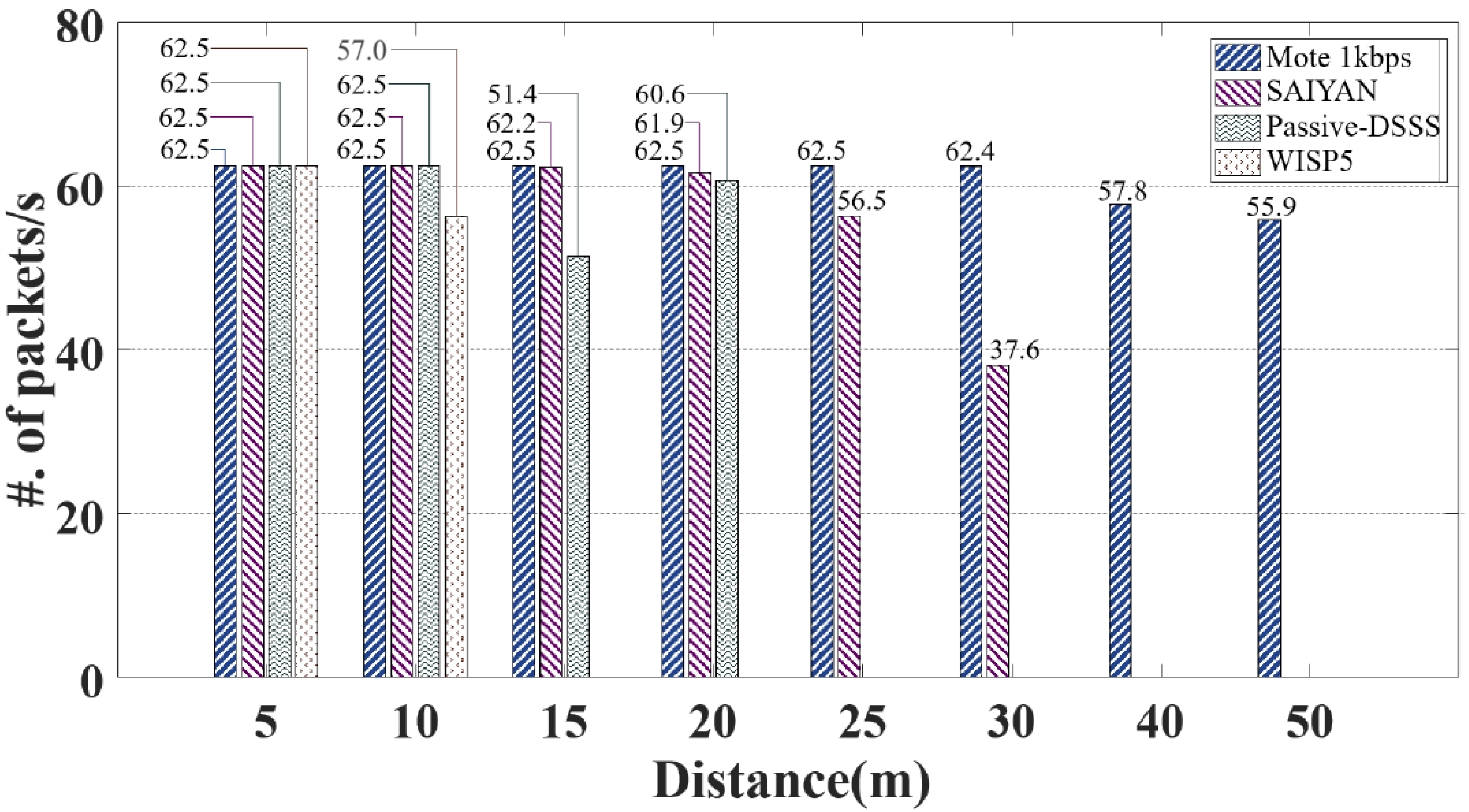
µMote @1kbps, 2kbps and 5kbps



Evaluation

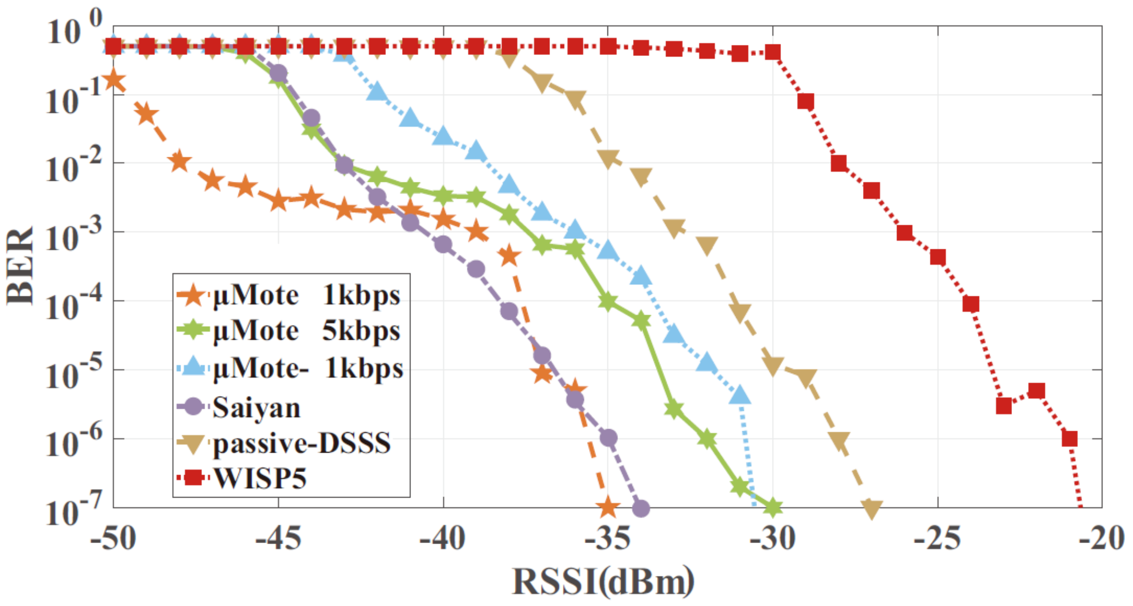
NLOS throughput: signal penetrates one wall

µMote and benchmarks @1kbps

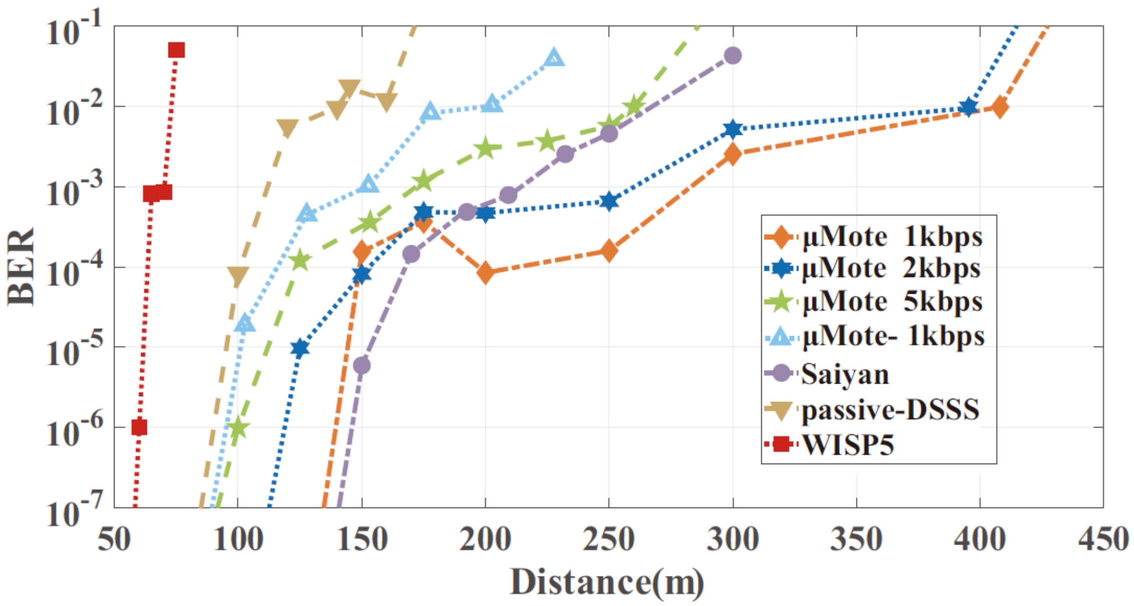


Evaluation

Receiving Sensitivity
(Calibrated by Agilent E4418b RF power meter)



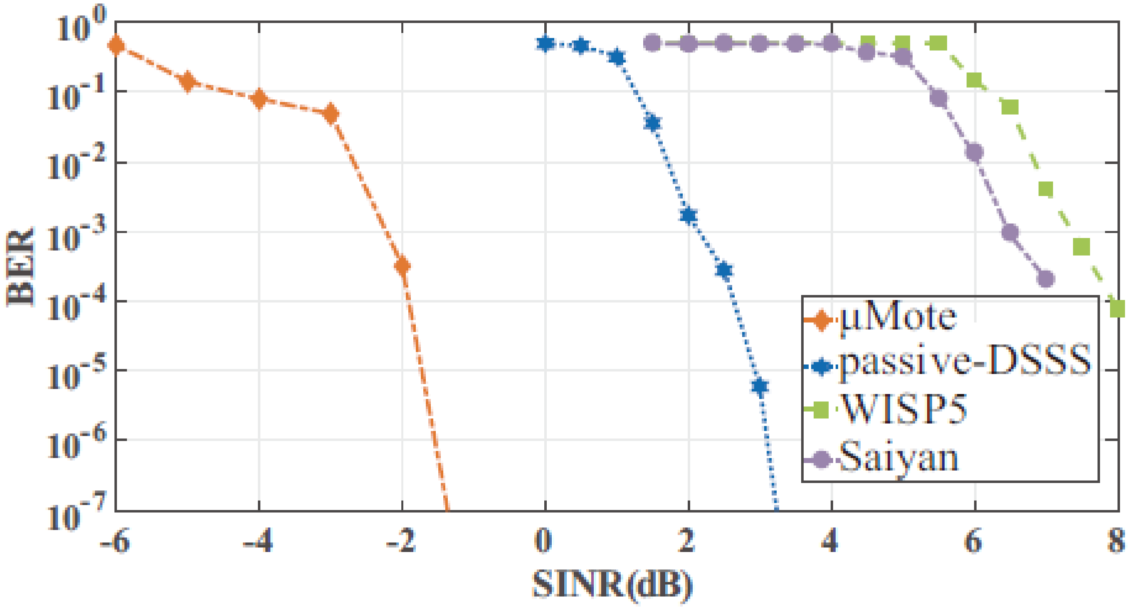
LOS Receiving Range



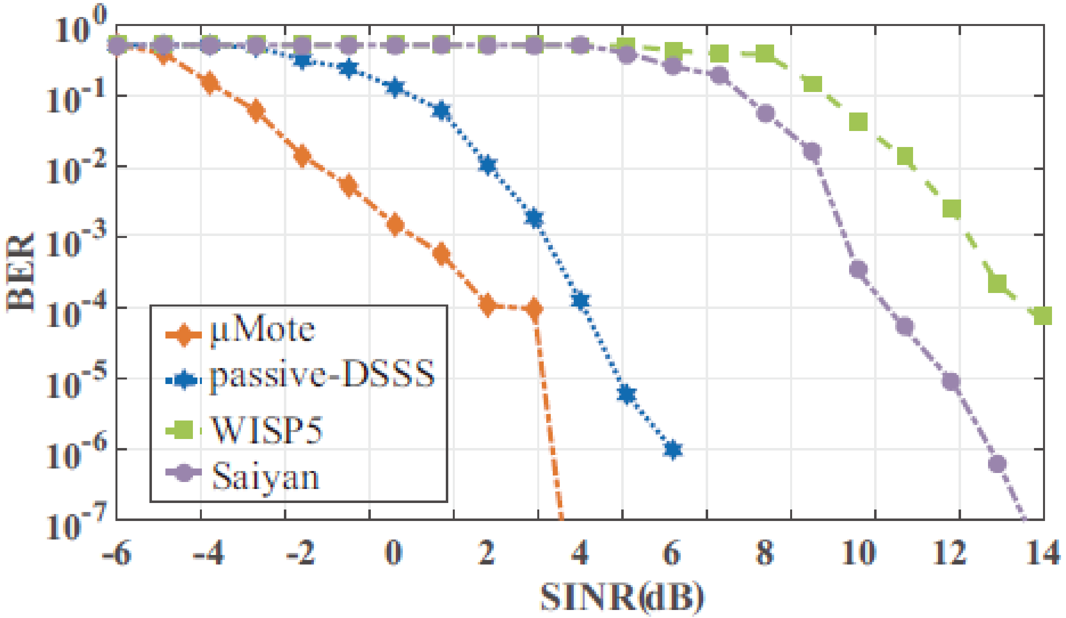
Evaluation

Interference Resistance

RFID interference



LoRa interference



Contributions

We propose the design of μMote, a novel μW-level receiver with hundreds of meters of receiving range which can effectively resist interference and work even under negative SINR.

We address three practical challenges we faced in realizing the receiver, i.e., the passive chirp de-spreading, low-power signal magnification, and low-power decoding.

We prototype μMote with COTS components and conduct extensive experiments to verify the feasibility and demonstrate the performance of our design.

Thank You!

songyihang@uestc.edu.cn