CurvingLoRa
to Boost LoRa Network Throughput via Concurrent Transmission

Chenning Li[1], Xiuzhen Guo[2], Longfei Shuangguan[3],
Zhichao Cao[1], Kyle Jamieson[4]
[1] Michigan State University [2] Tsinghua University
[3] University of Pittsburgh & Microsoft [4] Princeton University

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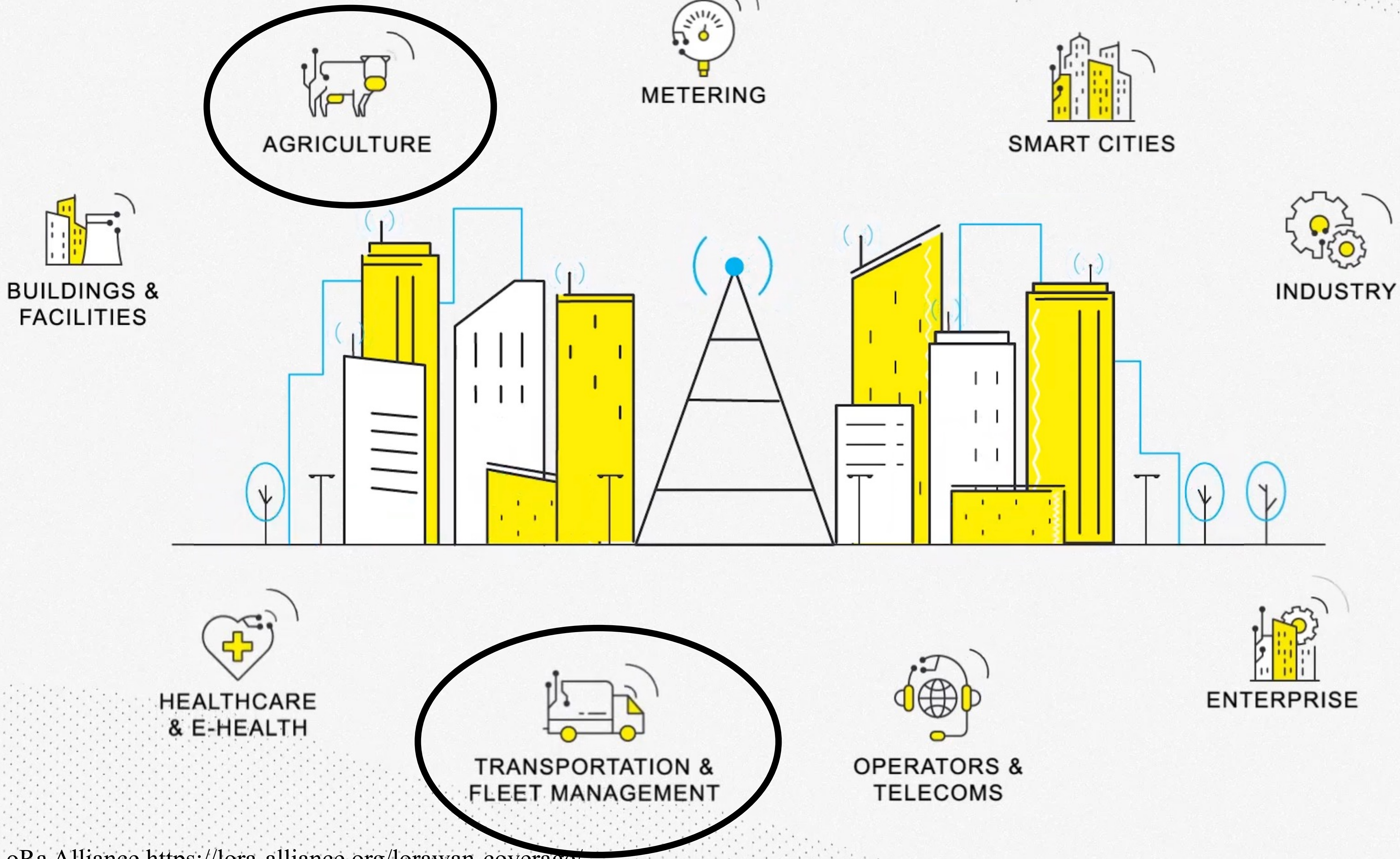
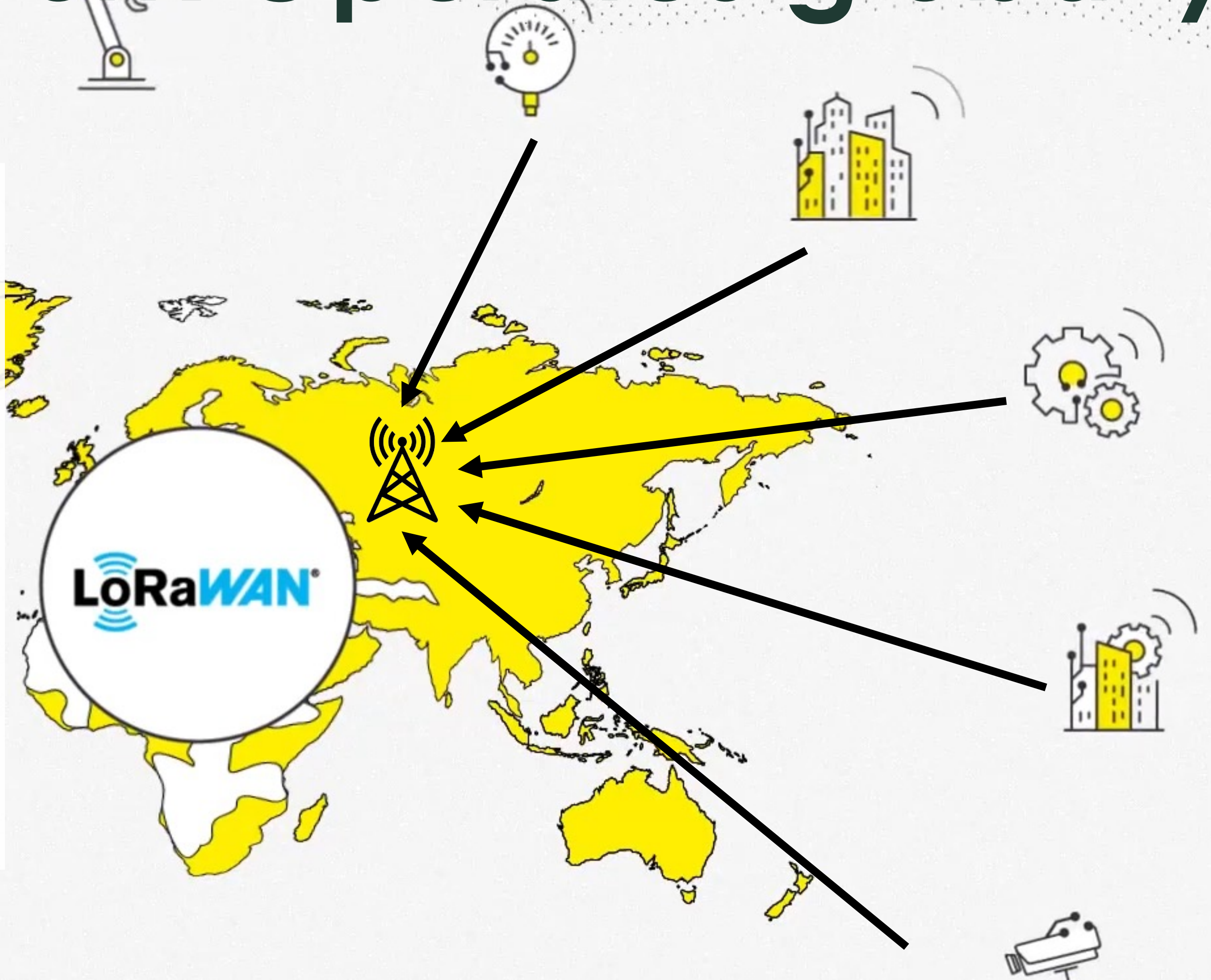
Smart World - 5G and LoRaWAN



Credits to LoRa Alliance https://lora-alliance.org/lorawan-coverage/

LoRaWAN Network Operates globally

- **>3.2 million gateways**
- **240 million end nodes**
- **>50% of all non-cellular Low Power Wide Area connections** will feature LoRa by 2026
  (ABI research)



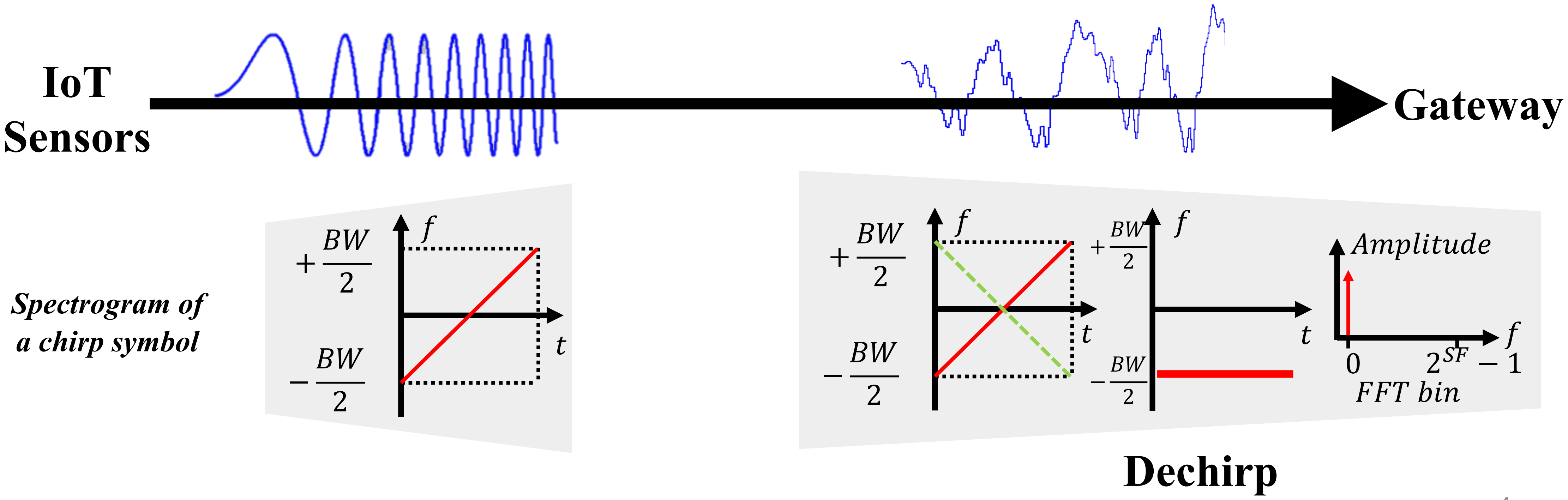
MAC Layer with a Pure ALOHA System makes the decoding suffer from concurrent transmissions

Credits to LoRa Alliance https://lora-alliance.org/lorawan-coverage/, https://www.semtech.com/lora

Background: LoRa's PHY Layer

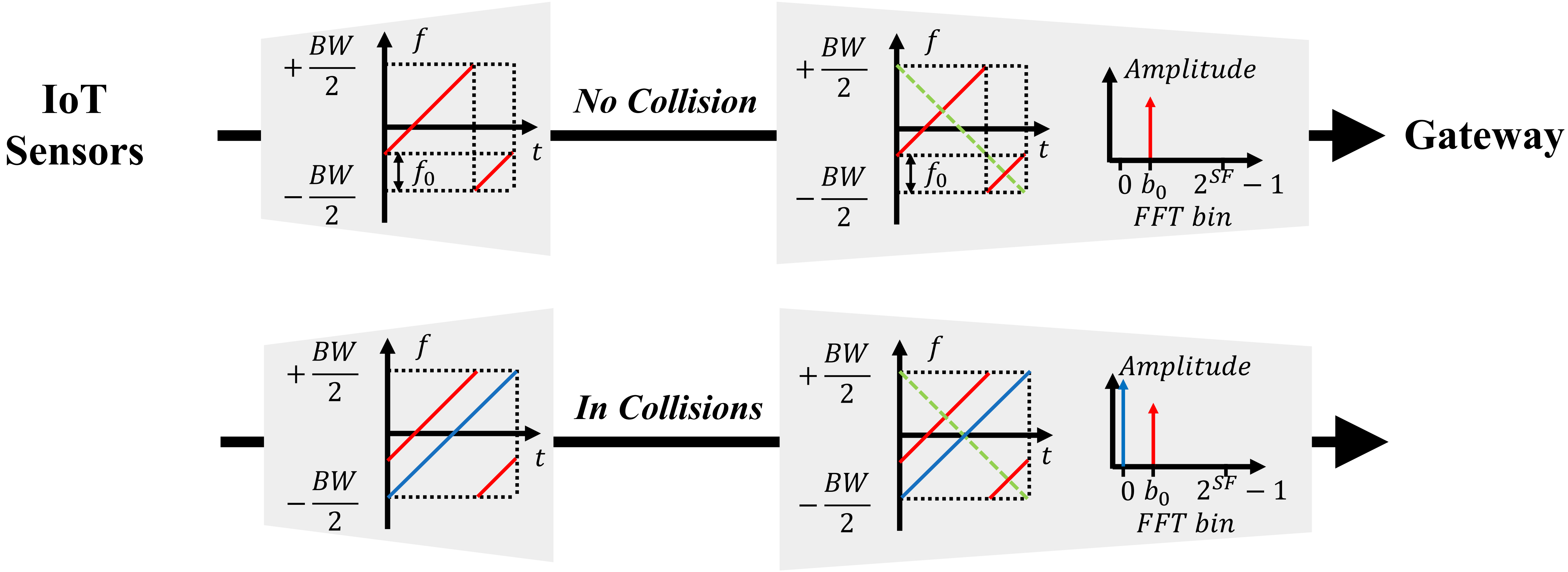
PHY Layer: Chirp Spread Spectrum Modulation

- **Bandwidth (BW):** *Fixed-bandwidth Channel, 125, 250, 500 KHz.*
- **Spreading Factor (SF):** *the amount of spreading code applied to the original data signal, from SF7 to SF12.*

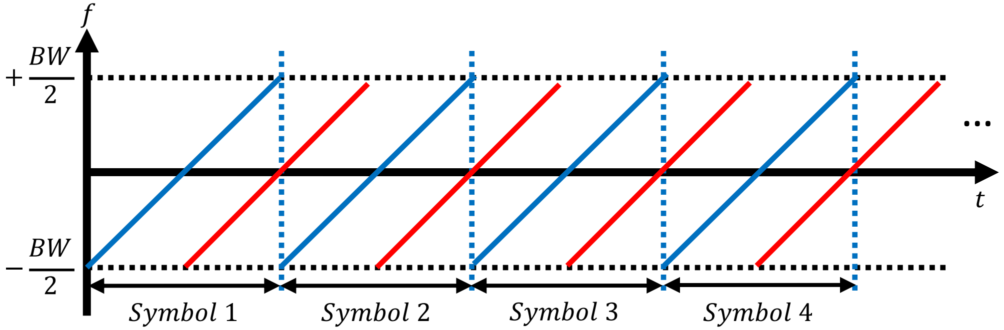


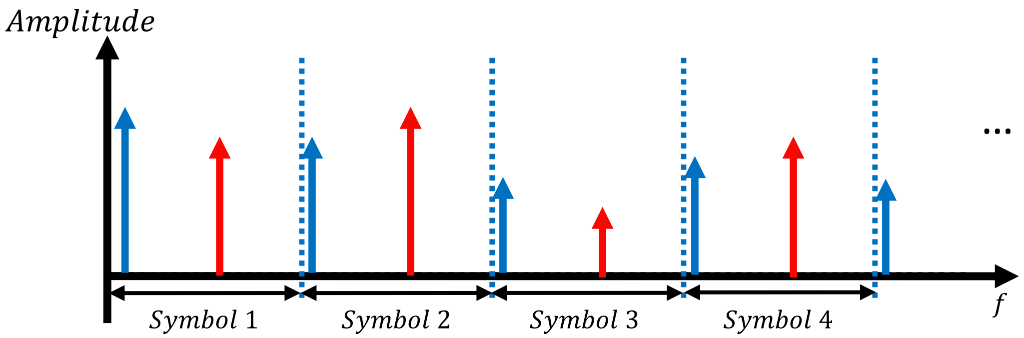
Background: LoRa's PHY Layer

PHY Layer: Chirp Spread Spectrum Modulation

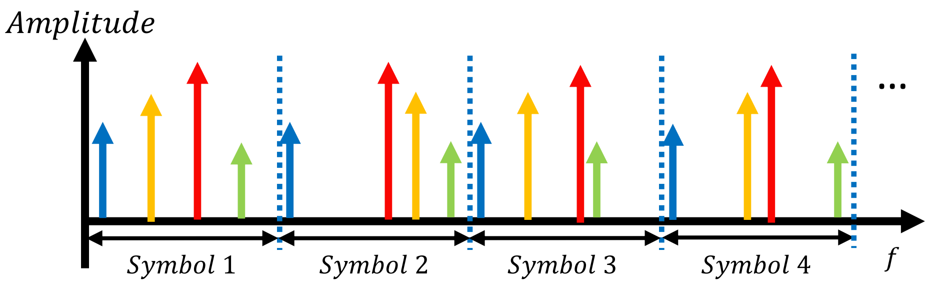


Background: LoRa's PHY Layer





- Concurrency



- SNR

Signal-Noise Ratio

- SIR

Signal-Interference Ratio

Existing Works

Time-domain feature design at PHY Layer

CIC
SIGCOMM ’21

mLoRa
ICNP ’19

FTrack
SenSys ’19

OCT
INFOCOM ’20

Suffers under Low SNR

Frequency-domain feature design at PHY Layer

NScale
MobiSys ’20

Choir
SIGCOMM’17

CoLoRa
INFOCOM ’20

SCLoRa
ICNP ’20

FlipLoRa
SECON ’20

Pyramid
INFOCOM ’21

AlignTrack
ICNP ’21

Limited by the SIR levels

Multi-channel Access at MAC Layer

LMAC
MobiCom ’20

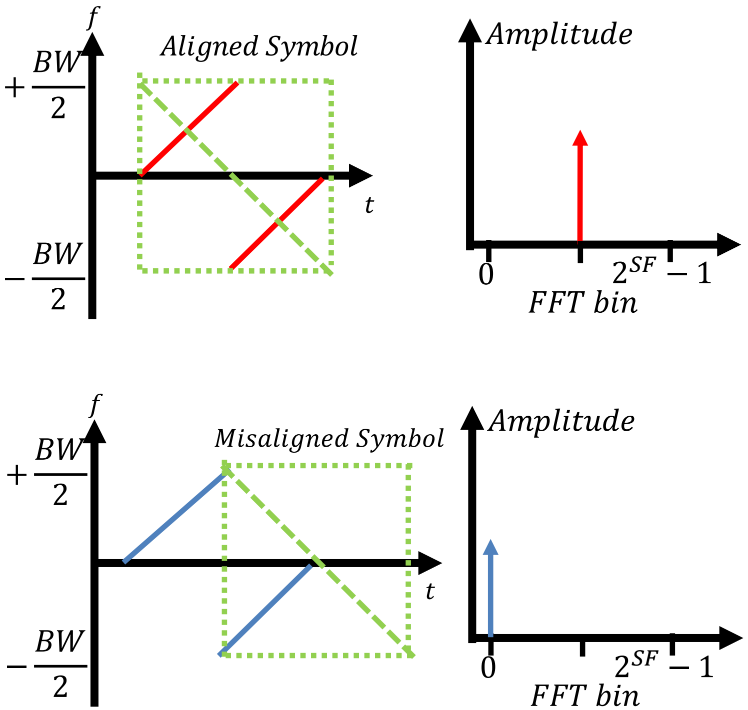
DeepSense
arXiv’19

p-CARMA
EWSN ’20

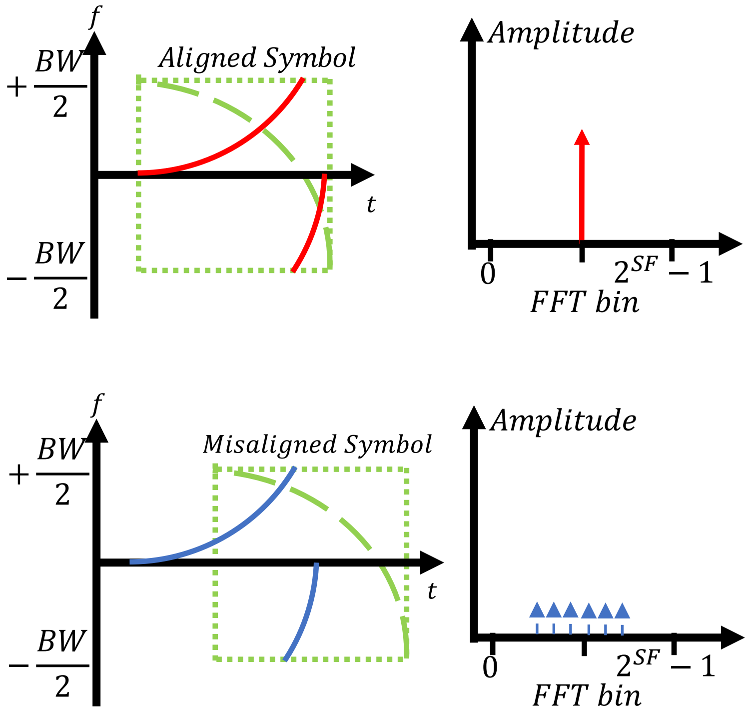
Extra Complexity and Cost

CurvingLoRa for Resolving Collisions

- **Replace the Linear Chirp with Its Non-linear Counterparts**

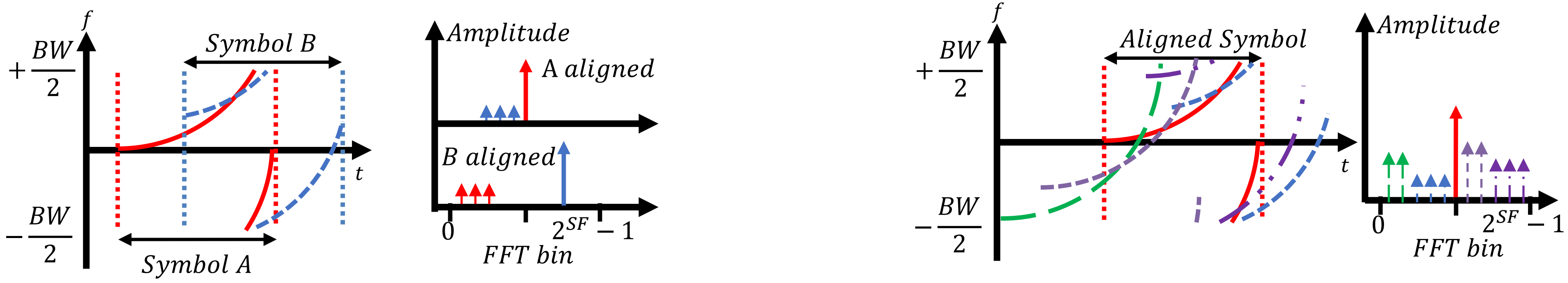


Scattering Effect



CurvingLoRa for Resolving Collisions

- **Scattering Effect of Non-linear chirps**

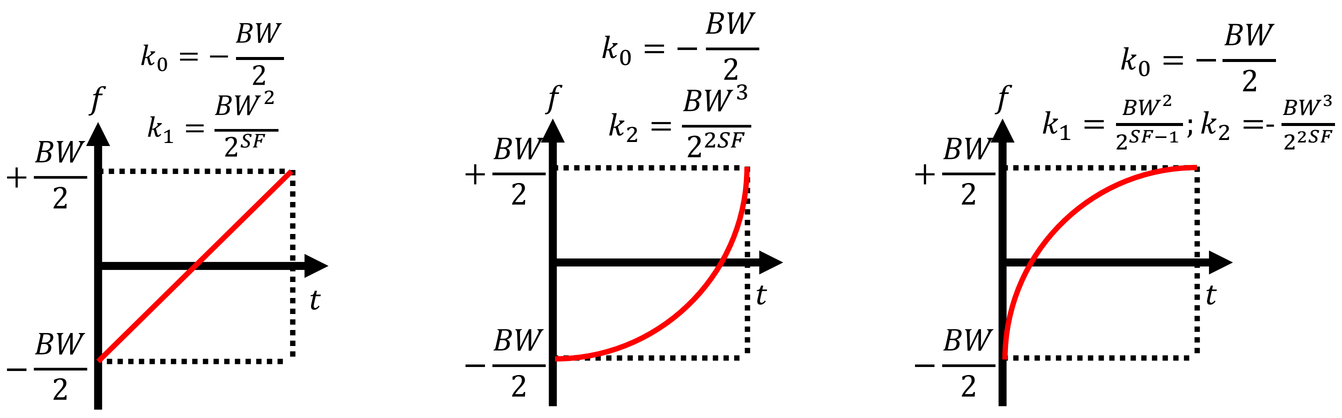


1. Formulation for Chirp-based Modulation

- *Given the BW and SF for Modulation:*

$$f_c(t) = \sum_{i=0}^{n} k_i t^i$$

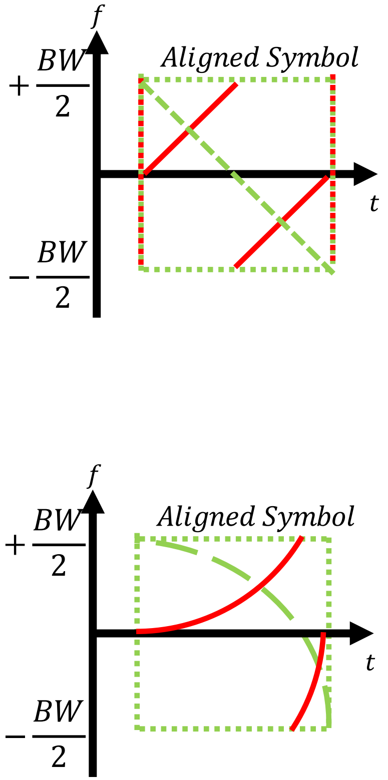
$$t \in [0, \frac{2^{SF}}{BW}], f_c(t) \in [-\frac{BW}{2}, \frac{BW}{2}]$$

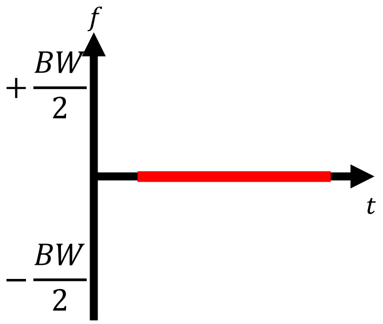


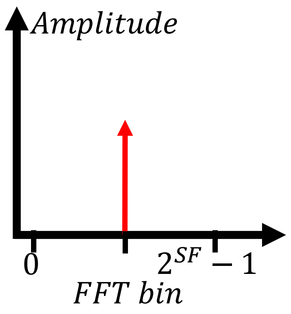
(1): $quadratic1—f(t) = t^2$	(2): $quadratic2—f(t) = -t^2 + 2t$
(3): $quartic1—f(t) = t^4$	(4): $quartic2—f(t) = -t^4 + 4t^3 - 6t^2 + 4t$
(5): $Sine1—f(t) = sin(t), t \in [-\pi/2, \pi/2)$	(6): $Sine2—f(t) = sin(t), t \in [-3\pi/8, 3\pi/8)$

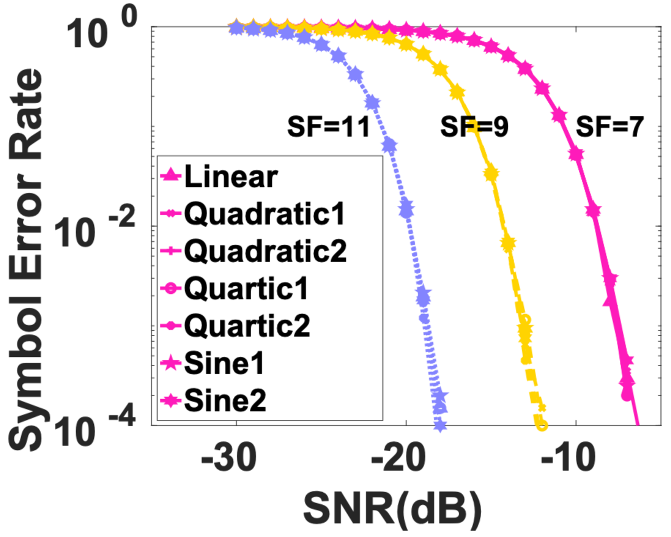
2. CurvingLoRa's Noise Resilience

- **Chirp Spread Spectrum Modulation Suppress Noises by Focusing the Spectral Energy into the Encoded Frequency Bin**





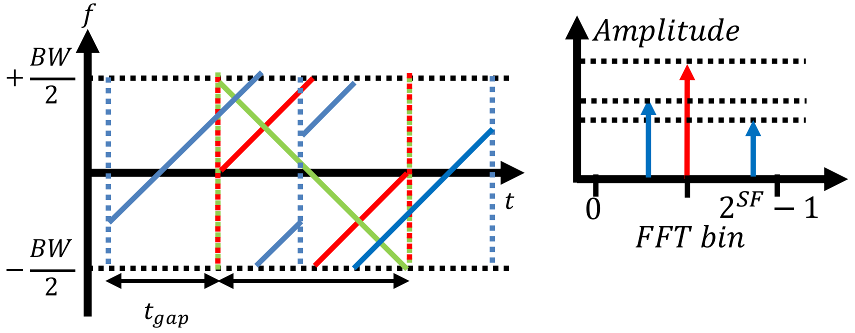


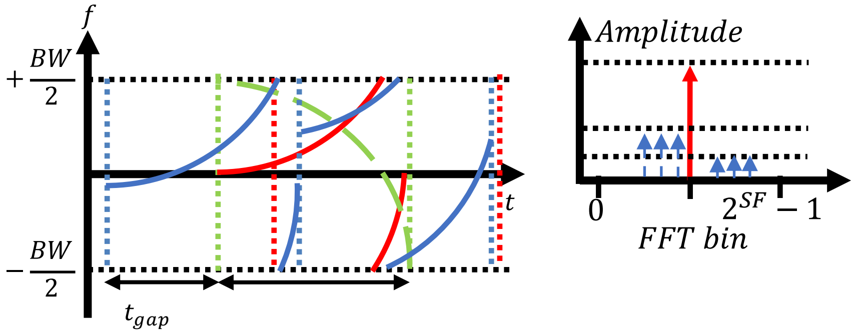


3. CurvingLoRa Under Collisions

- **CurvingLoRa's Scattering Effect for Misaligned Chirp Symbols**

$$f_c(t) = \sum_{i=0}^{n} k_i t^i$$





1. Modulate Data for Aligned Chirp Symbol

$$e^{j2\pi(f_0+f_c(t))t} * e^{-j2\pi f_c(t)t} = e^{j2\pi f_0 t}$$

2. Collided Chirps with a Time Offset t_{gap}

$$e^{j2\pi(f_0+f_c(t+t_{gap}))t} * e^{-j2\pi f_c(t)t} = e^{j2\pi F(t)t}$$

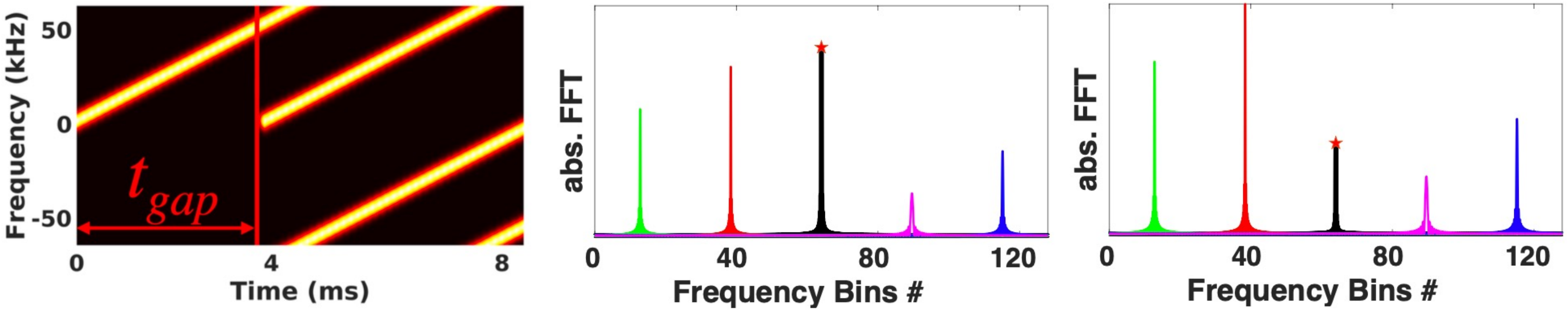
- *For Linear Chirps $fc(t)=k_1t+k_0$*
  $F(t) = f_0+k_1(t+t_{gap})+k_0 - (k_1t+k_0) = f_0 + k_1 t_{gap}$

- *For Non-linear Chirps e.g., $f_c(t)=k_2t^2+k_0$*
  $F(t) = f_0+k_2(t+t_{gap})^2+k_0 - (k_2t^2+k_0) = f_0+k_2 t_{gap}^2+2k_2t_{gap} \times t$

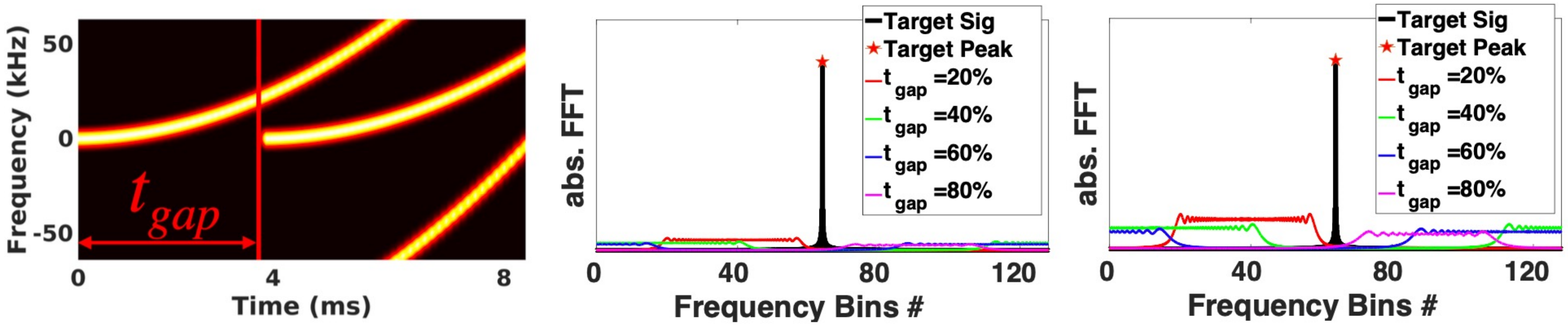
3. CurvingLoRa Under Collisions

- **Various SIRs, t_{gap}, and SFs**

$$quadratic1—f(t) = t^2$$



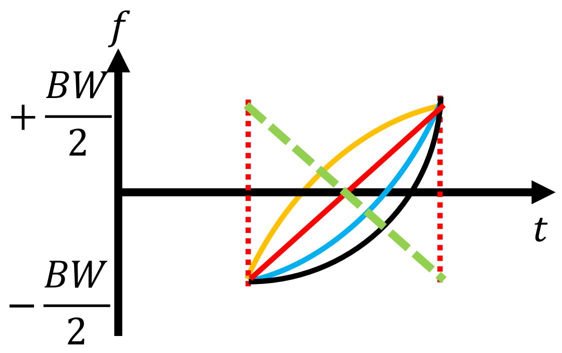
(a) Two collided linear chirps (b) SIR=-1dB (d) SIR=-10dB

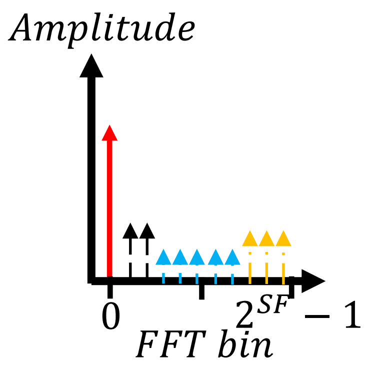


(e) Two collided non-linear chirps (f) SIR=-1dB (h) SIR=-10dB

4. CurvingLoRa's Coding Space

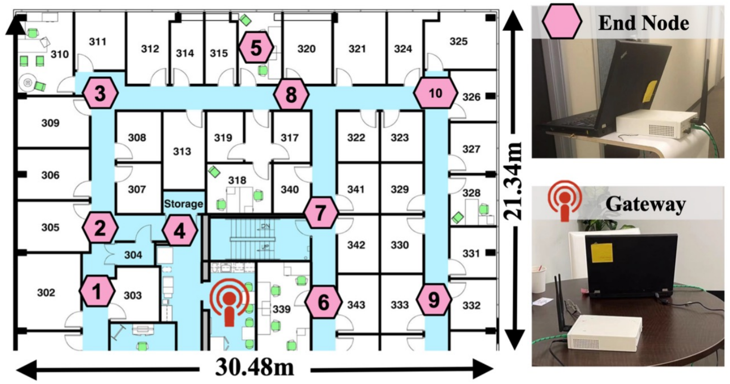
- **CurvingLoRa Extends the Orthogonal Coding Dimension**

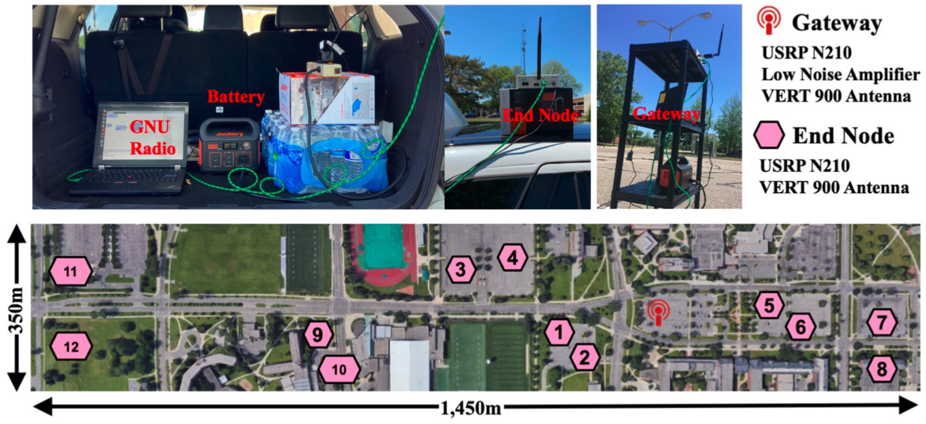




- **By assigning the data bits into the shape of chirp symbols**

Implementation





Metric:

- Symbol Error Rate (SER)
- Packet Delivery Rate (PDR)
- Throughput (Symbols/Second)

Baseline:

- Standard LoRaWAN
- mLoRa ICNP '19 at the time domain of PHY
- NScale MobiSys '20 at the frequency domain of PHY

Non-linear Chirp Candidate:

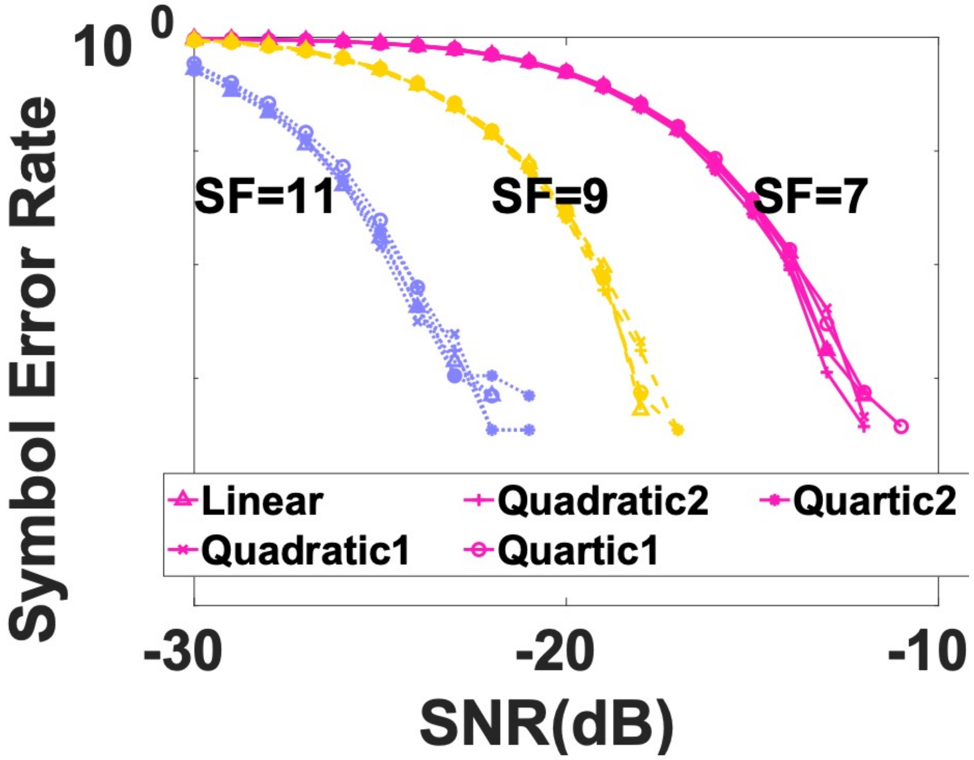
(1): $quadratic1 — f(t) = t^2$	(2): $quadratic2 — f(t) = -t^2 + 2t$
(3): $quartic1 — f(t) = t^4$	(4): $quartic2 — f(t) = -t^4 + 4t^3 - 6t^2 + 4t$

What We Care:

- Noise Resilience in SNRs
- Fluctuated SIRs
- Performance at the Campus Scale

Evaluation：Symbol Level Performance

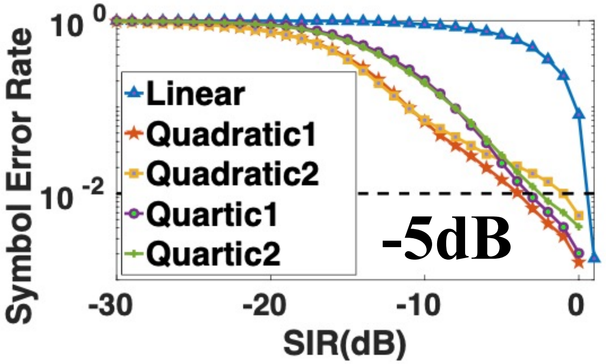
- **Same Noise Tolerance with the Linear Chirp**



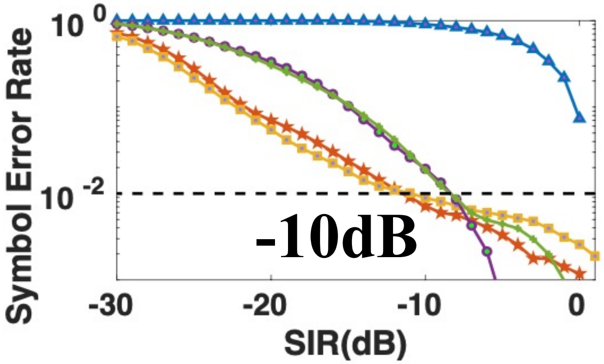
Noise resilience in the absence of collisions.

Evaluation: Symbol Level Performance

To maintain 1% SER:

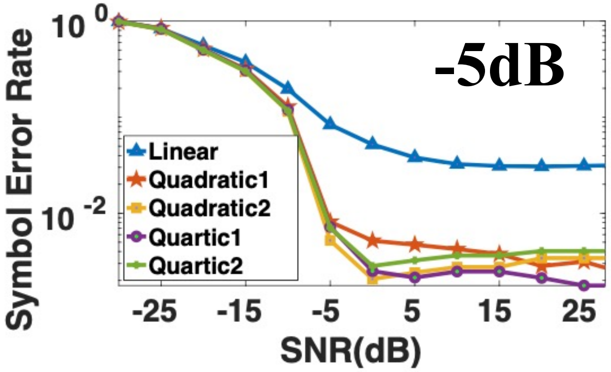


(a) SER vs. SIR when SF=8

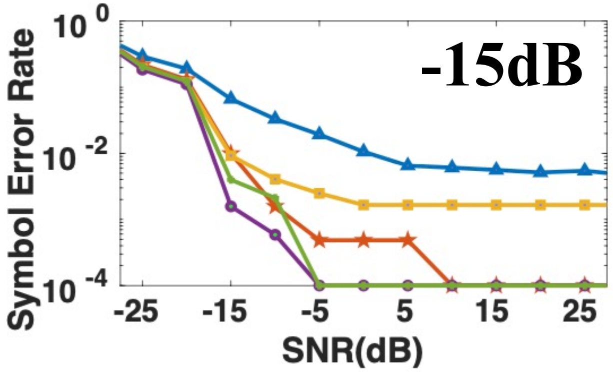


(c) SER vs. SIR when SF=12

Linear vs. non-linear: symbol error rate ($SNR > 30dB$)



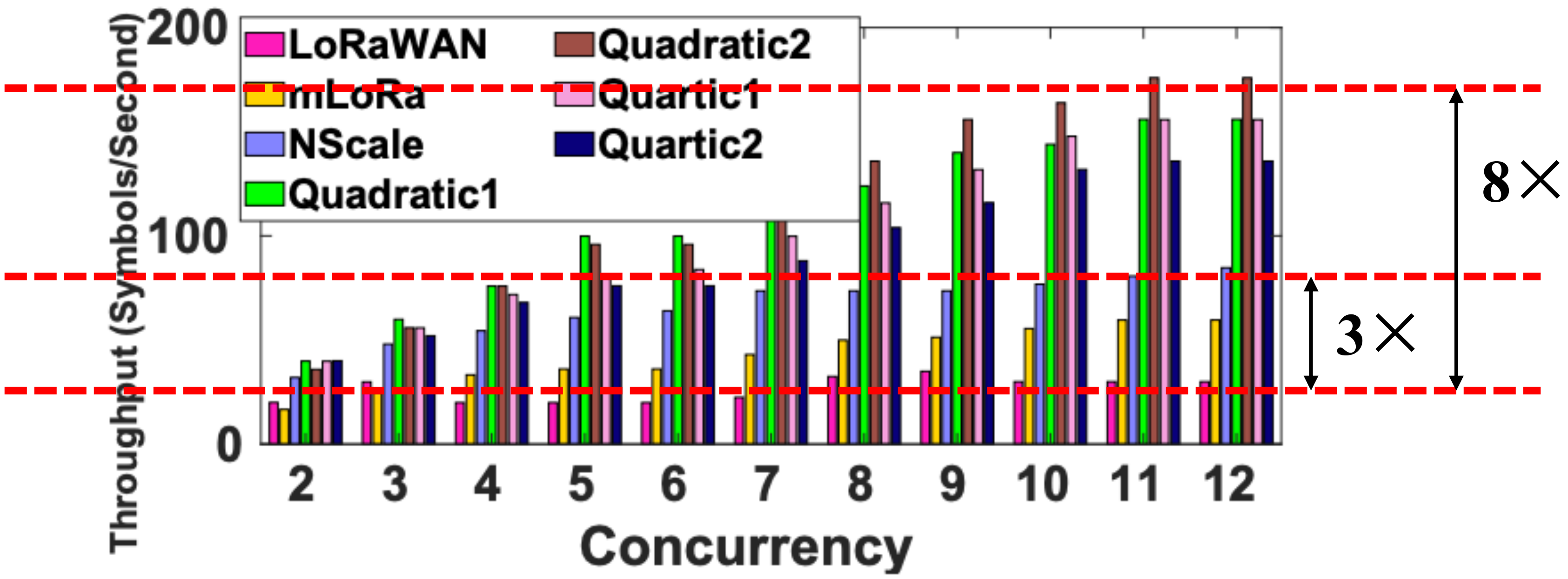
(a) SER vs. SNR when SF=8



(c) SER vs. SNR when SF=12

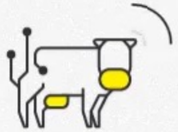
Linear vs non-linear: symbol error rate ($SIR \approx 0dB$)

Evaluation: Outdoor Performance



Outdoor experiment: examine the impact of concurrent transmissions

Conclusions & Future Work


AGRICULTURE


METERING

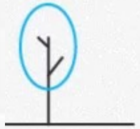

SMART CITIES


BUILDINGS &
FACILITIES


INDUSTRY

- CurvingLoRa Boosts Network Throughput via Concurrent Transmission

- Future Work
    - Non-linear Chirp Selection
    - CurvingLoRa at Higher Layers of LoRa Networking
    - Extend the Orthogonal Coding Space




HEALTHCARE
& E-HEALTH


TRANSPORTATION &
FLEET MANAGEMENT


OPERATORS &
TELECOMS

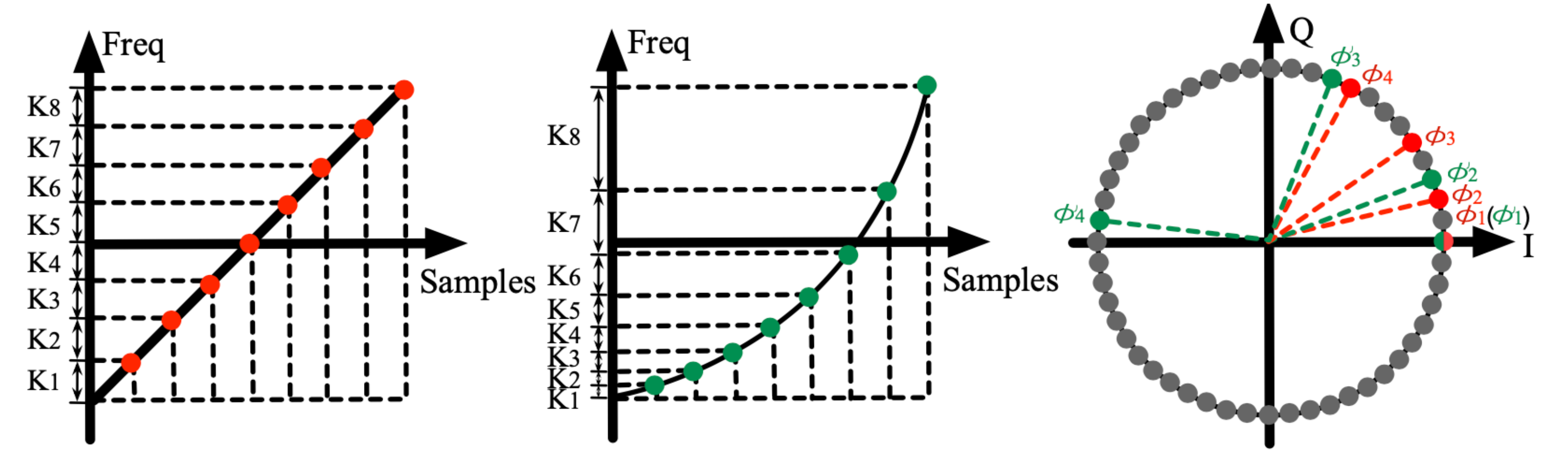

ENTERPRISE

The datasets and source codes are available at
https://github.com/liecn/CurvingLoRa_NSDI22

Credits to LoRa Alliance https://lora-alliance.org/lorawan-coverage/

Chirp Generation

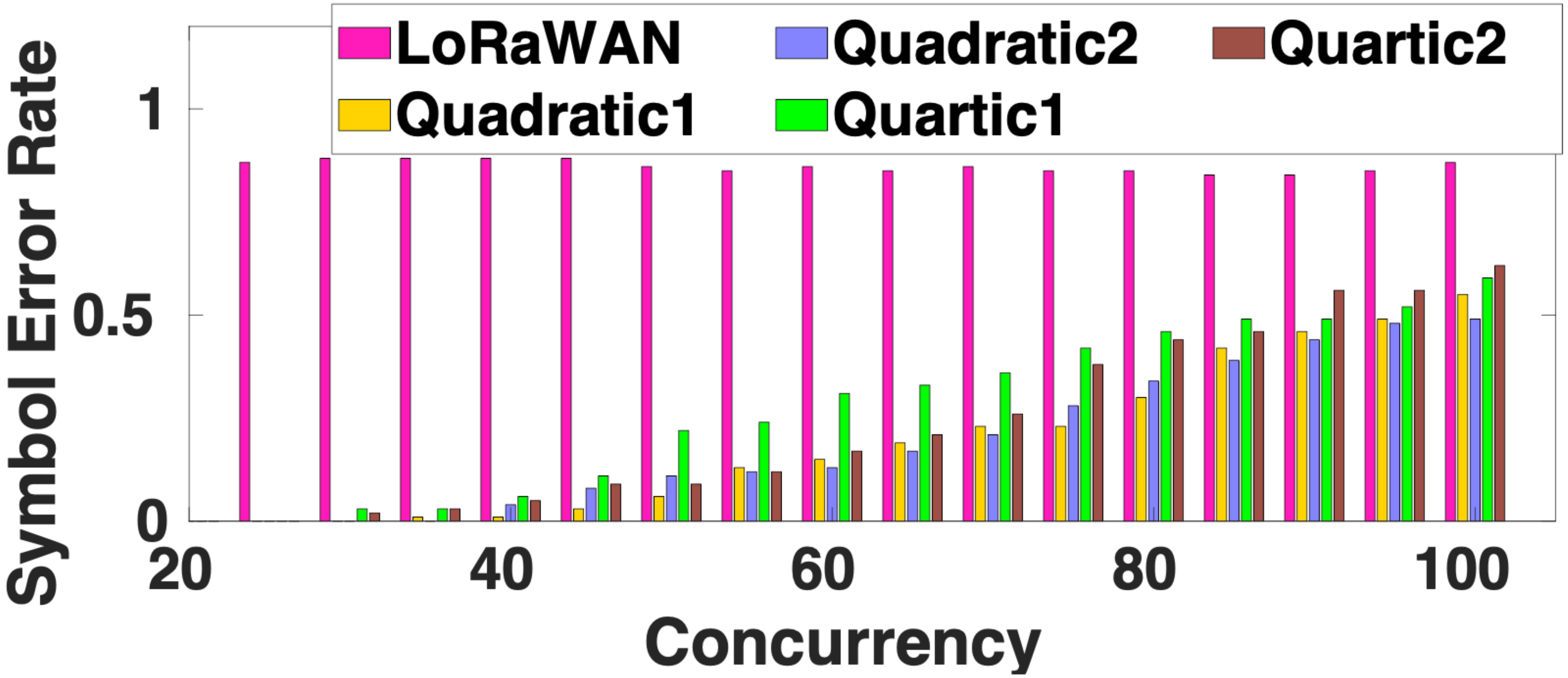
- **Comparable Power Consumption using the Direct Digital Synthesis (DDS) for Chirp Signal Generation**



(a) Frequency of a linear chirp (b) Frequency of a non-linear chirp (c) Phase of a linear/non-linear chirp

Figure 9: An illustration of DDS operation to generate the linear and non-linear chirps, respectively.

Evaluation：Emulation



Emulation of large-scale collisions.