Lecture 15
LPWANs Challenges

CS397/497 – Wireless Protocols for IoT

Branden Ghena – Spring 2024

With images from Swarun Kumar (CMU)
and Dinesh Bharadia (UCSD)

Materials in collaboration with
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Northwestern

Administrivia

- All remaining assignments are posted

- Hw: Cellular
  - Due Thursday next week (May 23rd)

- Lab: LoRa
  - Due Wednesday of last week of classes (May 29th)
  - Definitely the biggest lab, so account for that

- Final Design Project
  - Due Tuesday of exam week (June 4th)

Guest Lecture: May 23rd (next week Thursday)

- Dr. Meghan Clark
  - Research areas
    - Smart buildings
    - Network monitoring
  - PhD UC Berkeley (2021)
  - IoT Systems Research Scientist at Resideo
    - Smart home company
  - Talk is going to include more details on Matter and Smart Home IoT communication architectures

Today's Goals

- Consider LPWAN use cases,
  looking at a particular automotive study
- Explore academic research improving LoRaWAN capabilities
- Deep-dive into challenges LPWANs face

Outline

- **LPWAN Use Cases**
- LPWAN Challenges
- Improving LoRaWAN

Project Background

Research project with automotive company (circa 2019)

LPWAN protocols are potentially interesting for automotive uses

- New design points allow trading bandwidth, range, power, and cost.
- Could these enable new valuable applications?

Problem Statement

- Is there an opportunity to complement existing high-bandwidth low-latency networks, with emerging low-cost long-range networks for certain automotive use cases?

- What new uses cases can be realized by the addition of these new communications capabilities?

- How would future vehicle architectures change to support these networks?

Low-Power Applications

Now
(could be realized today)

Asset Tracking

Parked Status

Near
(could be realized soon)

Vehicle Security

Far
(longer-term ideas)

Distributed Data Collection

Asset Tracking Application (Now)

- Track the vehicle's location in real time from factory to point-of-sale.
- Envision a web application that can label each vehicle on a dealer's lot.
- Could be useful to owner as well for theft-tracking purposes.

- Would utilize:
  - GPS
  - Accelerometers (detect if vehicle is in motion)

Parked Status Application (Now)

- Alert the user of flat tires, dead batteries, or other issues that can occur while the vehicle is parked and off.
- Envision a smartphone app that could send owners a notification if something goes wrong.

- Would utilize:
  - Tire pressure sensors
  - Battery status sensors
  - Door, trunk, window, and roof opened/closed sensors
  - Fuel level sensor
  - Accelerometers (collision detection)

Vehicle Security Application (Near Term)

- Detect suspicious activity around the vehicle and send notifications to the owner.
- Envision a smartphone app that notifies the owner with a picture of the nearby activity.
- Would be enabled by sensors already in place for vehicle autonomy purposes.

- Would utilize:
  - Cameras
  - Motion sensors
  - Door, trunk, window, and roof opened/closed sensors
  - Accelerometers

Distributed Data Collection Application (Far Term)

- Collect and collate various sensor data from cars parked throughout a region.

- Parked vehicles can be used as a city-scale sensor network to determine various phenomena.
  - Track weather down to local levels.
  - Measure air quality throughout a city.
  - Sense and report nearby traffic congestion.

- This is a little further-term than other applications, but cities and researchers could benefit greatly from available data.

Break + Analysis

- How well does LoRaWAN meet these application needs?
- What about LTE-M / NB-IoT?

Now (could be realized today)	Near (could be realized soon)	Far (longer-term ideas)
Asset Tracking **Parked Status**	**Vehicle Security**	**Distributed Data Collection**

Project Takeaways

Unlicensed LPWANs seem limited in applicability to vehicles

- Coverage areas and bandwidth capabilities are too limited

Cellular LPWANs can enable inactive vehicle applications

- Applications have long lifetimes, even using a backup battery
- Architecture changes to support low-power communications appear feasible

Low-power, inactive-vehicle applications are worth further investigation

- Asset tracking and parked vehicle status are realizable in near-term
- What would the costs of realizing these applications be?
- How much value would they add for customers and company

Outline

- LPWAN Use Cases
- **LPWAN Challenges**
- Improving LoRaWAN

Challenge for Unlicensed LPWANs Paper

Challenge: Unlicensed LPWANs Are Not Yet the Path to Ubiquitous Connectivity

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ABSTRACT

Low-power wide-area networks (LPWANs) are a compelling answer to the networking challenges faced by many Internet of Things devices. Their combination of low power, long range, and deployment ease has motivated a flurry of research, including exciting results on backscatter and inter-

ACM Reference Format:

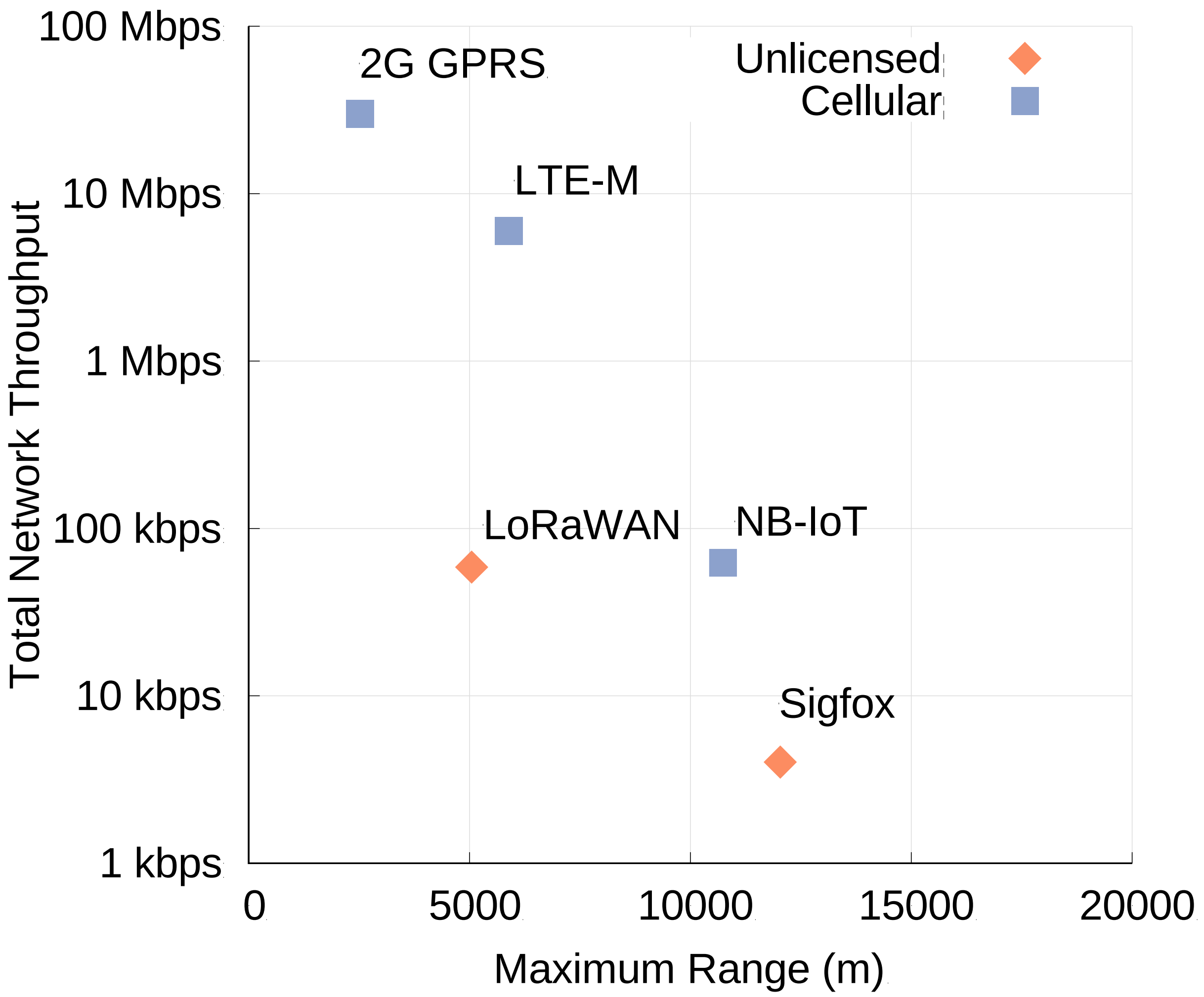
Branden Ghena, Joshua Adkins, Longfei Shangguan, Kyle Jamieson, Philip Levis, and Prabal Dutta. 2019. Challenge: Unlicensed LPWANs Are Not Yet the Path to Ubiquitous Connectivity. In *The 25th Annual International Conference on Mobile Computing and Networking (MobiCom'19), October 21–25, 2019, Los Cabos, Mexico.* ACM, New York, NY, USA, 12 pages. https://doi.org/10.1145/

- MobiCom 2019

Two major categories of low-power, wide-area network protocols

- **Unlicensed LPWANs**
  - Sigfox, LoRaWAN, etc.
  - Unlicensed band, 915 MHz (US)
  - Managed or user deployable

- **Cellular IoT**
  - LTE-M and NB-IoT
  - Licensed cellular bands
  - Managed networks
  - Rolled out US-wide



Do novel networks meet application needs?

- How do we compare varied requirements and capabilities?
  - Networks have throughput per gateway and range of gateway.
  - Applications have throughput per device and deployment area.

- Each gateway must support throughput for all devices in its coverage area.
  - Deployment areas are often wider than a single gateway’s range.

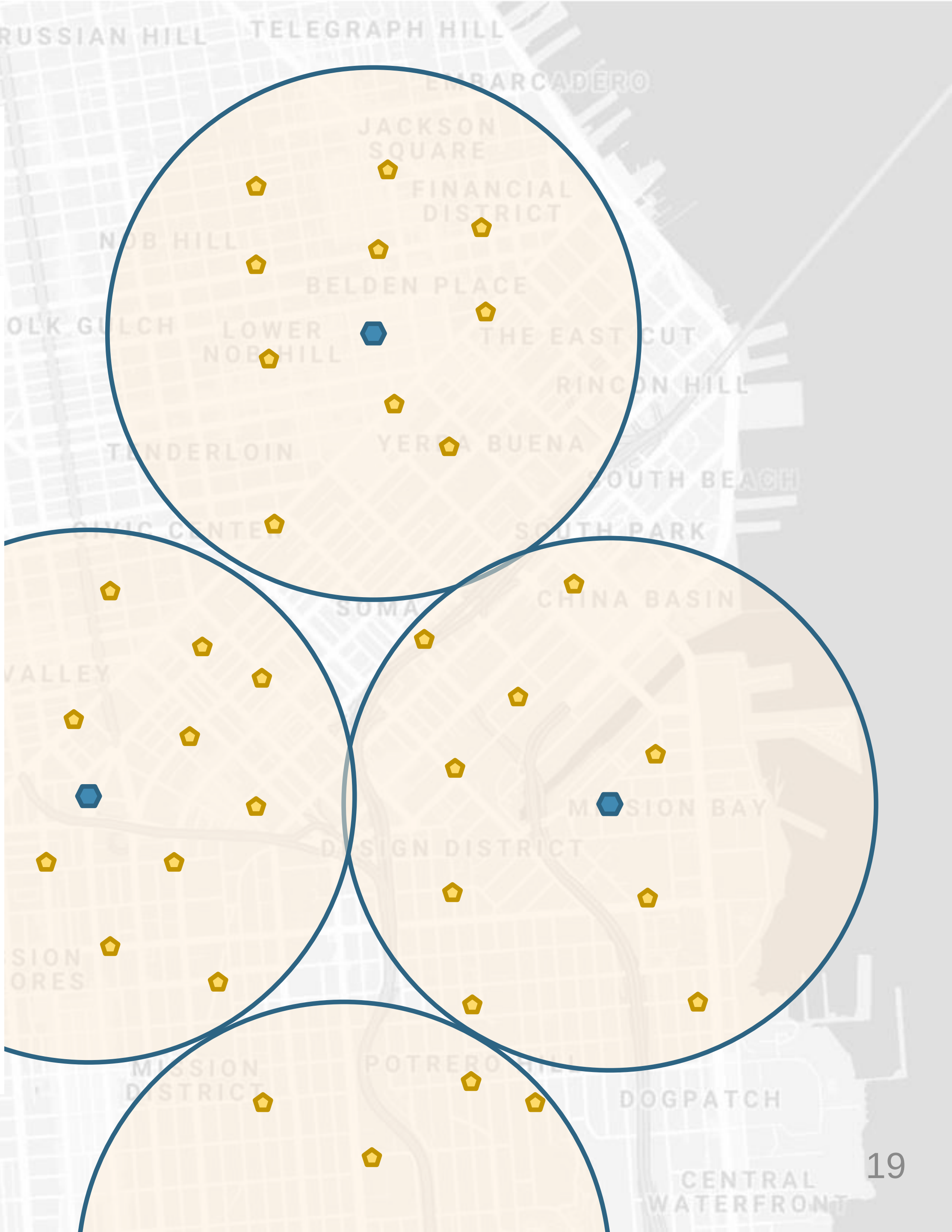
- Solution: compare the density of communication.
  - Data communication rate per unit area.

New metric for wide-area communication.

Our proposed metric: **bit flux**

- $$bit\ flux = \frac{network\ throughput}{coverage\ area}$$
- Units: bit per hour / m^2
- First suggested by Mark Weiser

Branden Ghena, et al. "Challenge: Unlicensed LPWANs Are Not Yet the Path to Ubiquitous Connectivity." *MobiCom'19*

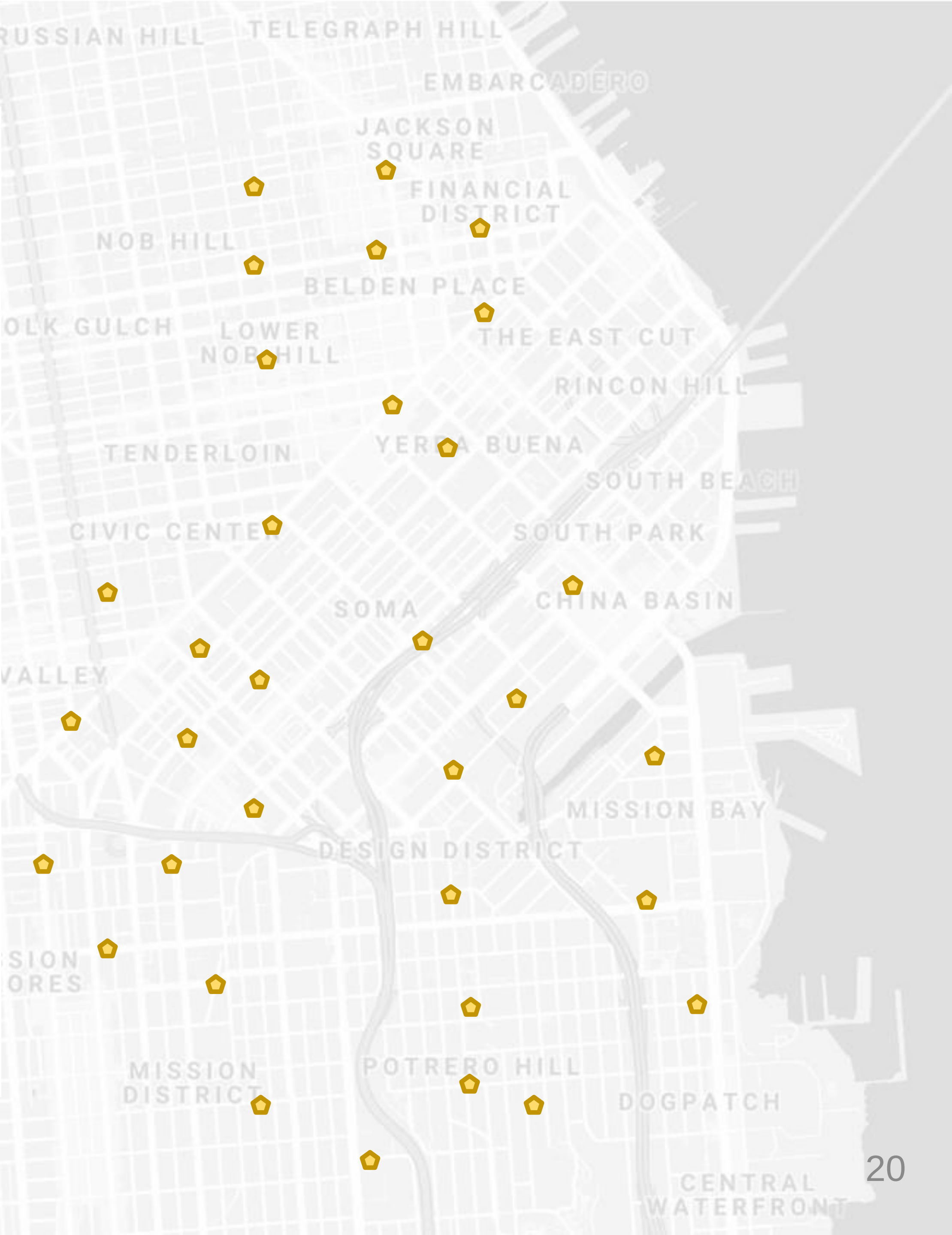


Bit flux can measure application needs.

For an application:

$$bit\ flux = \frac{\sum each\ device's\ uplink}{deployment\ area}$$

- Assumes a relatively homogeneous distribution.

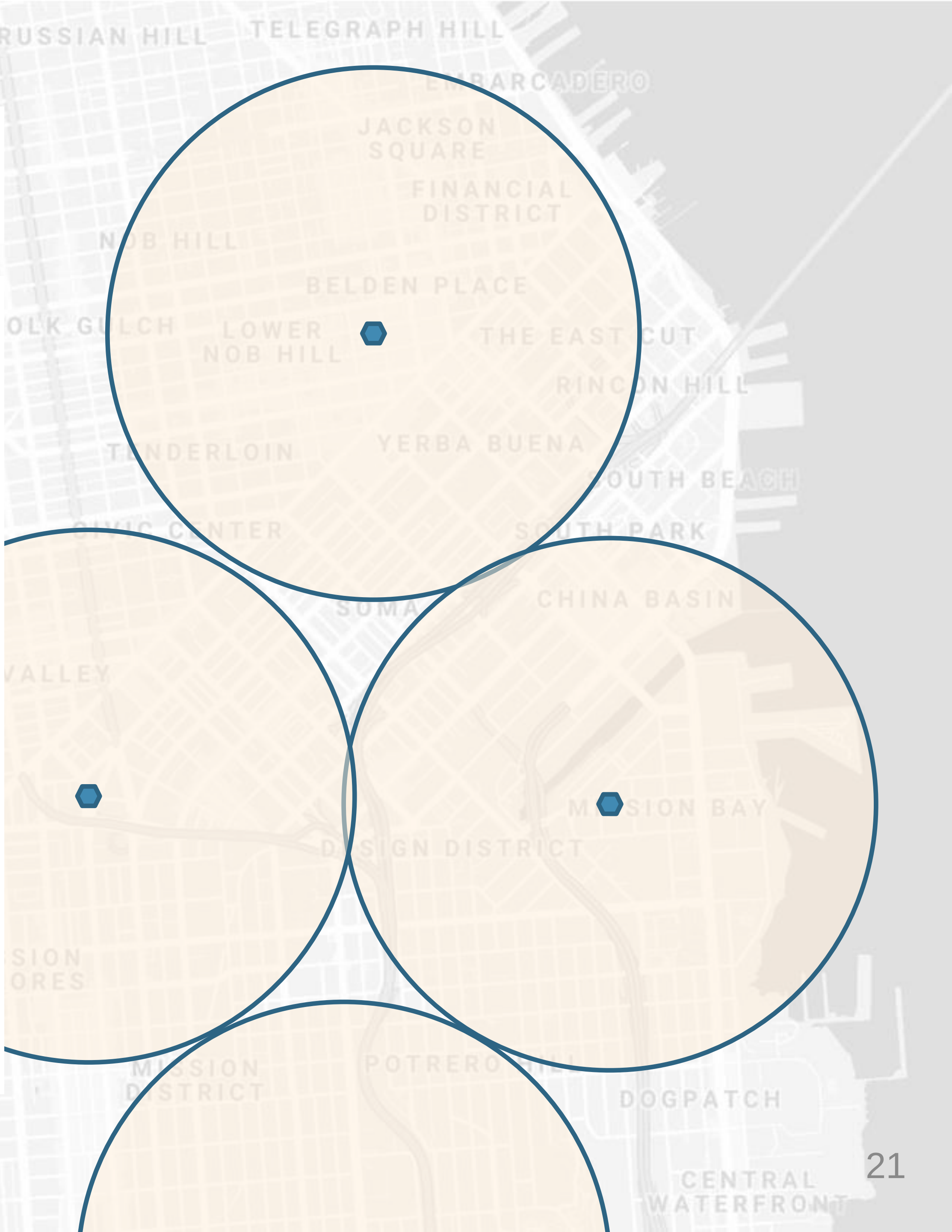


Bit flux can measure network capabilities.

For a network:

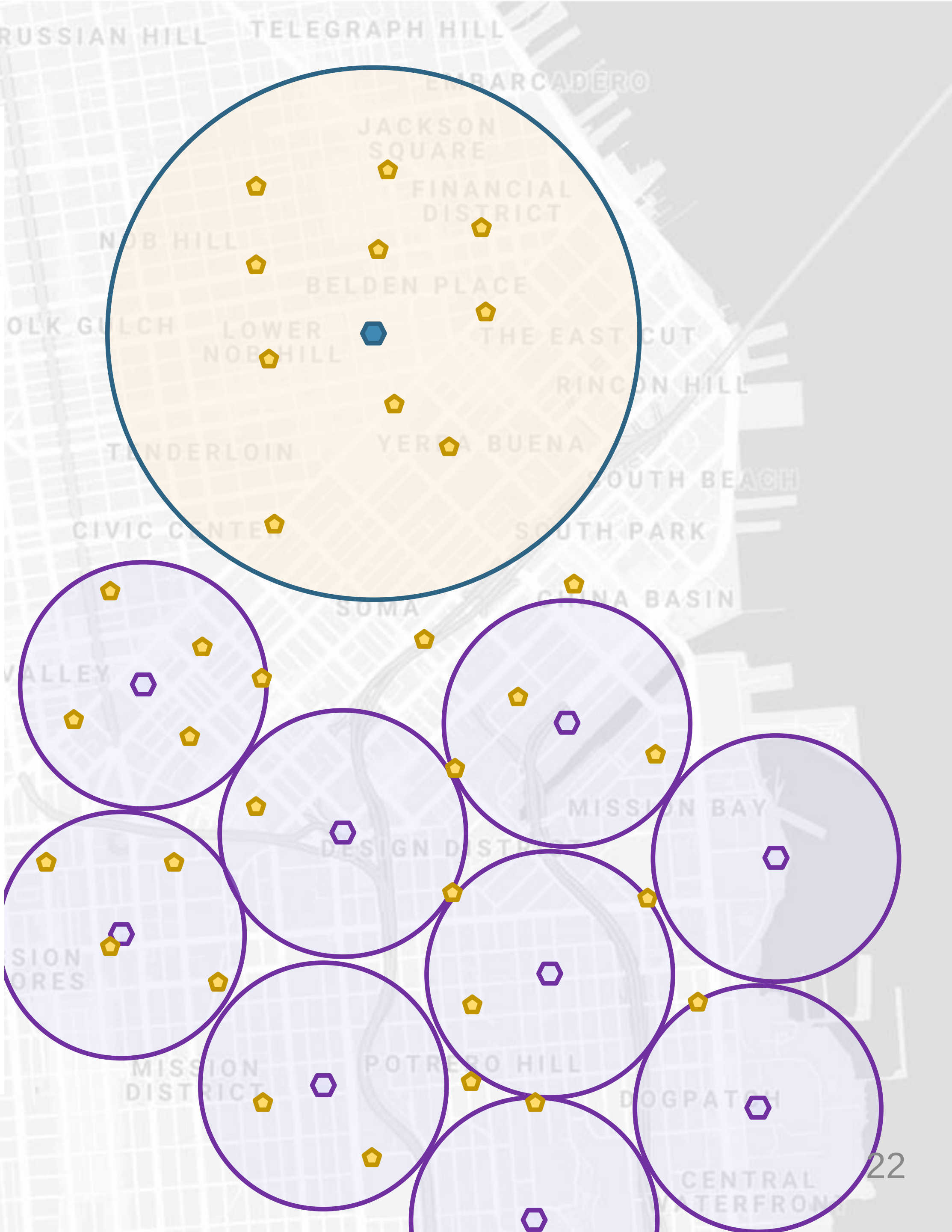
$$bit\ flux = \frac{gateway\ goodput}{gateway\ coverage\ area}$$

- Assumes a non-overlapping deployment of gateways.
- Note that bit flux alone ignores the total number of gateways required.



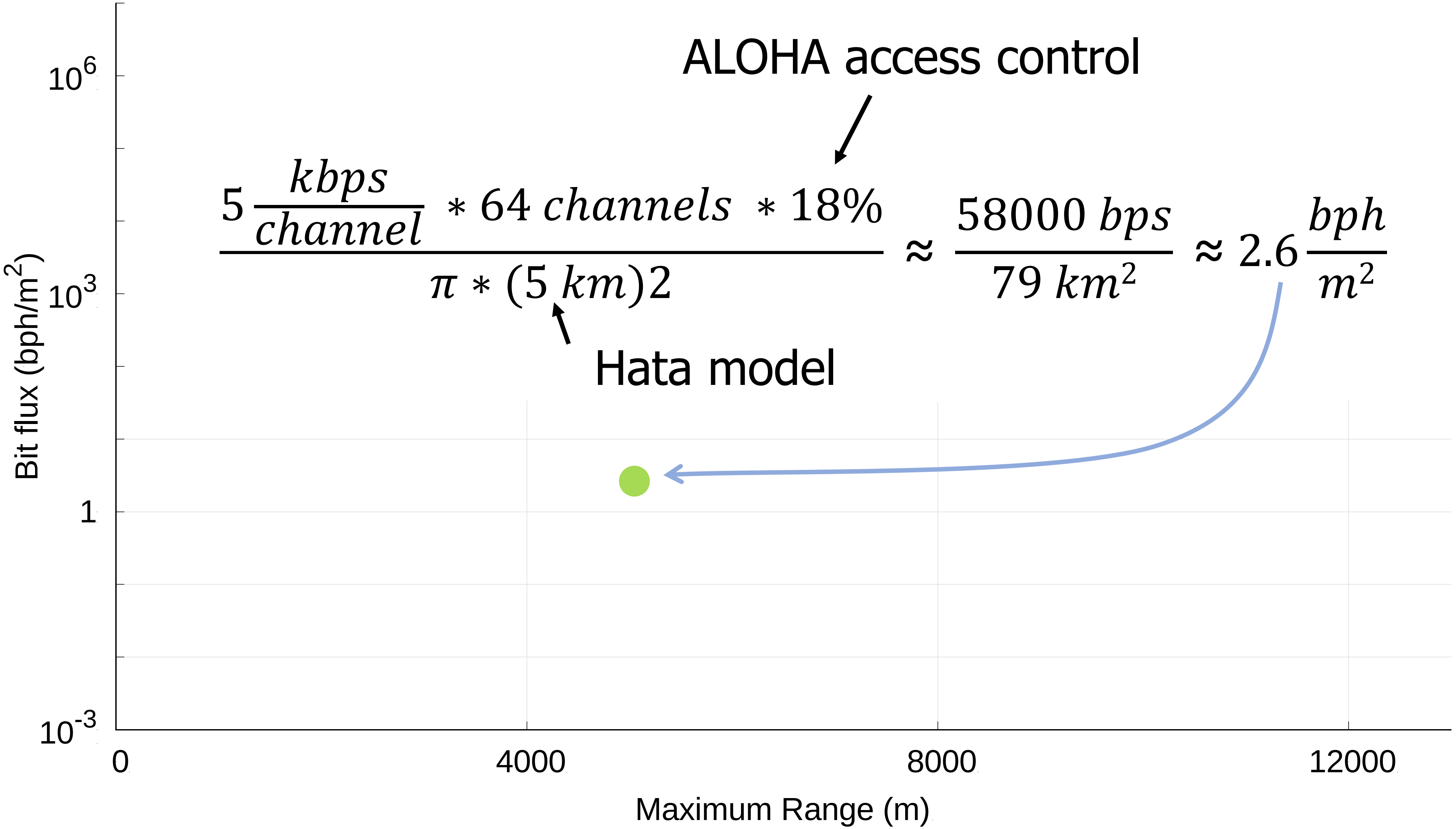
Bit flux accounts for spatial reuse.

- Reducing coverage area and deploying additional gateways improves capacity.
- $bit\ flux \uparrow = \dfrac{gateway\ goodput}{coverage\ area \downarrow}$

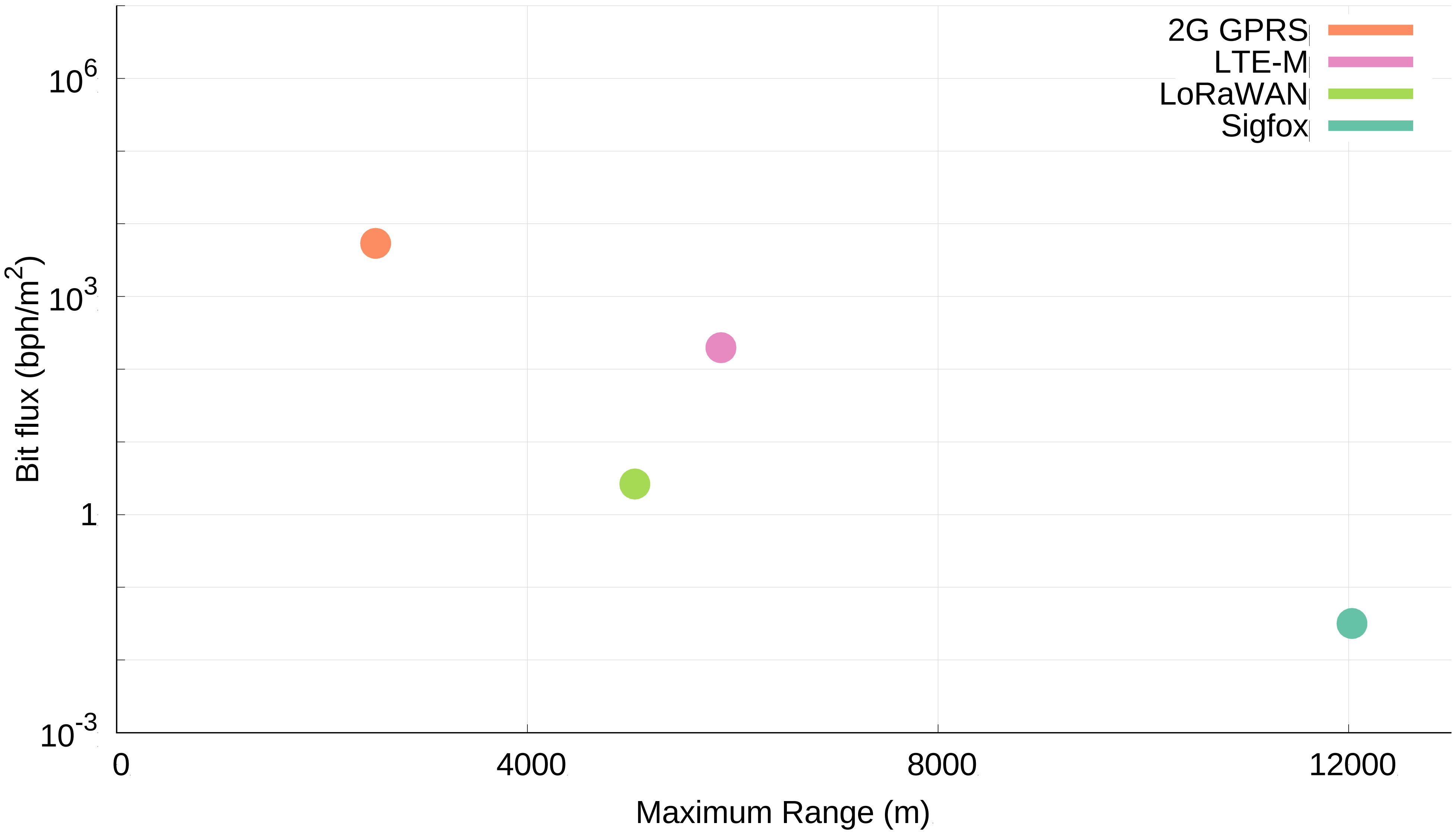


Bit flux measurement for LoRaWAN.

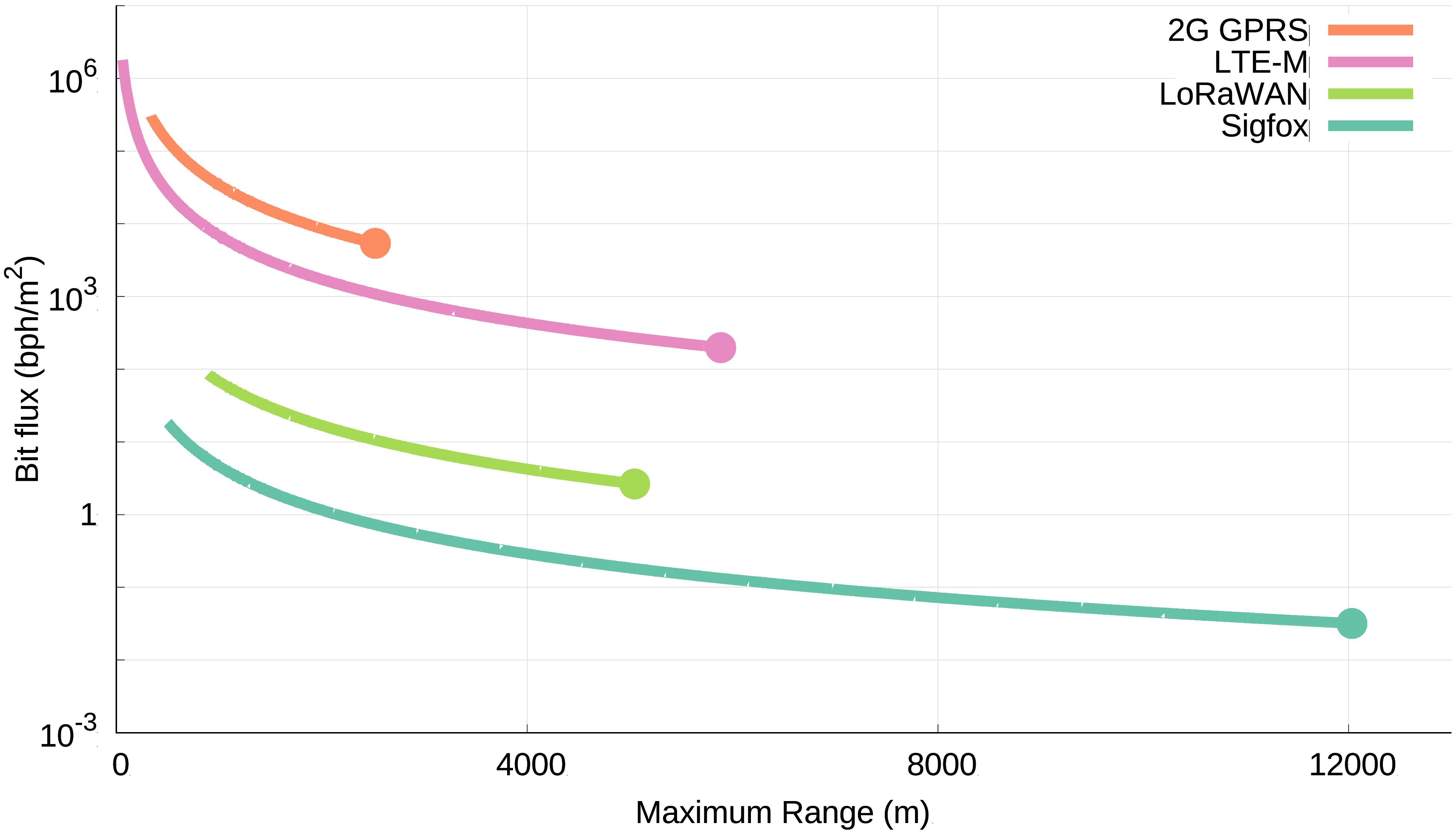
$$\frac{5\frac{kbps}{channel} * 64\ channels * 18\%}{\pi * (5\ km)2} \approx \frac{58000\ bps}{79\ km^2} \approx 2.6\frac{bph}{m^2}$$



Networks differ in capability by orders of magnitude.



Range reduction results in a bit flux curve for each network.



Let's compare network capabilities to a real-world application.

Smart household electric meters.

- ~250 bytes of data every 4 hours
- ~370000 electric customers in San Francisco

$$\frac{\frac{250\ bytes}{4\ hours} * 370000\ devices}{120\ km^2} \approx \frac{51000\ bps}{120\ km^2} \approx 1.5\frac{bph}{m^2}$$

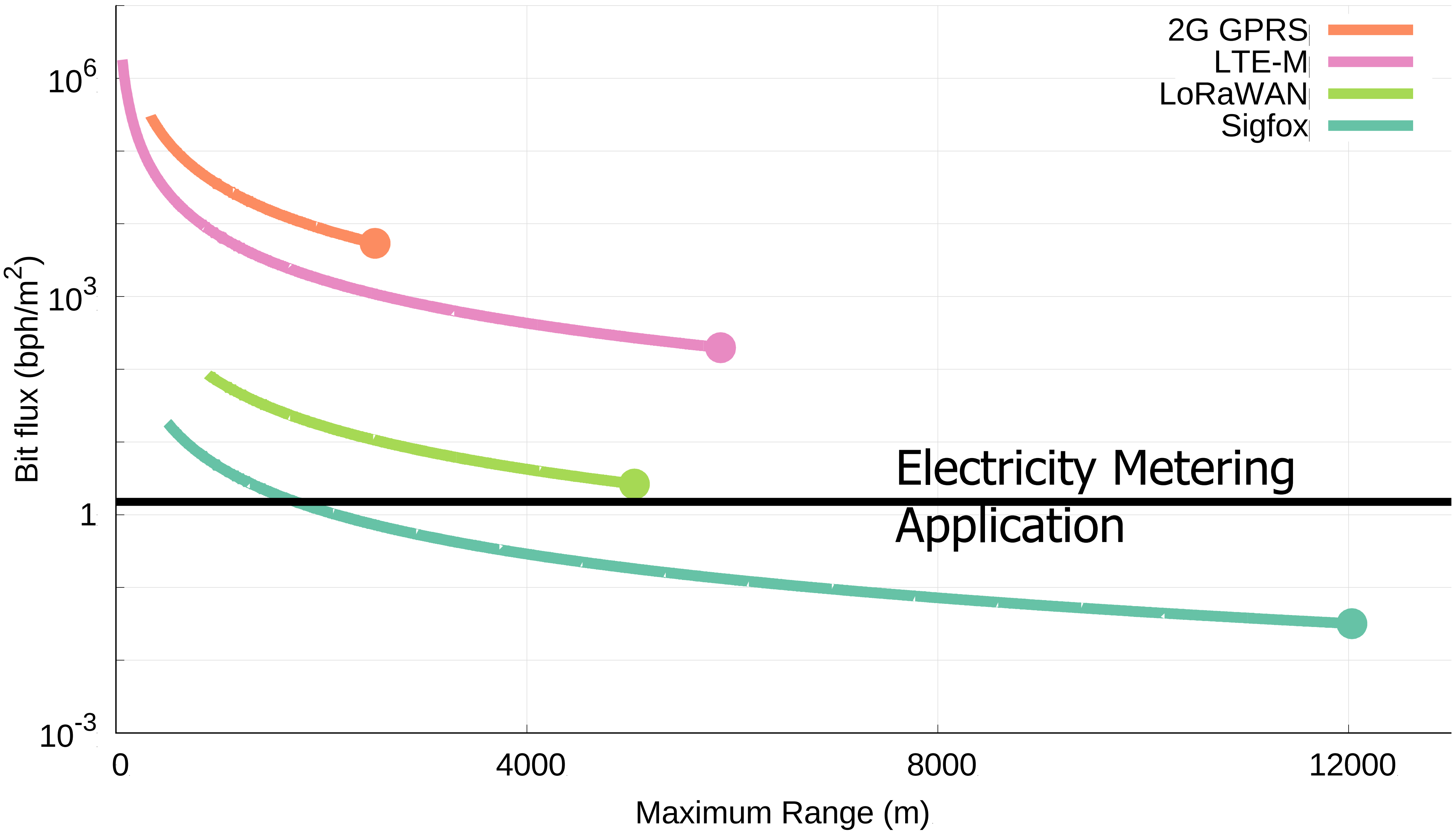
Bitflux for various applications

- See paper for full details on each application
- Creates a comparison point between applications and networks!

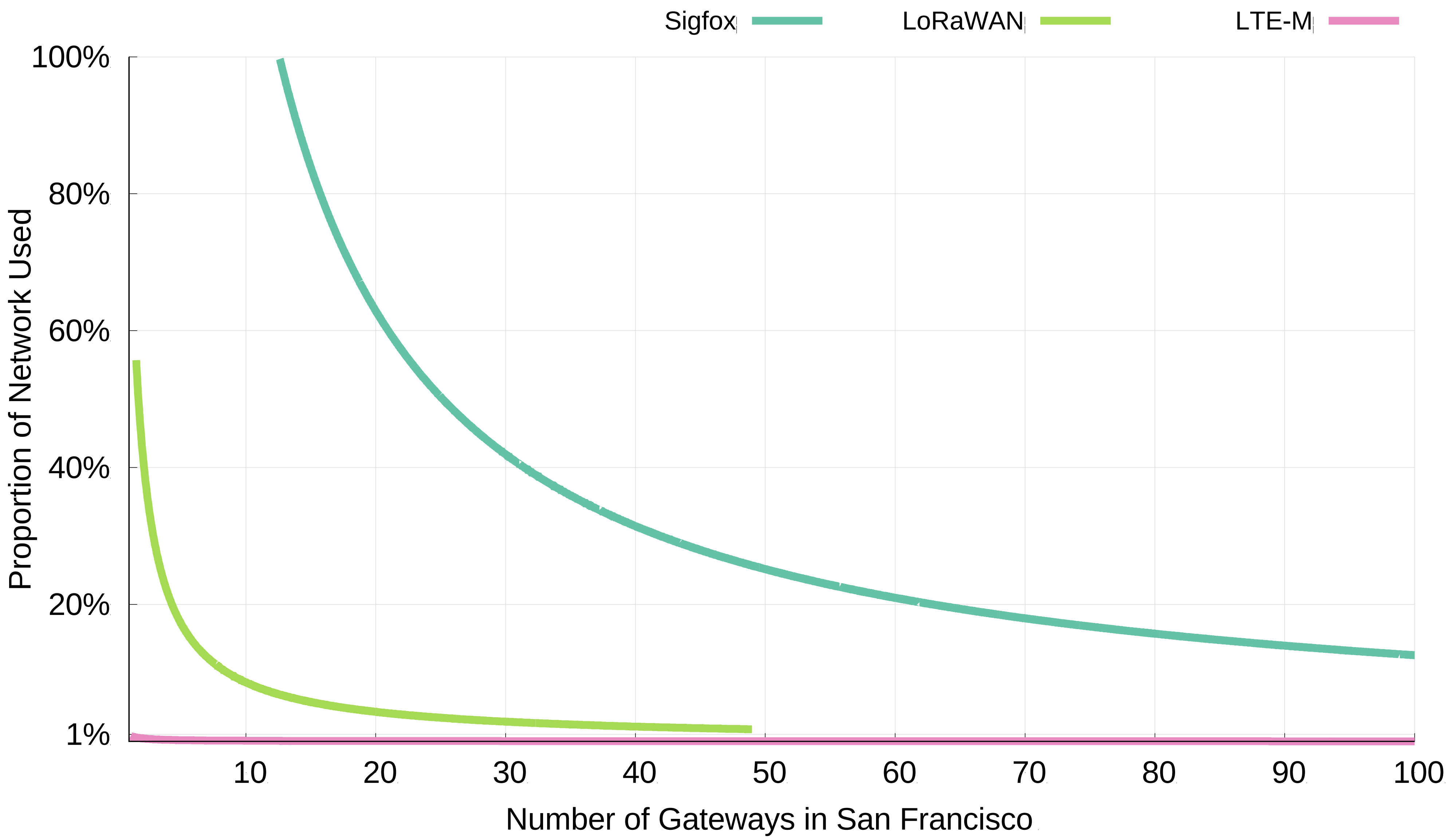
Application	Single Location Throughput (*bps*)	Single Location Radius (*m*)	Pervasive Bit Flux ($\frac{bph}{m^2}$)
Zebranet [63]	53	75	0
Trash can monitoring [4]	0.38	370	0.003
Hospital clinic [6]	11	20	0.02
Volcano monitoring [61]	520	1,500	0.2
CitySee [30, 64]	20,400	5,700	1
Electricity metering [12, 39]	51,389	6,180	1.5
Habitat monitoring [29]	10	10	9
H1N1 [22]	18,000	60	43
IMT-2020 [18, 19]	35,556	564	128
Macroscope [52]	12	4	221
GreenOrbs [33, 64]	5,600	80	1,000

https://brandenghena.com/projects/lpwan/ghena19lpwans.pdf

All networks are capable of meeting the data needs of electricity metering.

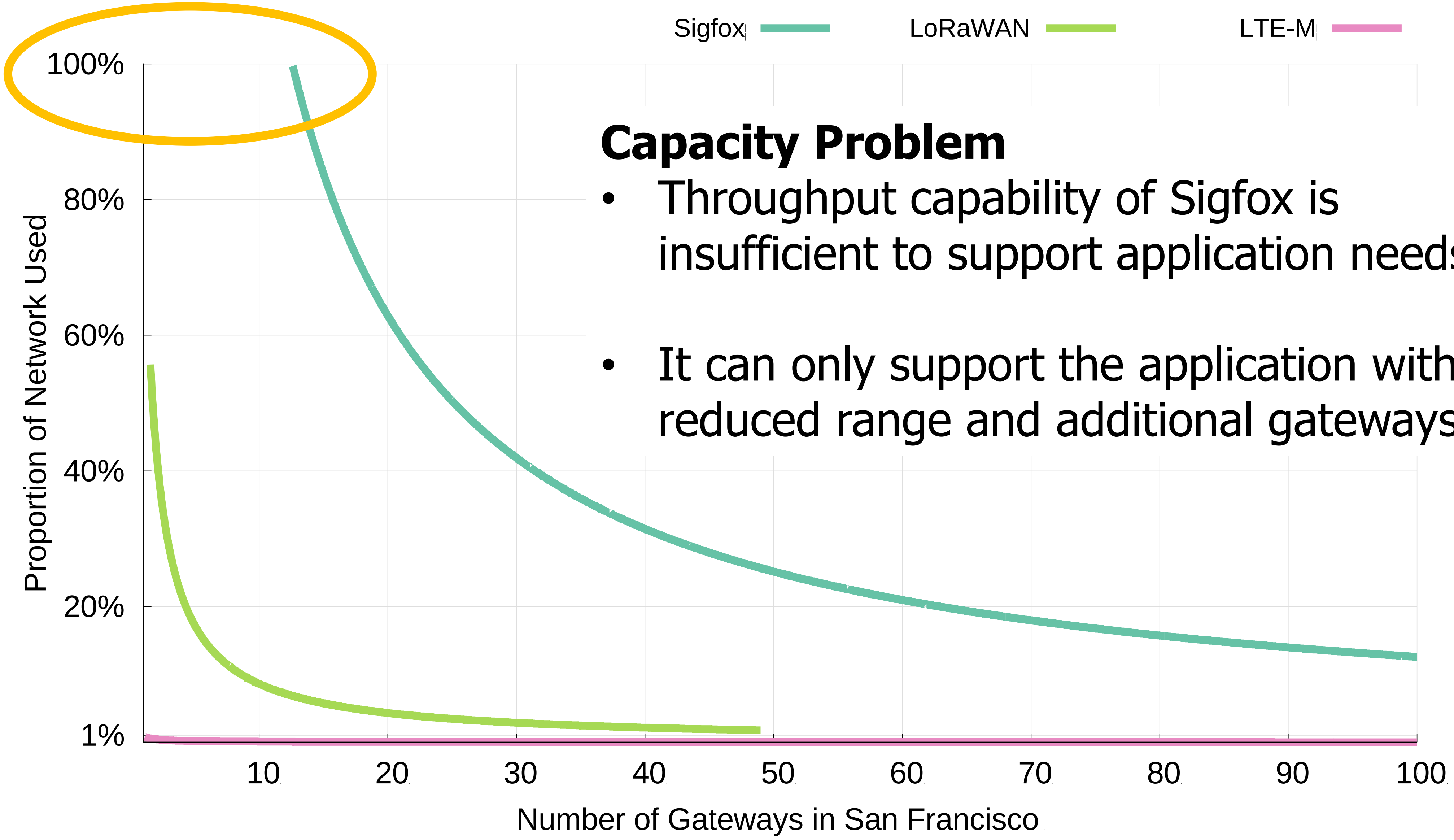


Unlicensed LPWANs lag behind Cellular IoT in ability to support applications.



2G < 0.03% utilized

Sigfox requires range reduction to meet application needs.



Capacity Problem

- Throughput capability of Sigfox is insufficient to support application needs
- It can only support the application with reduced range and additional gateways

Capacity solutions are relatively straightforward.

- Better access control mechanisms. Explore CSMA?
- Recover simultaneous transmissions (Choir and Charm).
- Increase bandwidth (TV white spaces).

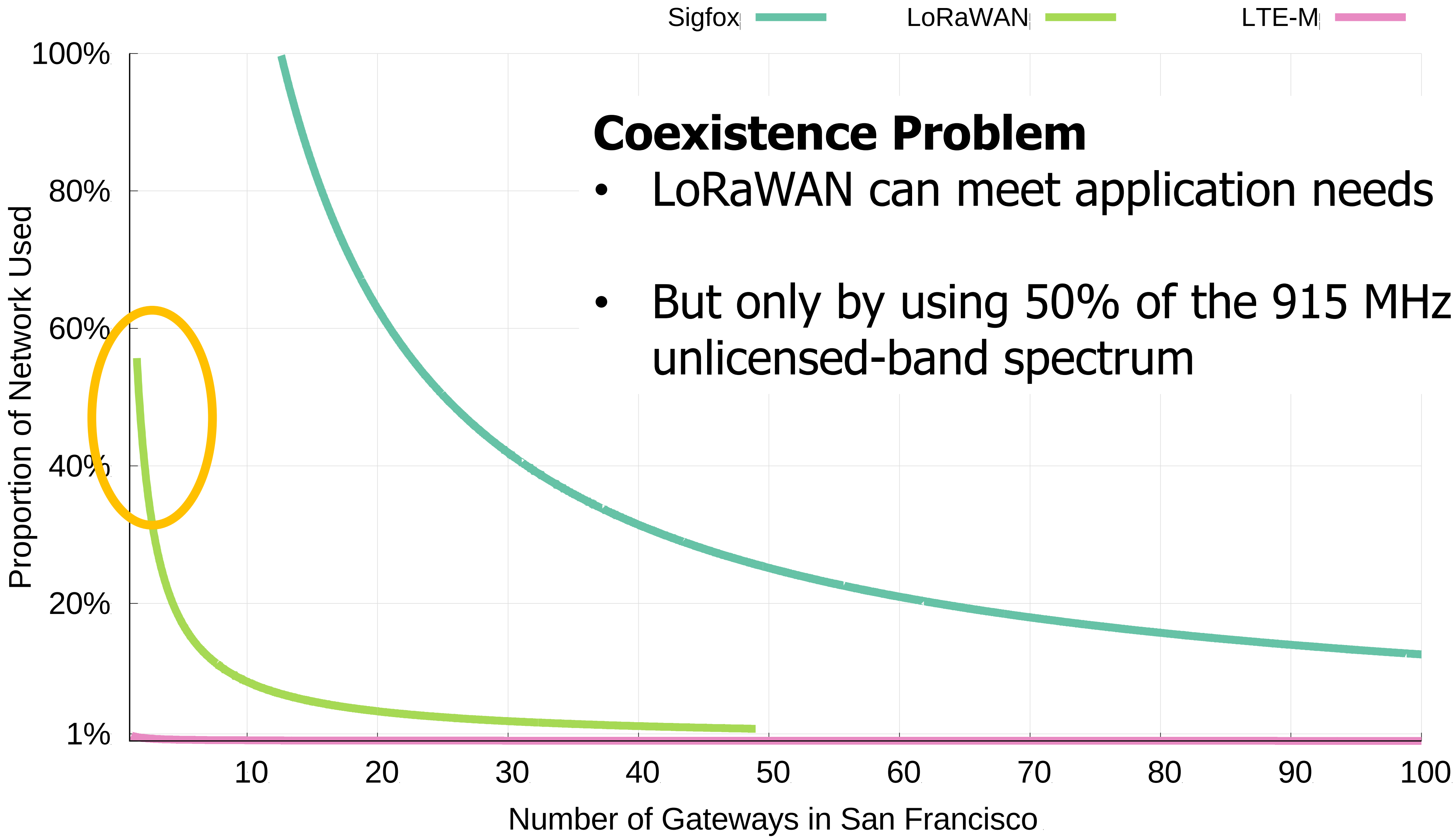
- All likely come at the cost of increased energy usage…
  - Results in a protocol that looks pretty similar to cellular…

Adwait Dongare, et al. "Charm: exploiting geographical diversity through coherent combining in low-power wide-area networks.“ *IPSN'18*

Rashad Eletreby, et al. "Empowering low-power wide area networks in urban settings." *SIGCOMM'17*

Abusayeed Saifullah, et al. "SNOW: Sensor network over white spaces." *SenSys'16*

LoRaWAN devotes most of its network capacity to a single application.

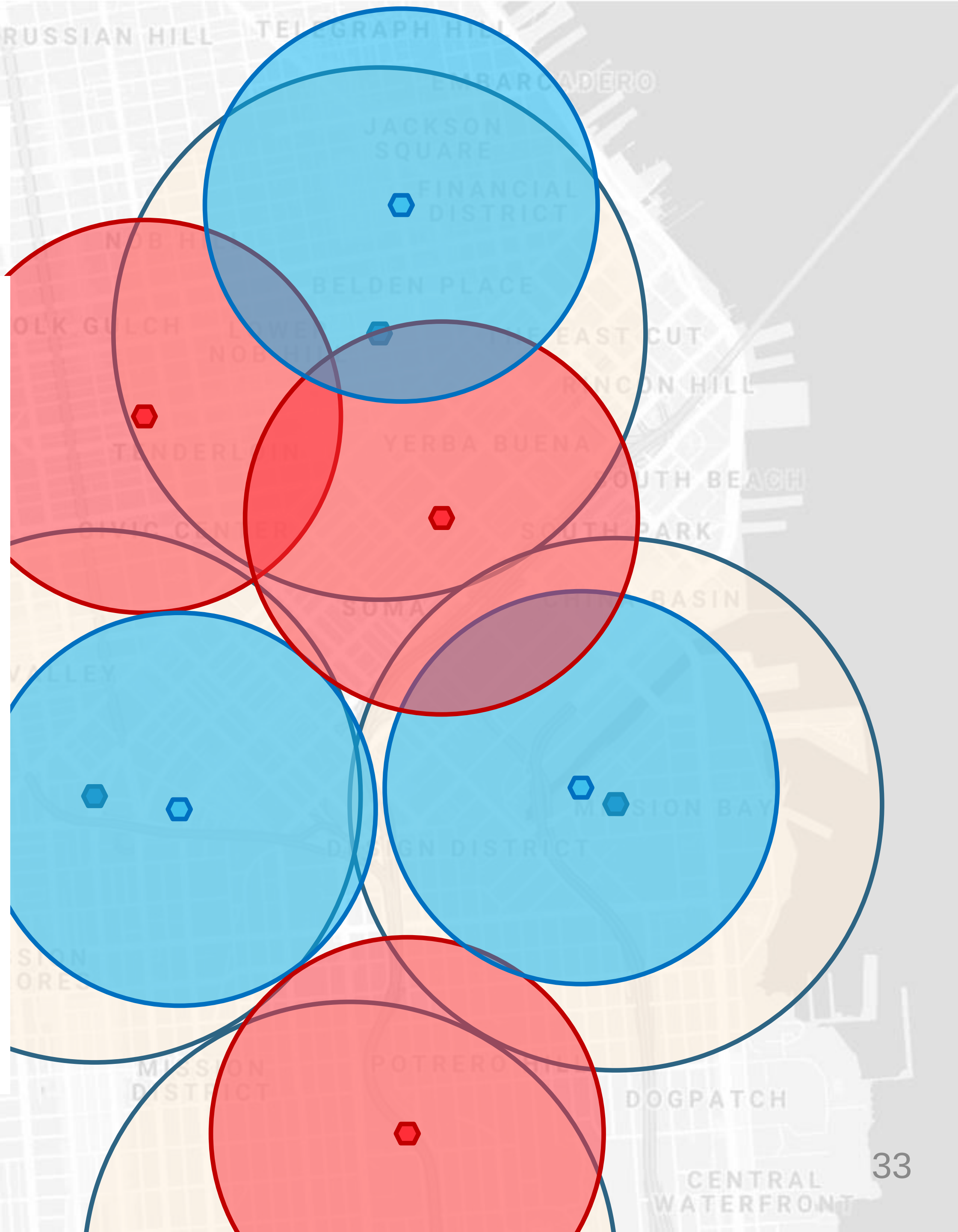


Coexistence Problem

- LoRaWAN can meet application needs
- But only by using 50% of the 915 MHz unlicensed-band spectrum

Coexistence is inevitable in urban areas.

- Urban environments and long range lead to many overlapping deployed networks.
- Capacity problems worsen coexistence by devoting more bandwidth to one application.
- It’s not just electricity metering…



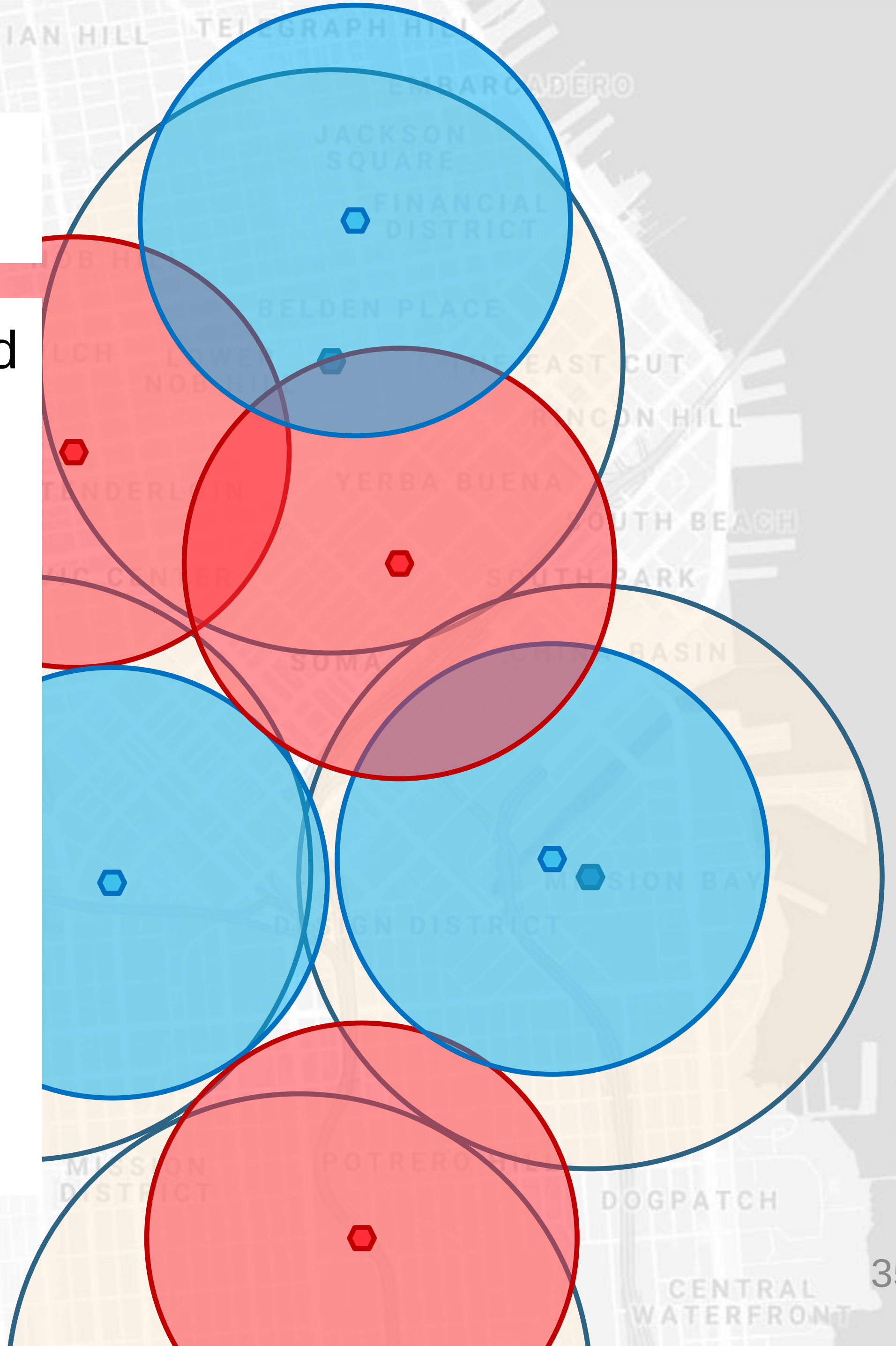
Coexistence in unlicensed bands is a more difficult problem.

- No methods for inter-network negotiation so far.
- Without buy-in from most deployments, all access control becomes uncoordinated.

- **Cellular IoT does not have this problem**

Cellular may dominate future deployments.

- LTE-M and NB-IoT are now deployed in the US (and worldwide).
- Licensed bandwidth avoids the coexistence problem.
- Cellular may solve many applications but is not a perfect solution.
  - Still has higher energy and monetary costs for use.
  - Also limited to where service is already available.



Unlicensed LPWANs are still useful for some scenarios.

- Controlled or unoccupied regions have reduced coexistence concerns.
  - Industrial factories, farms, parks and forests.

- Unlicensed networks are very exciting for research.
  - Anyone can deploy a network wherever they want.
  - Much easier to explore protocol modifications and new technologies.

- Research suffers without real-world applications.
  - Problem areas are strong recommendations for new research.
  - New research is only useful if they will have real-world impacts.

Implications – Low-Power Wide-Area Networks.

- Existing unlicensed LPWANs face significant challenges in supporting urban applications.
  - Best suited for industrial or agricultural uses in controlled environments.

- Research directions for unlicensed LPWANs:
  - improve network capacity,
  - and enable coexistence.

- Cellular IoT networks (LTE-M and NB-IoT) are positioned to solve the needs of city-scale sensing.
  - If the money and energy costs are there.

Break + Question

- How important is a homogenous distribution?
- Can you come up with a scenario where this breaks?

For an application:

$$bit\ flux = \frac{\sum each\ device's\ uplink}{deployment\ area}$$

- Assumes a relatively homogeneous distribution.

Break + Question

- How important is a homogenous distribution?
- Can you come up with a scenario where this breaks?
- Consider densely populated pockets of transmission over wide areas
  - Deployment area needs to correspond to pockets, not to entire range

For an application:

$$bit\ flux = \frac{\sum each\ device's\ uplink}{deployment\ area}$$

- Assumes a relatively homogeneous distribution.

Outline

- LPWAN Use Cases
- LPWAN Challenges
- **Improving LoRaWAN**

Resources

- Swarun Kumar (CMU) - https://swarunkumar.com/lpwan.html

- Choir
  - https://swarunkumar.com/papers/choir-sigcomm2017.pdf
  - https://swarunkumar.com/slides/choir-sigcomm2017.pdf

- Charm
  - https://swarunkumar.com/papers/charm-ipsn2018.pdf

- Opportunistic Packet Recovery
  - https://swarunkumar.com/papers/opr-mobisys2020.pdf

- BSMA
  - https://github.com/ucsdwcsng/bsma_lora/blob/09b998355498d6268ab0c1e940b395ec62a026a0/docs/full_paper_3495243.3560544.pdf

Choir Paper

Empowering Low-Power Wide Area Networks in Urban Settings

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ABSTRACT

Low-Power Wide Area Networks (LP-WANs) are an attractive emerging platform to connect the Internet-of-things. LP-WANs enable low-cost devices with a 10-year battery to communicate

1 INTRODUCTION

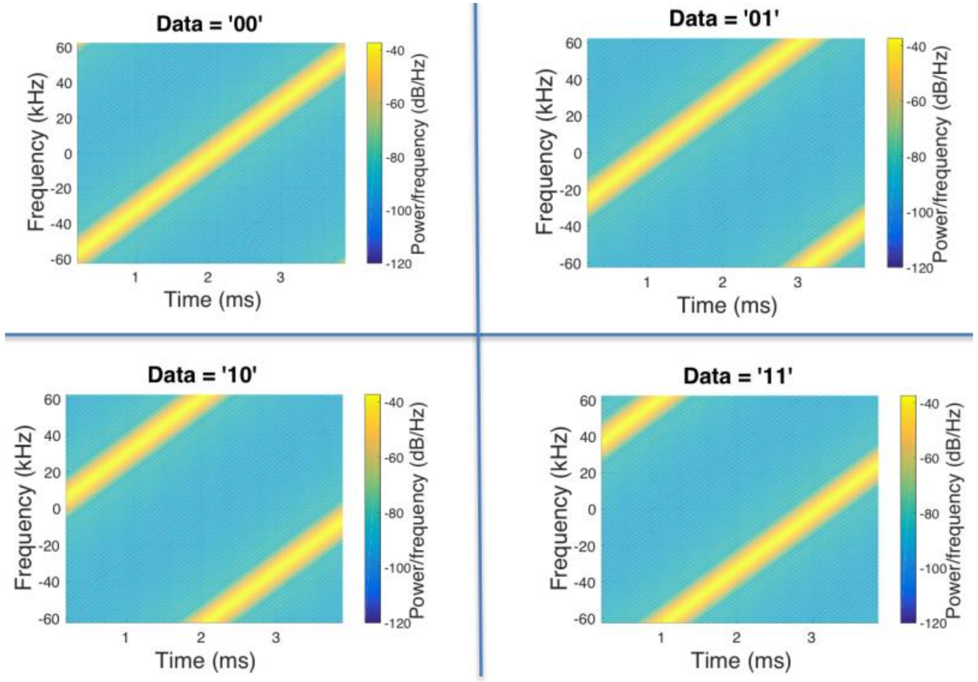
Recent years have witnessed Low-Power Wide Area Networks (LP-WANs) emerge as an attractive communication platform for the Internet of Things (IoT) [37]. LP-WANs enable low-power devices

- SIGCOMM 2017

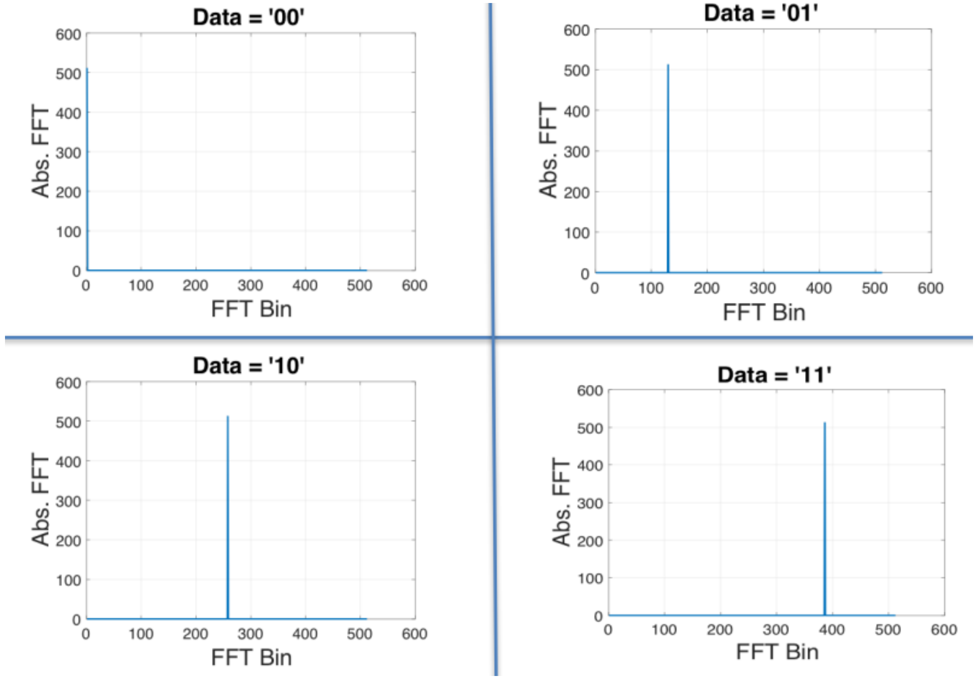
Choir concept

- Can we distinguish data from LoRa chirps that have collided?
  - Yes! By applying signal processing to the problem

Data in time domain

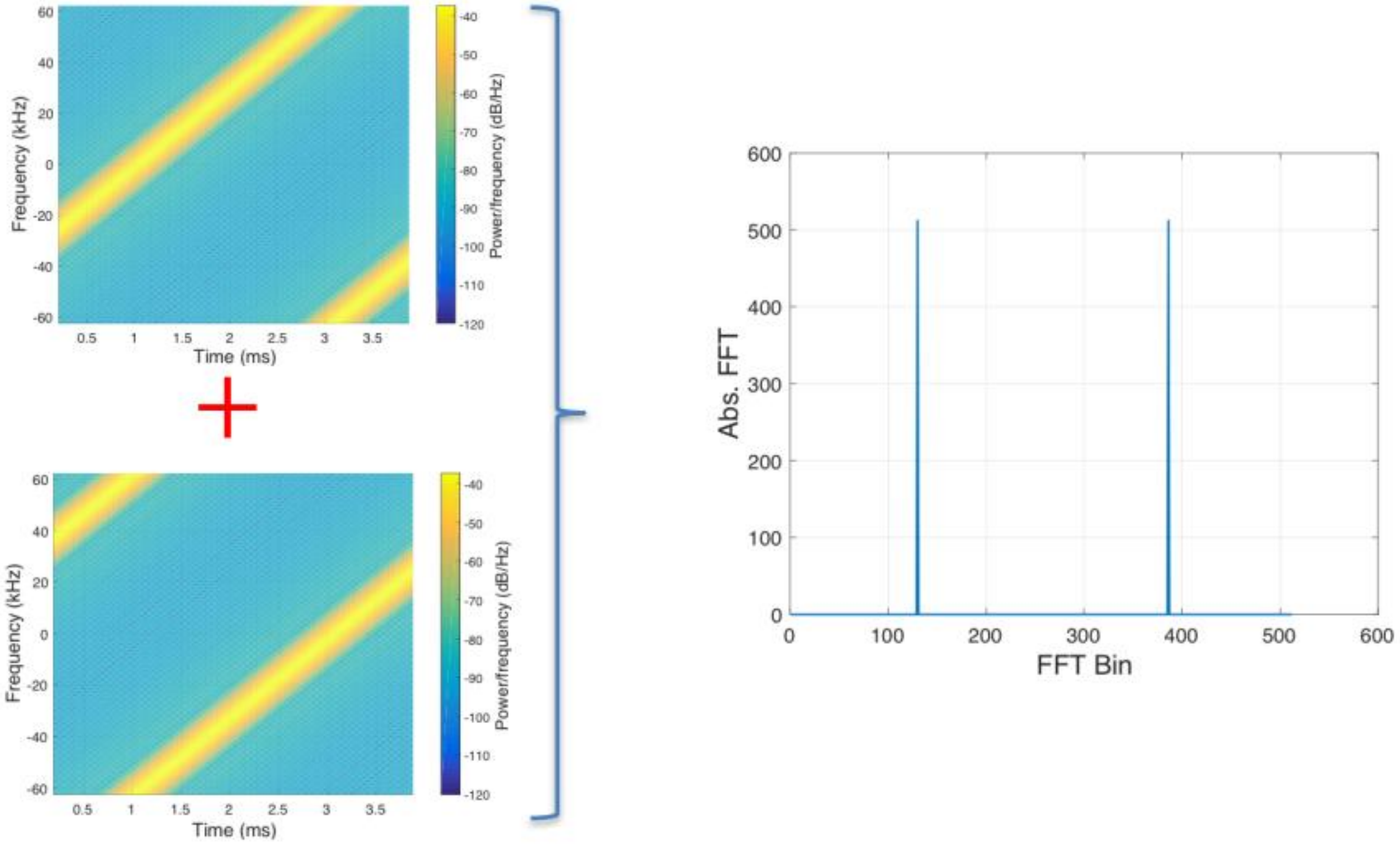


Data in frequency domain



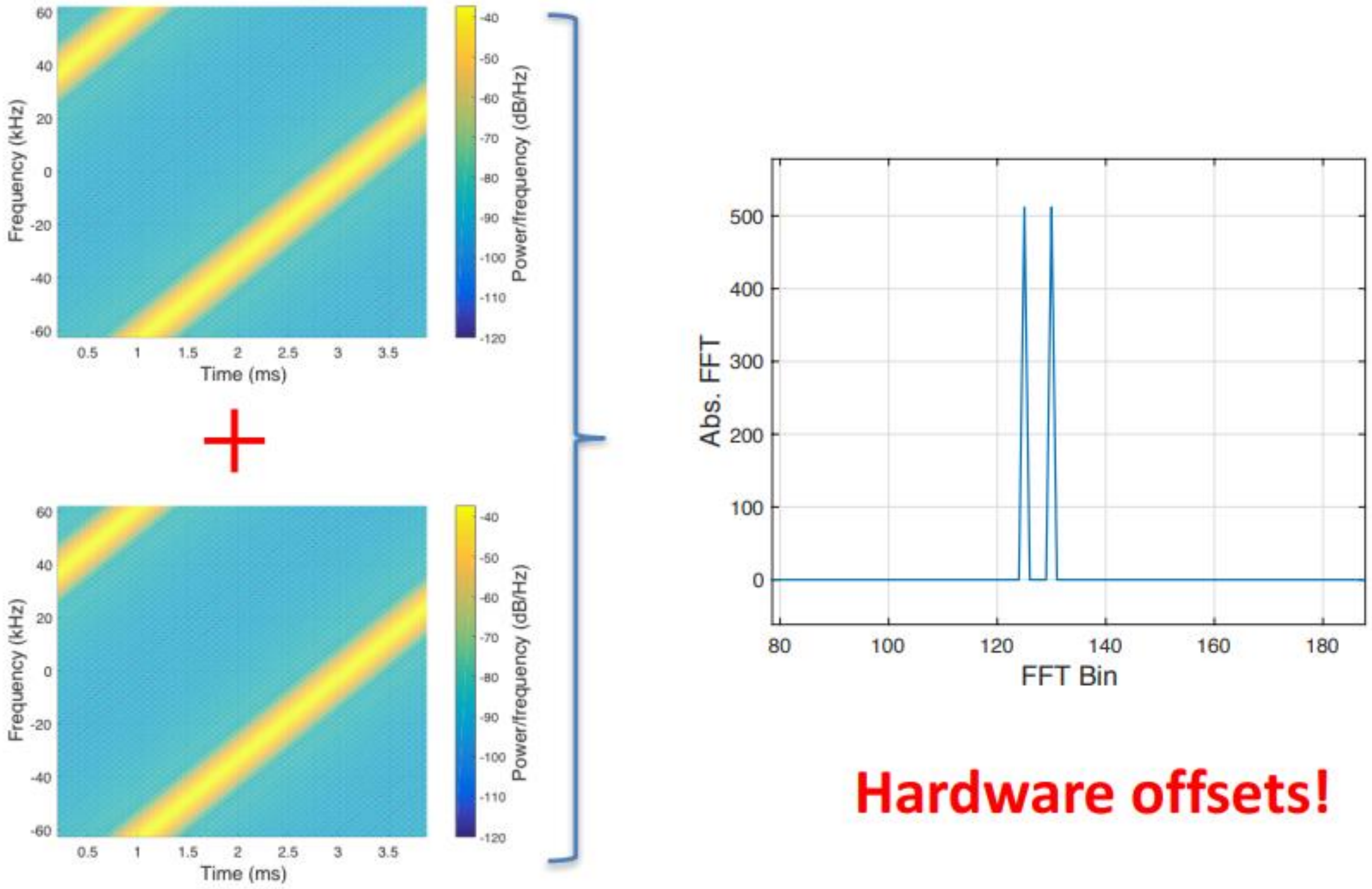
What happens when LoRa chirps collide?

Different data



What happens when LoRa chirps collide?

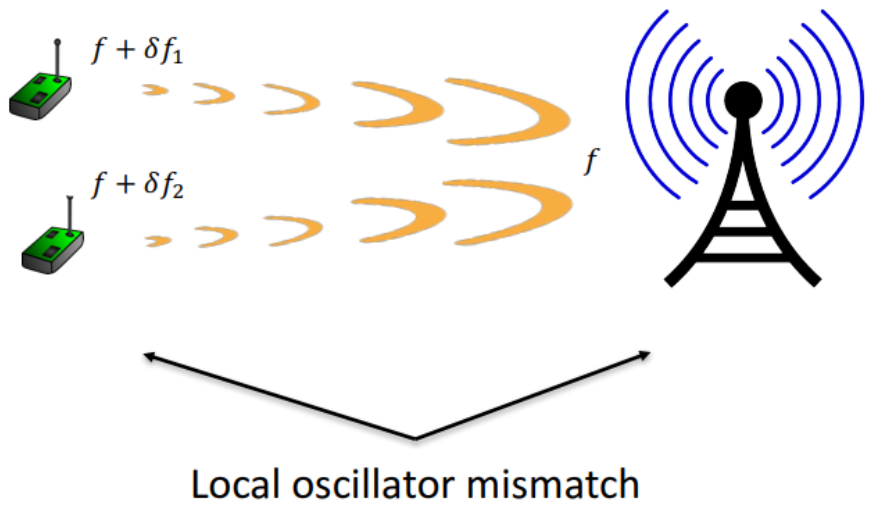
Same data



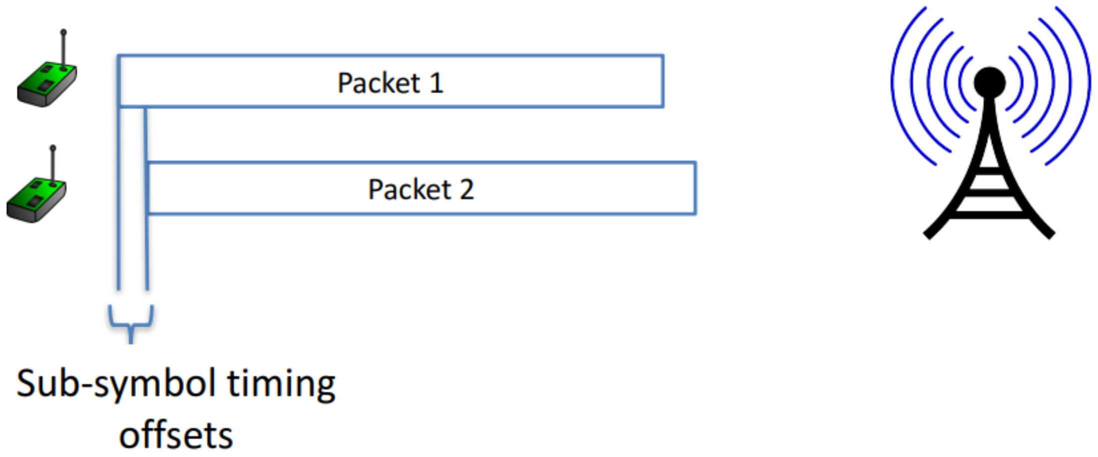
Hardware offsets!

Imperfections in hardware create offsets

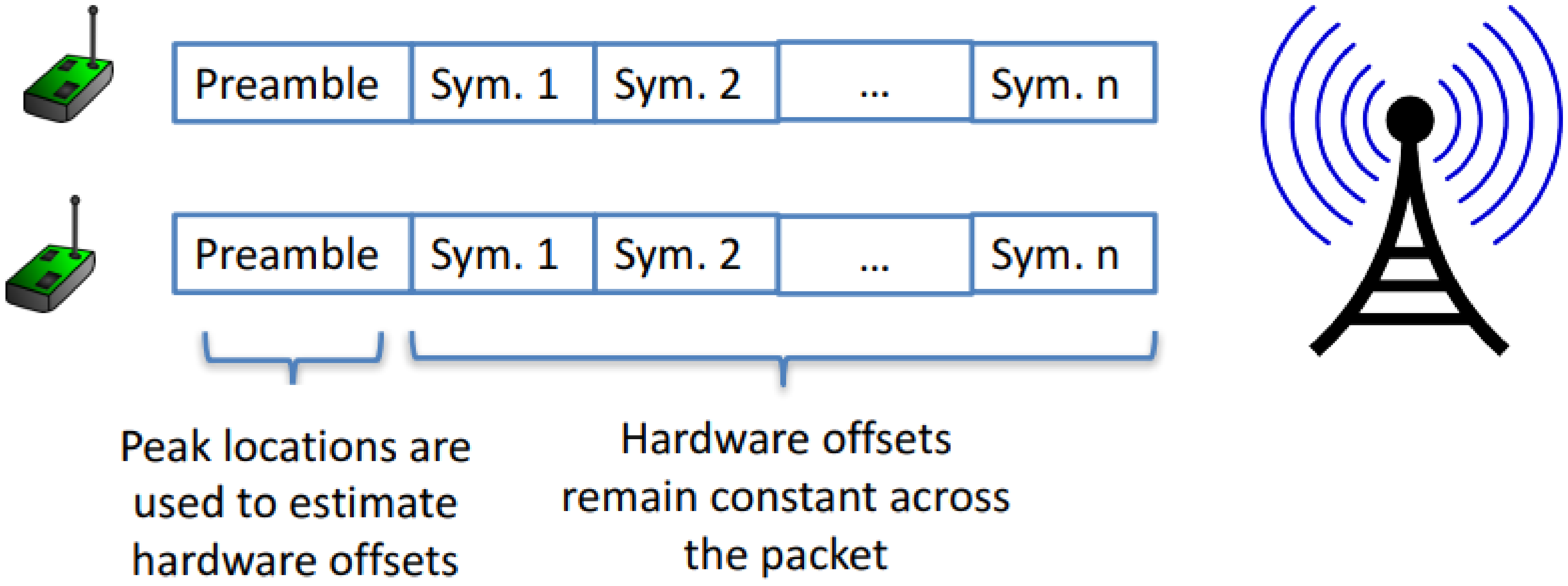
Carrier frequency offsets (CFO)



Timing offsets (TO)

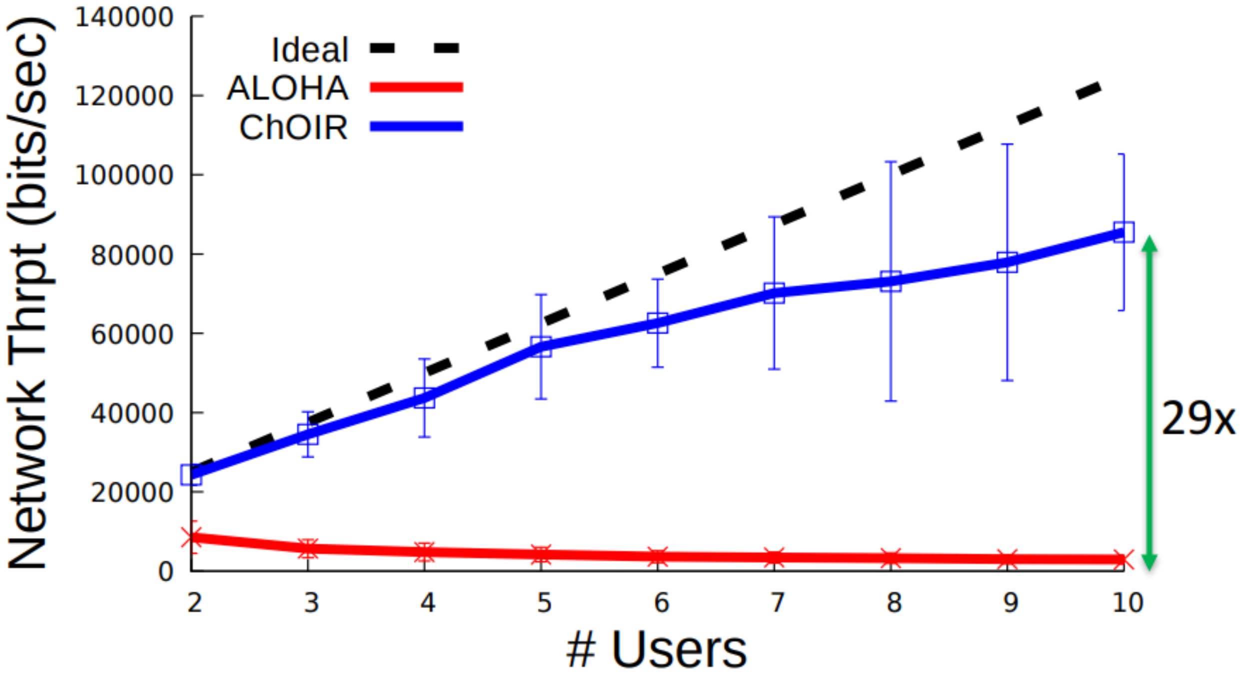


Decoding colliding packets



Choir results

- Recovering collided packets resolves losses due to Aloha transmission!
- Increases maximum throughput on the network considerably!
- Requires hardware modifications on gateways



Charm Paper

Charm: Exploiting Geographical Diversity Through Coherent Combining in Low-Power Wide-Area Networks

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ABSTRACT

Low-Power Wide-Area Networks (LPWANs) are an emerging wireless platform which can support battery-powered devices lasting

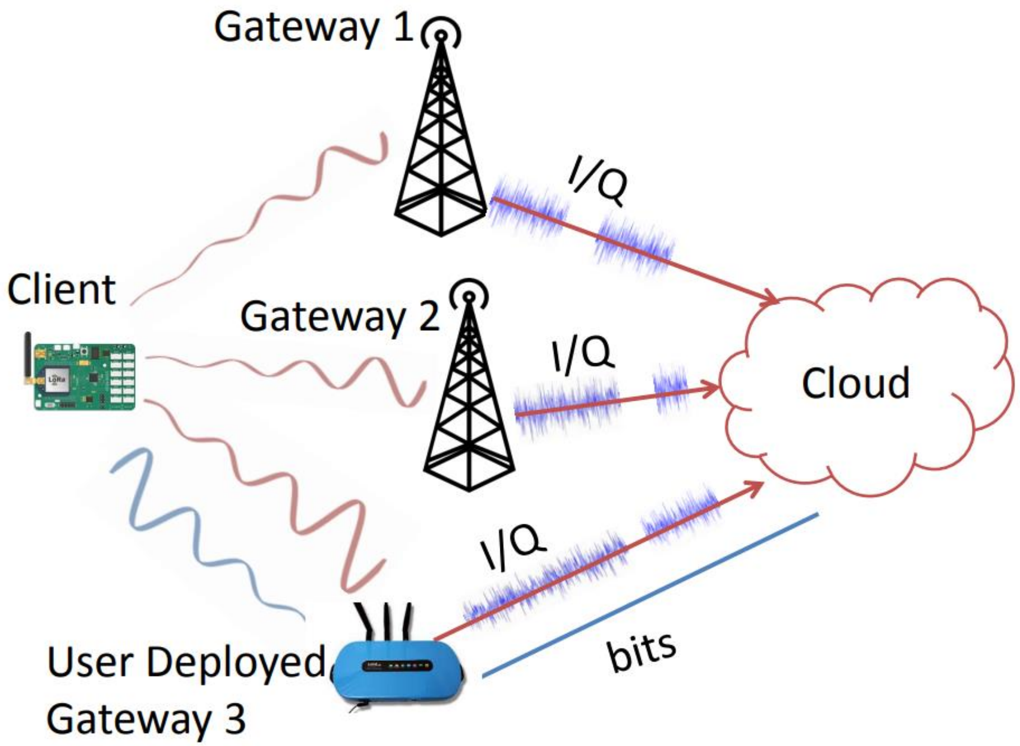
KEYWORDS

LPWAN, sensor networks, coherent combining, diversity

- IPSN 2018

Charm

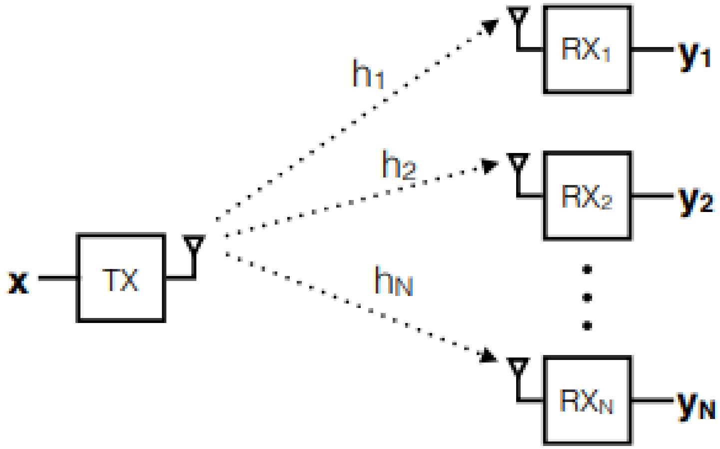
- Take advantage of multiple gateways in range of a device
- Combine signals received at each gateway to recover packets that weren't received cleanly
- Particularly useful at decoding weak signals



Coherent combining

- Signal received at each receiver is a combination of
  - Signal
  - Wireless channel
  - Random noise

- Signal and wireless channel are similar at all receivers
- Noise is different though! Possibly independent?



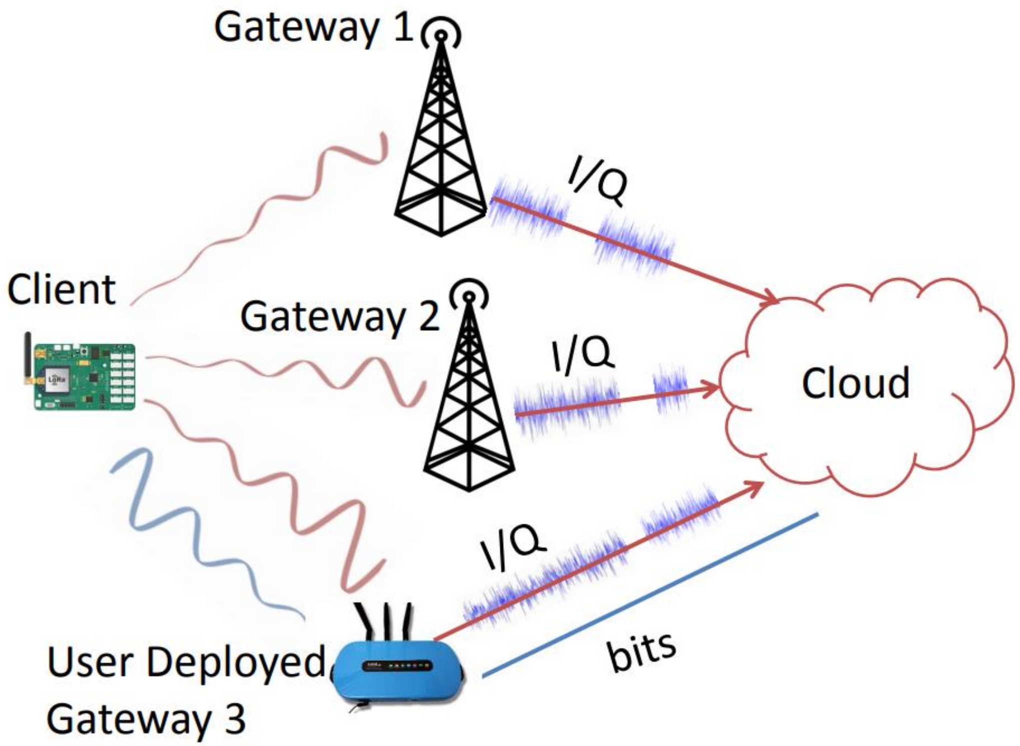
- When combined, signals are coherent (build in strength) whereas noise is incoherent (spreads out)

Charm uses coherent combining across gateways

- Gateways send signal data to the cloud

- The cloud can perform combining on the data and recover signals

- Challenges
  - Only send the data when it's needed
  - Tight time synchronization on the data
  - Gateway hardware changes



Opportunistic Packet Recovery Paper

A Cloud-Optimized Link Layer for Low-Power Wide-Area Networks

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ABSTRACT

Conventional wireless communication systems are typically designed assuming a single transmitter-receiver pair for each link. In Low-Power Wide-Area Networks (LP-WANs), this one-to-one design paradigm is often overly pessimistic in terms of link budget because client packets are frequently detected by multiple gateways

ACM Reference Format:
Artur Balanuta, Nuno Pereira, Swarun Kumar, and Anthony Rowe. 2020. A Cloud-Optimized Link Layer for Low-Power Wide-Area Networks. In *The 18th Annual International Conference on Mobile Systems, Applications, and Services (MobiSys '20), June 15–19, 2020, Toronto, ON, Canada.* ACM, New York, NY, USA, 13 pages. https://doi.org/10.1145/3386901.3388915

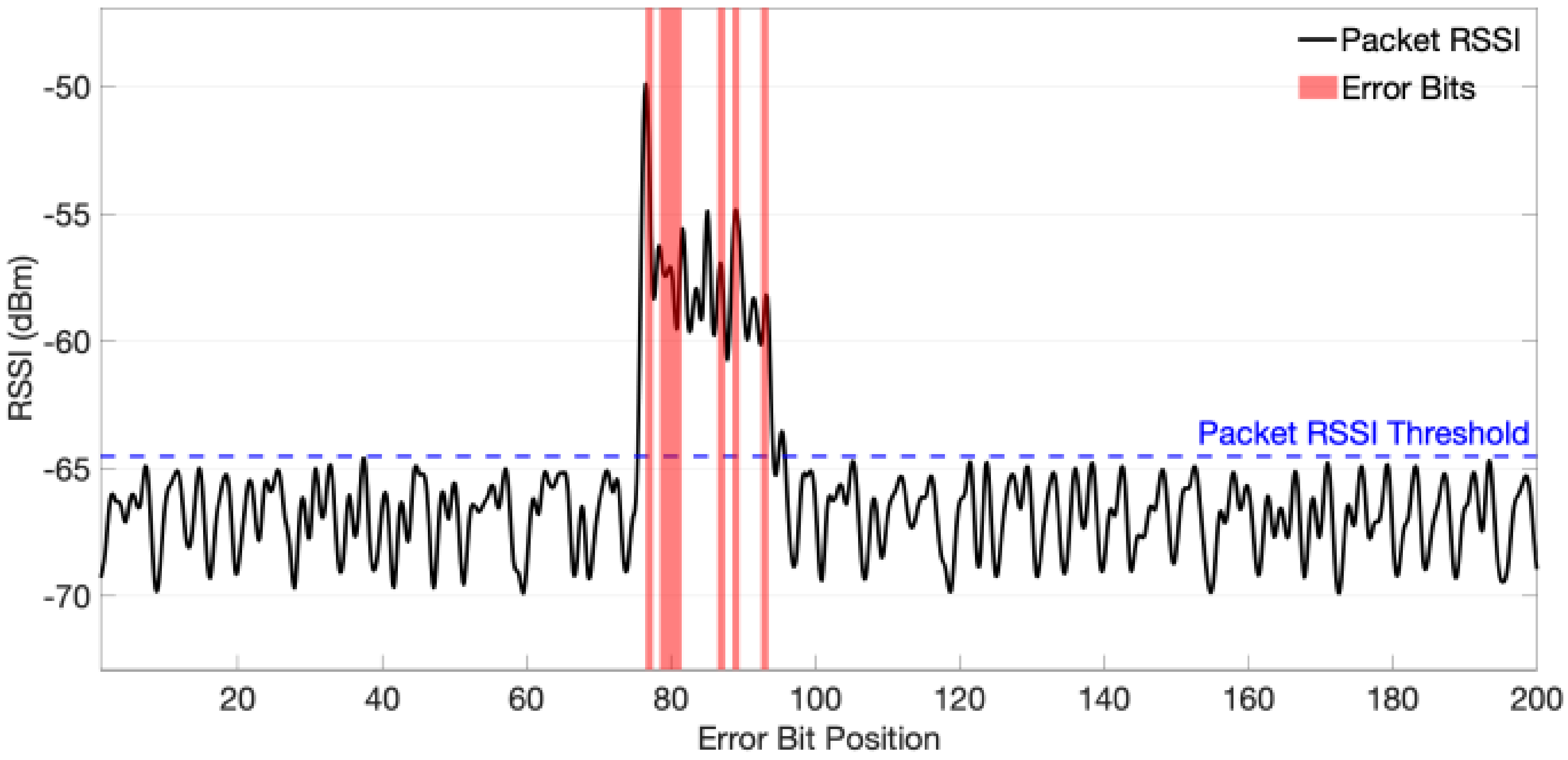
- MobiSys 2020

Opportunistic Packet Recovery (OPR)

- Can we recover packets that have bad CRCs?
  - What if we have some information about where the interference might have occurred during the signal transmission?
  - OPR demonstrates that we can recover packets!

- Process
  1. Receive bits even for bad packets
  2. Measure RSSI for each bit along the way
  3. Look for changes in RSSI that signals interference
  4. Try different values for the effected bits until the CRC succeeds!

Detecting error bits in transmitted packets



Correctly identifies 83% of the corrupted bits with 17% false positives

Multiple gateways do even better

- If multiple gateways receive the packet, they can compare their received data

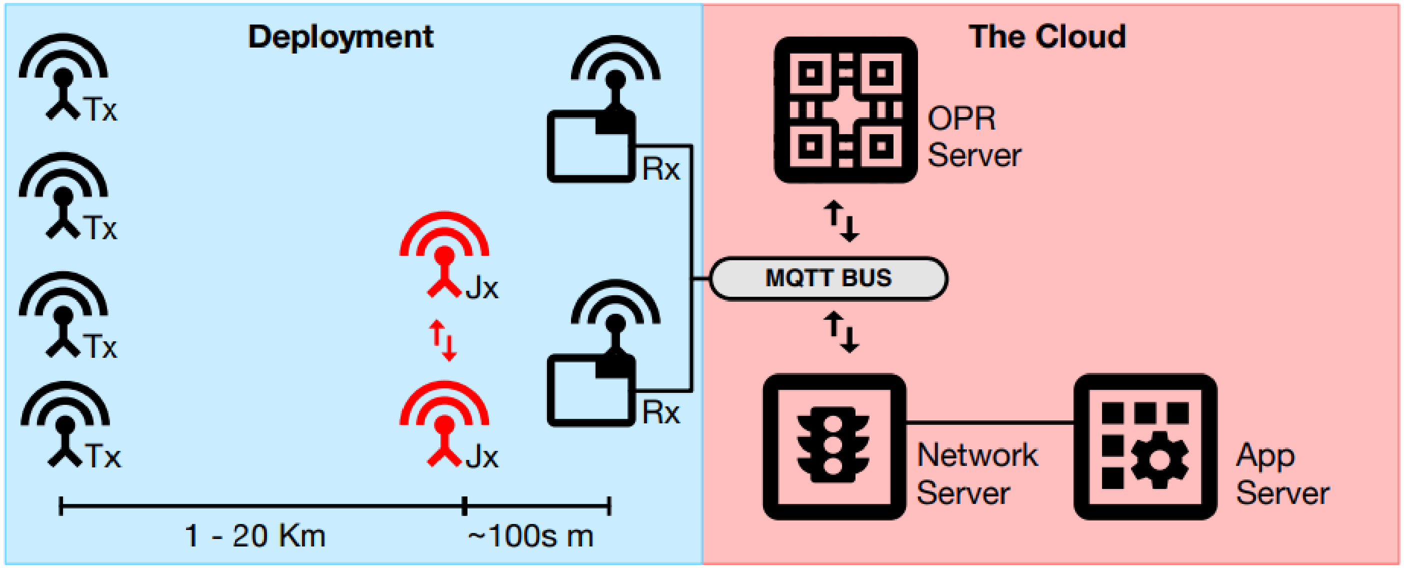
- Common bits are likely correct, while differences are likely interference

Node	Payload Hex	Bit Errors
TX	00000000000000000000000000000000	-
RX1	00000000000020080000000000000000	2
RX2	00000000020014060000000000000010	6
RX3	00000000010020040000000000000000	3

OPR total design

- Bad packets are sent to the OPR Server for handling along with RSSI data

- OPR server attempts to reconstruct the packet



- In practice, system can correct up to 72% of CRC errors!
  - Also completes correction in time for the ACK response (within 1 second)

Busy-Signal Multiple Access (BSMA) Paper

BSMA: Scalable LoRa networks using full duplex gateways

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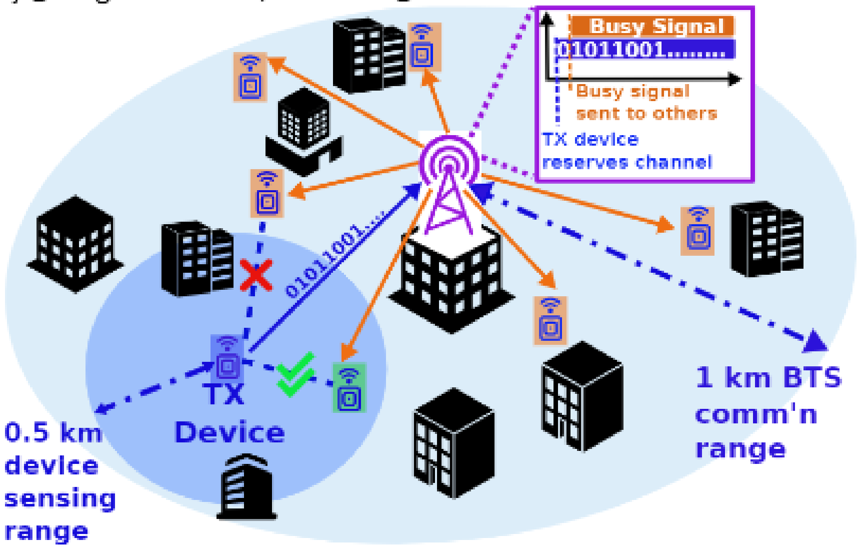
Abstract

With its ability to communicate long distances, LoRa promises city-scale IoT deployments for smart city applications. This long-range, however, also increases contention as many thousands of devices are connected. Recently, CSMA has been proposed as a viable MAC for resolving contention in LoRa networks. *In this paper, supported by measurements, we demonstrate that CSMA is ineffective in urban deployments.* While gateways stationed at rooftops enjoy a long communication range, 70% of the devices placed at street level fail to sense each others' transmissions and remain hidden, owing to obstructions by tall structures. *We present Busy Signal Multiple Access (BSMA), where the LoRa gateway transmits a downlink busy signal while receiving an uplink transmission.* The IoT devices defer up-



- MobiCom 2022

CSMA provides better throughput than Aloha

- Current LoRaWAN uses Aloha for uplink communication
  - So there’s nothing stopping devices from colliding

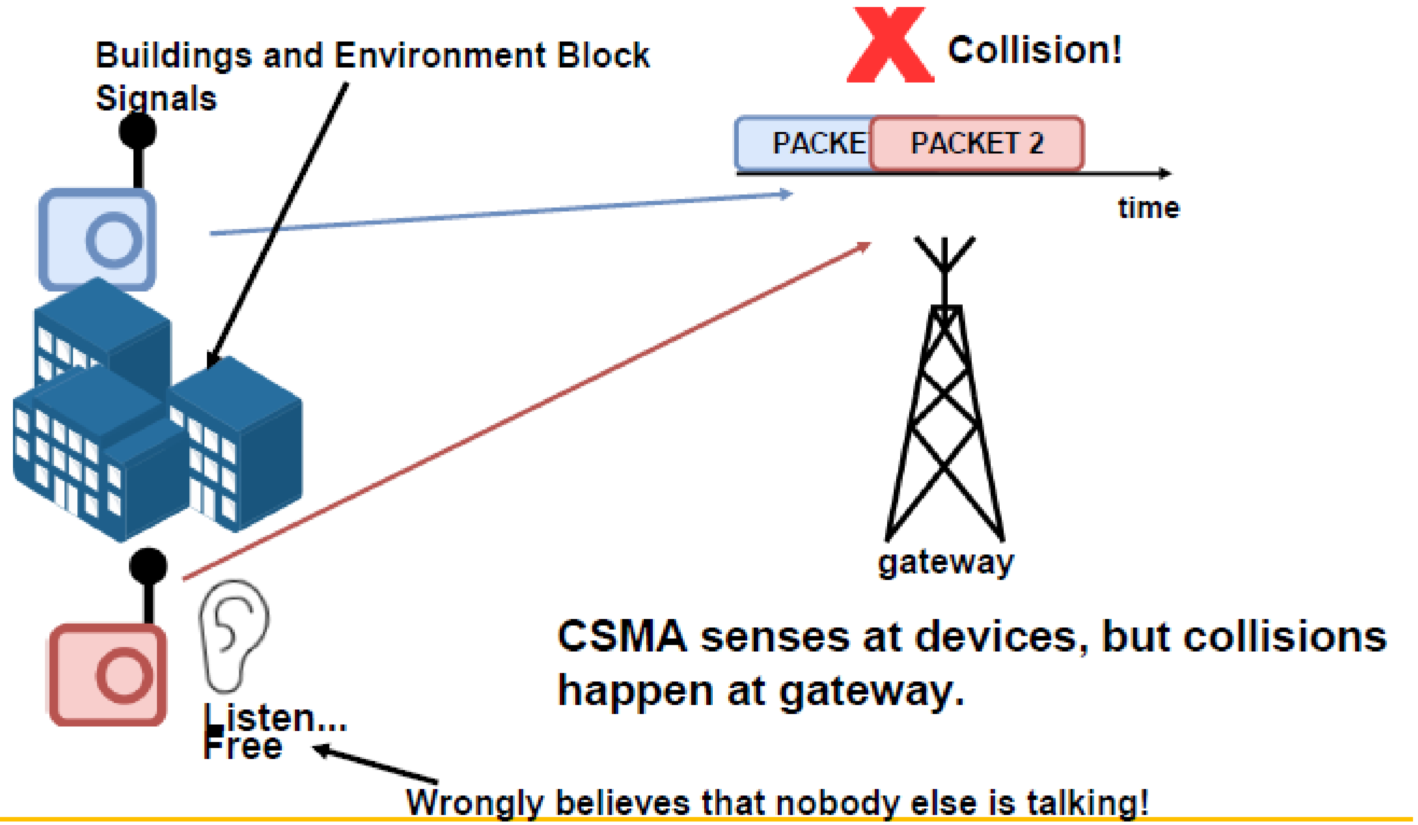
- Switching to CSMA could provide significantly more throughput
  - Reduces time and energy wasted on packet collisions

- Concern: does CSMA for LoRa actually work in the real world?

Obstructions cause hidden terminal problem

- Hidden terminal problem is a concern here
  - Devices may not be able to hear each other

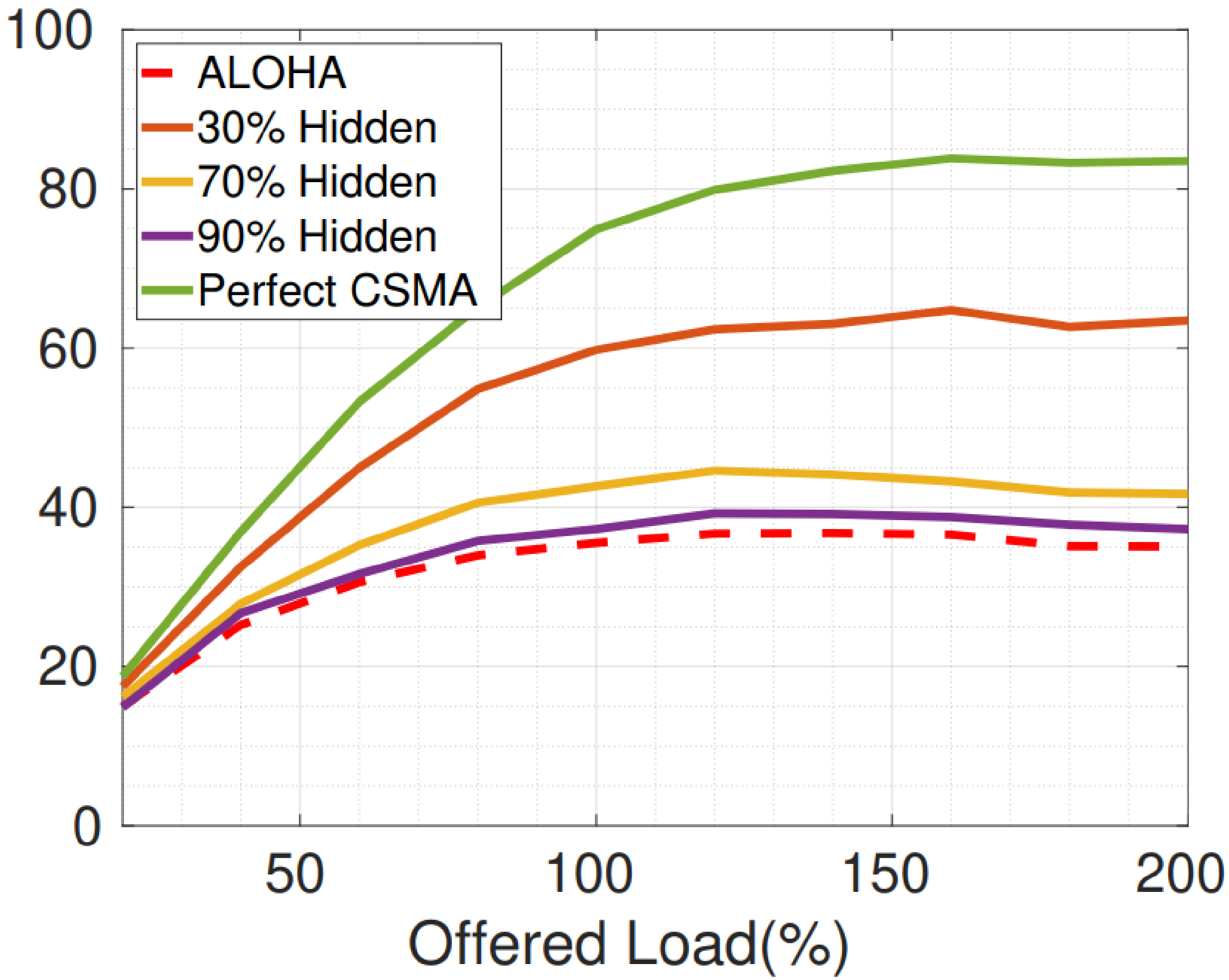
- Measured reality: devices fail to detect simultaneous transmissions 70% of the time!!



Hidden terminals greatly reduce CSMA throughput

- Perfect CSMA could provide twice the throughput of Aloha

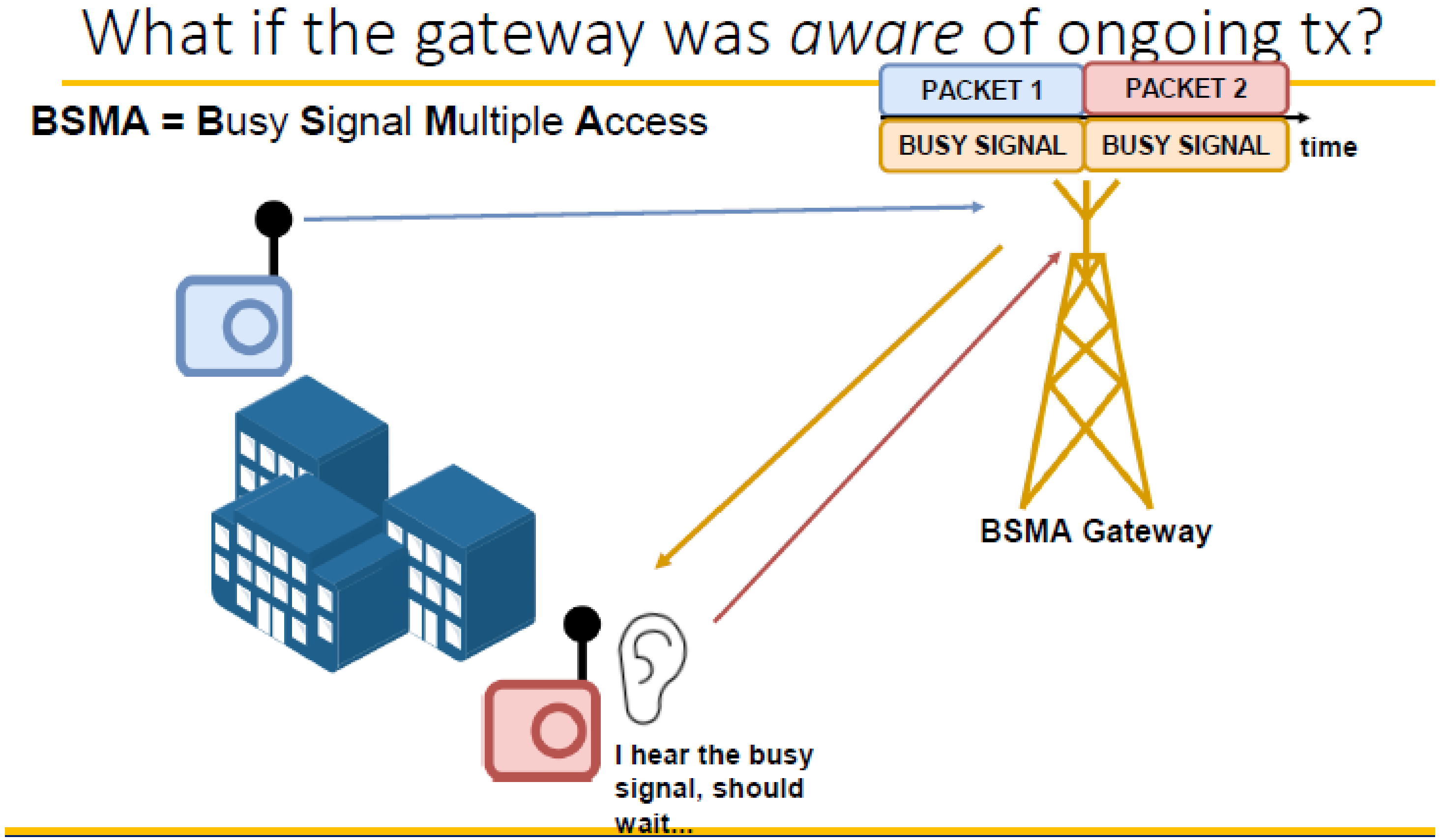
- But, at 70% failure for CSMA, it's not really an improvement over Aloha



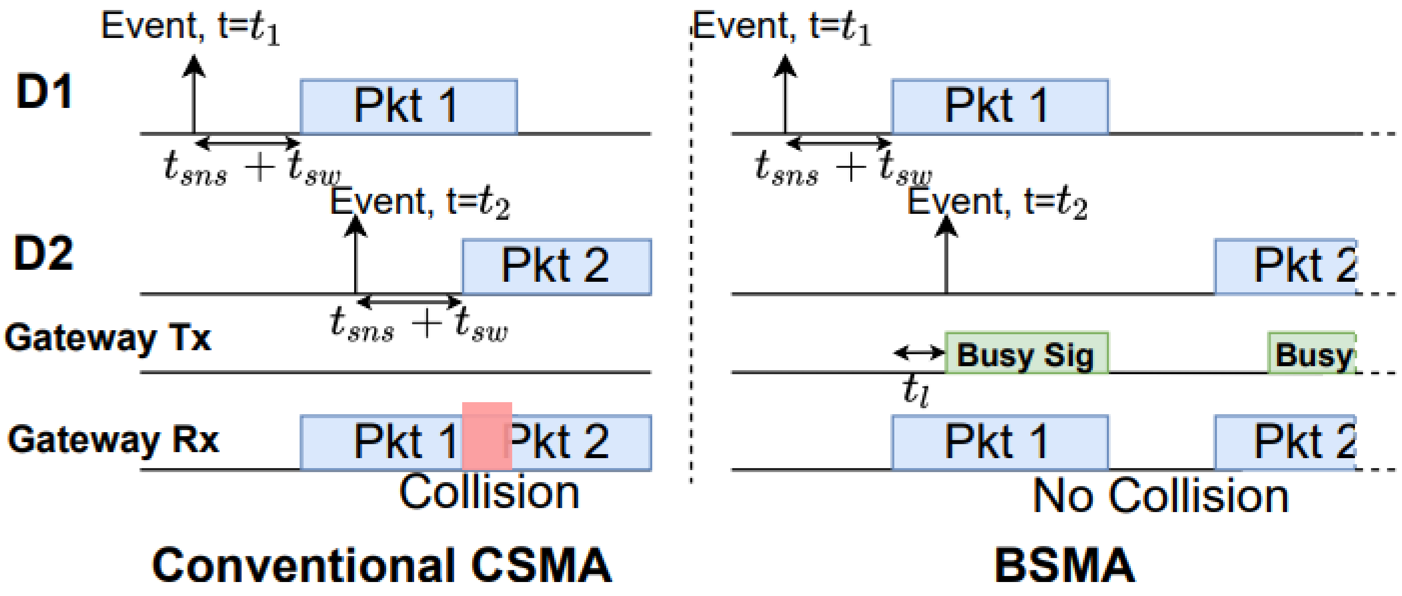
Busy-signal can alleviate this problem!

- Idea: have the Gateway transmit a "busy signal" on one of the downlink channels while an uplink is in progress

- Other devices can hear the gateway, even if they can't hear each other



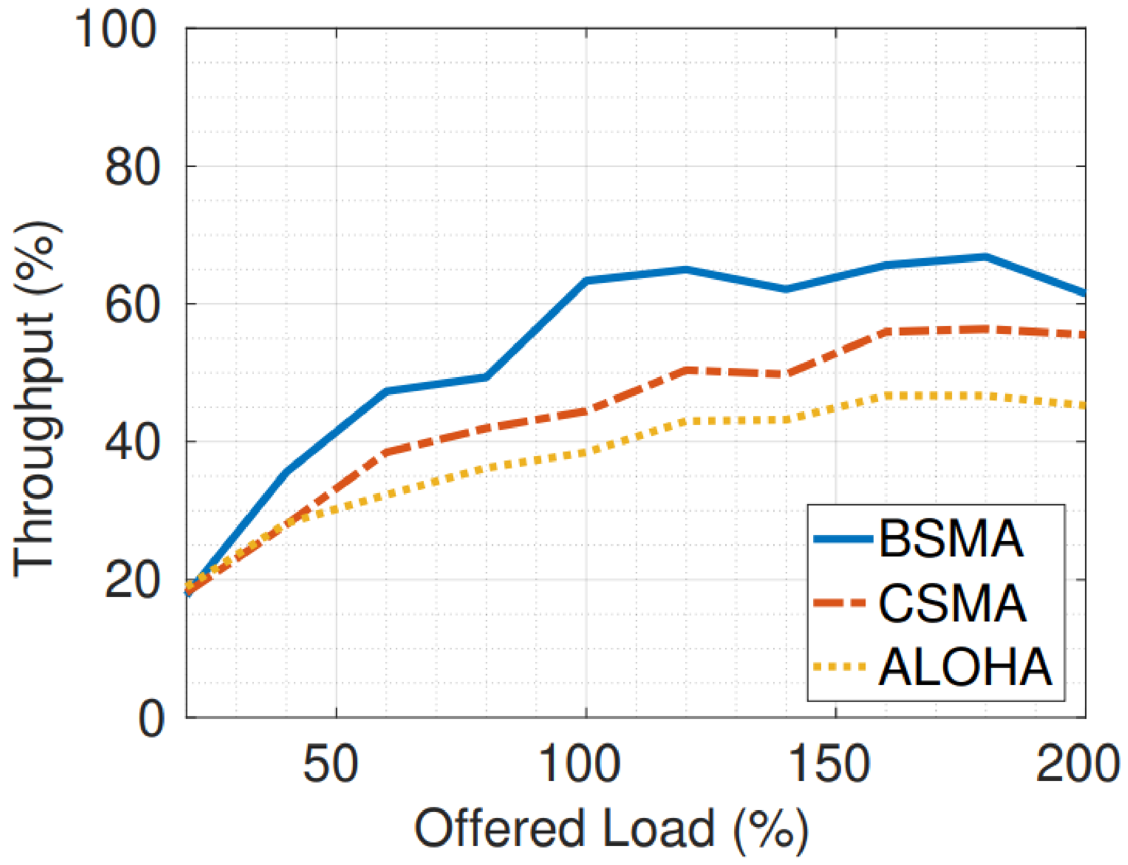
BSMA design



- End devices do not attempt to transmit while a busy signal is present
  - Instead, they defer transmission for a random duration, and go back to sleep
  - When waking up, they sense for a busy signal again before transmitting

Real-world improvements from BSMA application

- 50% improvement over Aloha when network is under load
  - Still some packets are lost due to collisions
- Could be combined with other approaches to still recover collided data
  - Maybe even intentionally send busy signal based on number of acceptable collisions
- Greatly reduced energy per packet as well
  - Since they're more likely to be received, and sensing doesn't cost too much



Translating research into the real world

- What are the challenges in translating this research into real-world use?

  - Improve gateway hardware: how do people buy/make it?
    - Needs a manufacturer to be interested

  - Multiple gateways are necessary
    - Not applicable to very small deployments
    - Network operators (TTN or Helium) would be good targets
    - They also have backend stuff running anyways, so adding OPR should be possible!

Outline

- LPWAN Use Cases
- LPWAN Challenges
- Improving LoRaWAN