CSE 291: Wireless and Communication in the Internet of Things

LPWANs

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Goals

- Understand LPWAN design design constraints

- Survey unlicensed LPWANs
  - Deep dive on LoRa
  - Coverage of the competition

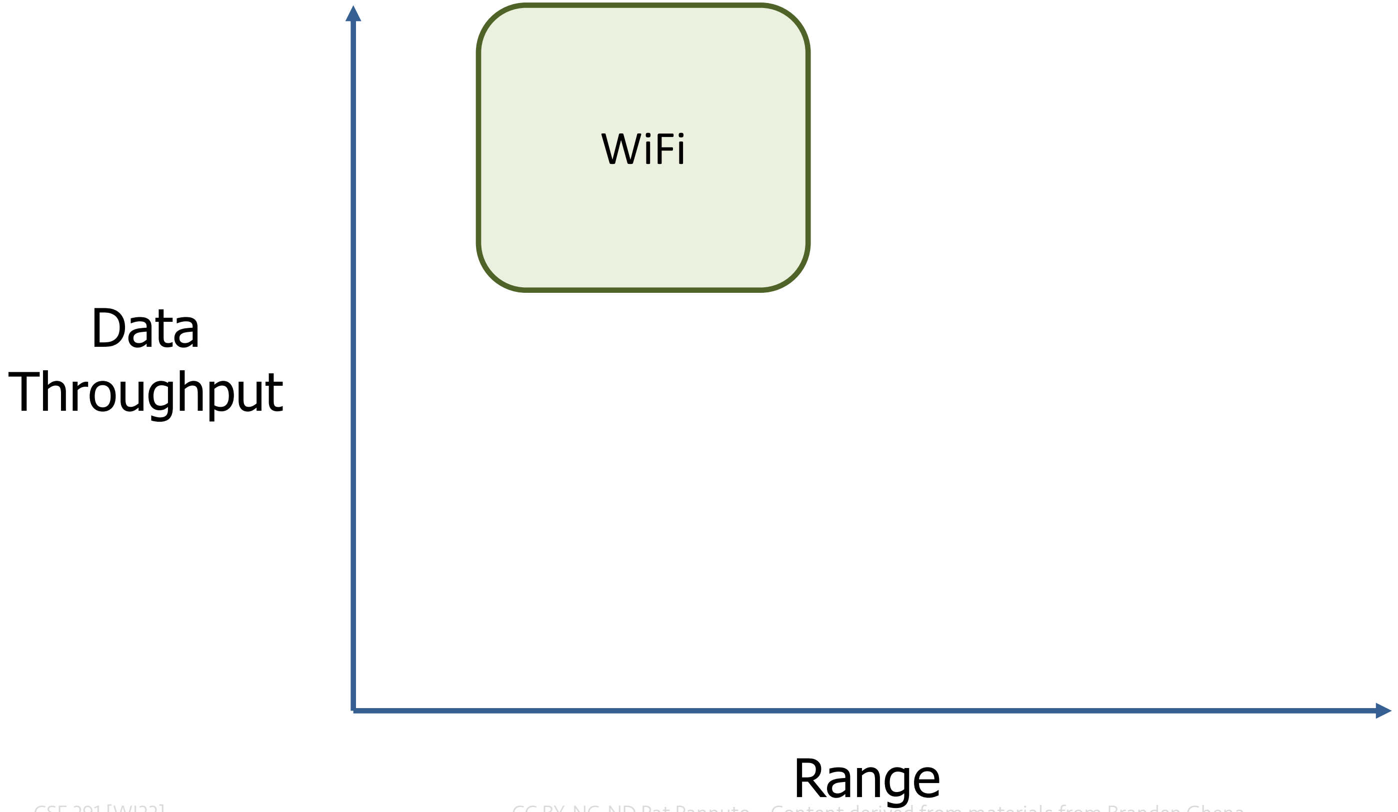
Outline

- Wide-Area Networks & LPWAN design
- LoRa & LoRaWAN
- Other LPWANs
  - Sigfox
  - 802.11ah
  - TV Whitespaces
- LPWAN Challenges

Wide area networks

- Communication at the region/city scale rather than the building/residence scale
  - Throughout cities
  - Agricultural deployments
  - Industrial facilities

Long-range, low-data needs haven't historically been met



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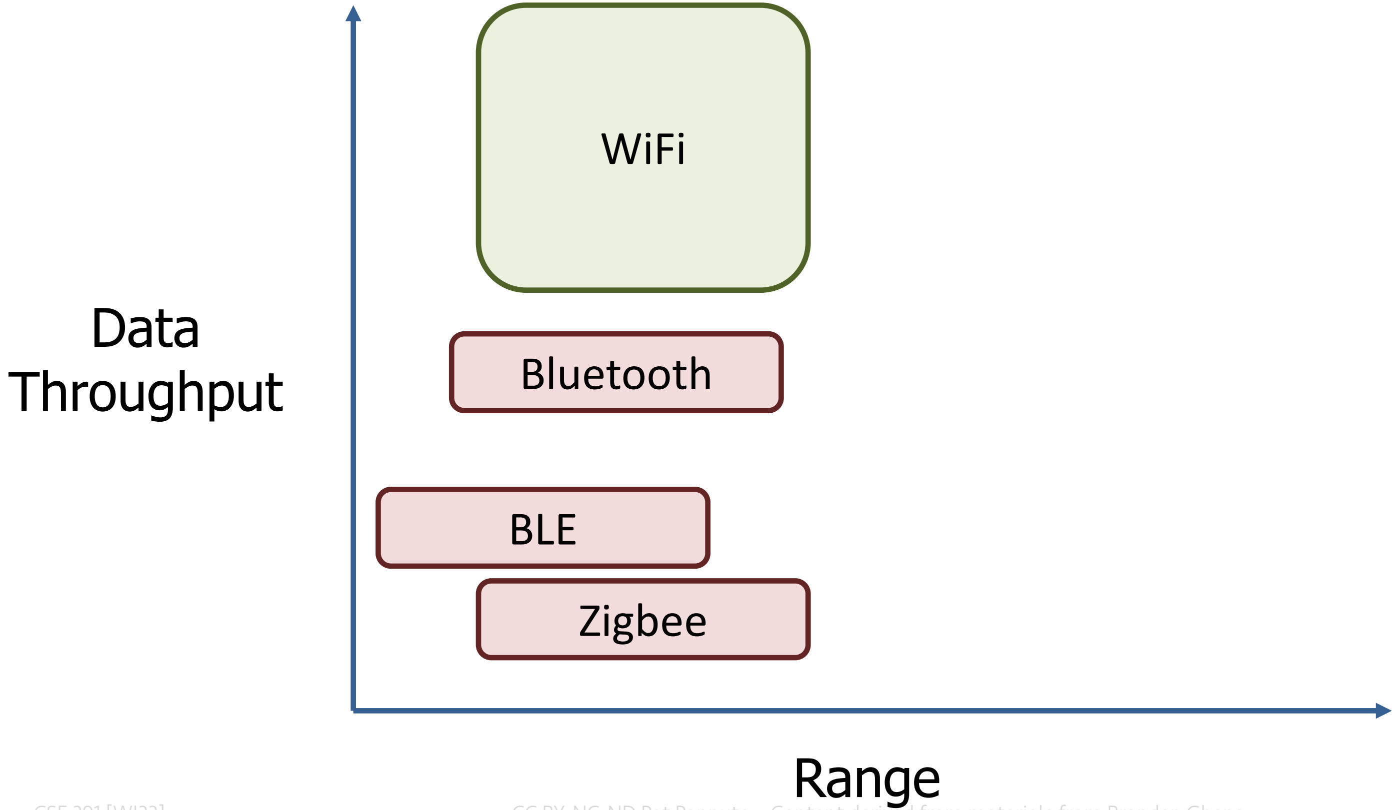

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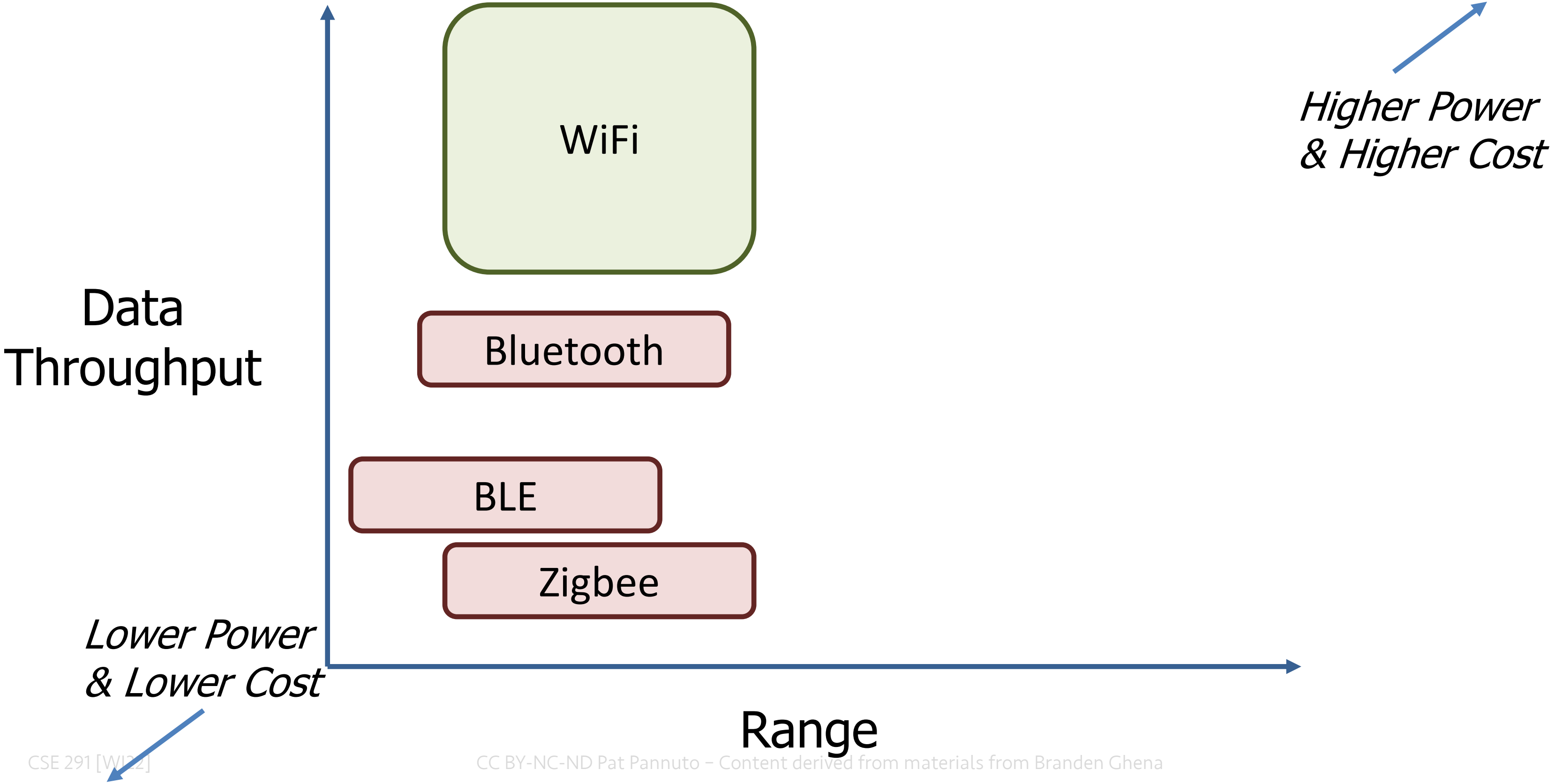

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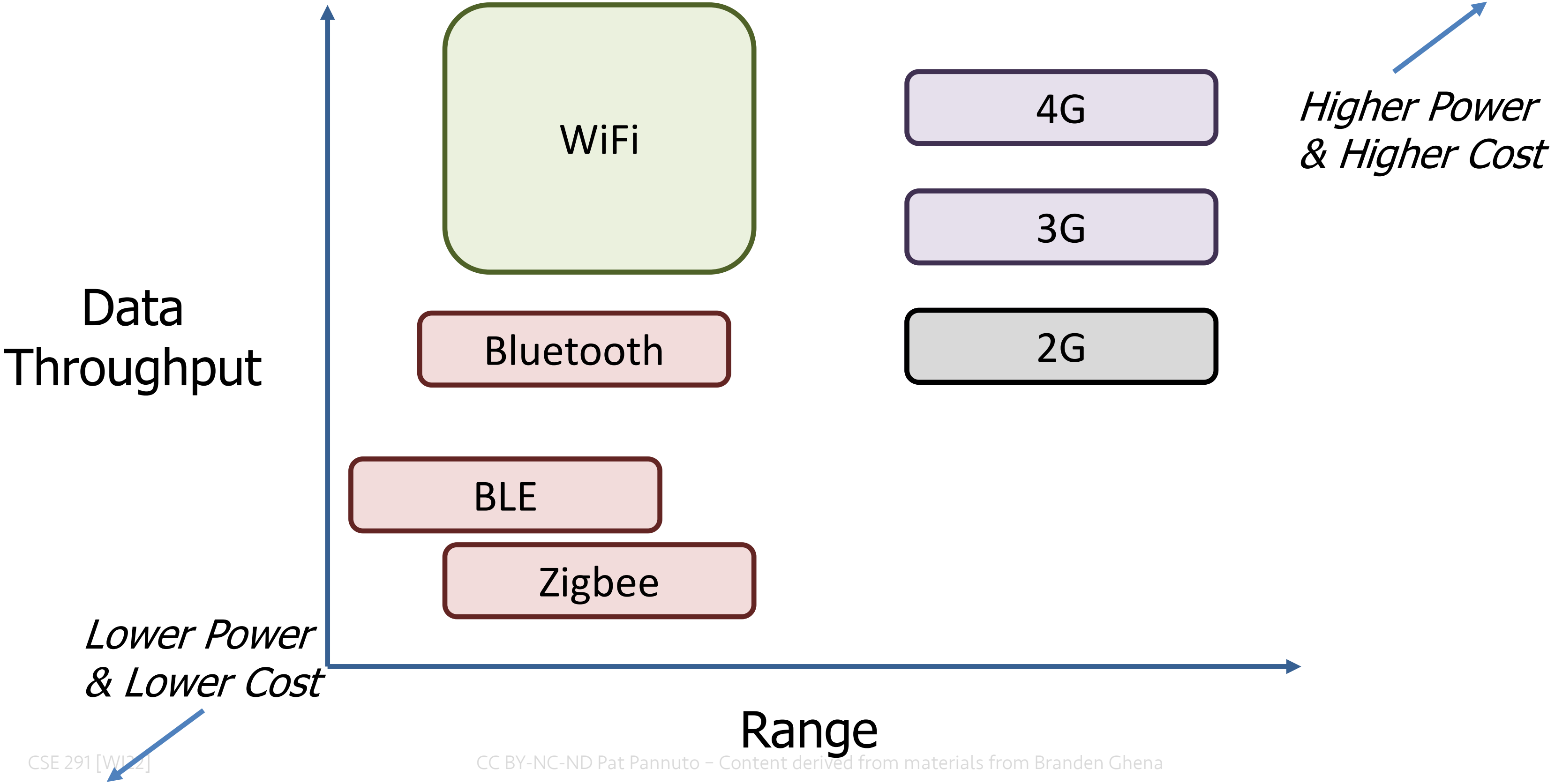

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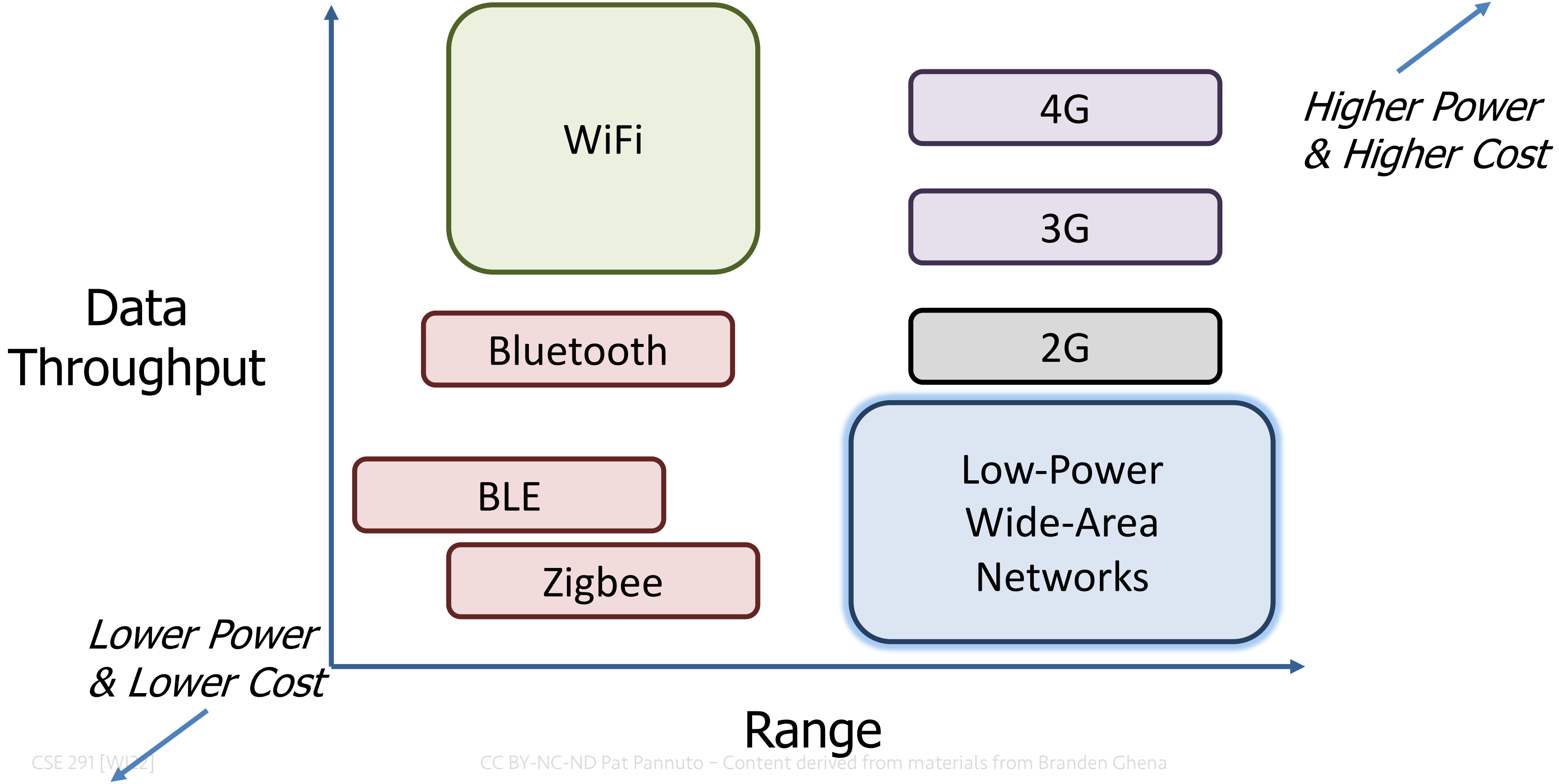

LTE-M and NB-IoT design constrained by fitting within existing cellular ecosystem

- What might a fresh design look like?

- *Caveat:* In ISM bands!

Design a wide-area network (ignore low-power for now)

- What PHY choices would you make?

Design a wide-area network (ignore low-power for now)

- What PHY choices would you make?
  - Modulation
  - Tx Power
  - Carrier Frequency Band
  - Data Throughput
  - Channel Bandwidth

Design a wide-area network (ignore low-power for now)

- What PHY choices would you make?
  - Modulation
    - Unclear. Can't be too crazy for cheap devices.
  - Tx Power
    - High (much higher than 0 dBm)
  - Carrier Frequency Band
    - Low (something lower than 2.4 GHz, 915 MHz or lower?)
  - Data Throughput
    - Low (much lower than 1 Mbps)
  - Channel Bandwidth
    - Unclear. Likely smaller for lower frequency carrier.

Design a low-power wide-area network

- Any particular MAC choices for lower power?

Design a low-power wide-area network

- Any particular MAC choices for lower power?
  - Diversity of devices in network
    - High power gateway, low power devices in star topology
  - Devices should be off whenever possible
    - Listen-after send for downlink
  - Remove requirements for synchronization
    - No TDMA access control if it can be avoided
    - Aloha, ~~CSMA~~

Long-range CSMA is problematic

- Long-range makes everything more challenging
  - Kilometers of range mean kilometers between devices

- Detection of channel use is less reliable
  - Active research in clear channel assessment for LPWANs

- Hidden terminal problem has a wider range
  - Might make RTS/CTS more important

- Result: CSMA doesn’t dominate LPWANs like it does WLANs

LPWANs overview (common qualities)

- Unlicensed 915 MHz band (902-928 MHz)
- Higher power transmissions: ~20 dBm (100 mW)
- Low data rate 100 kbps or less
- Range on the order of multiple kilometers
- Simple Aloha access control

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LoRaWAN

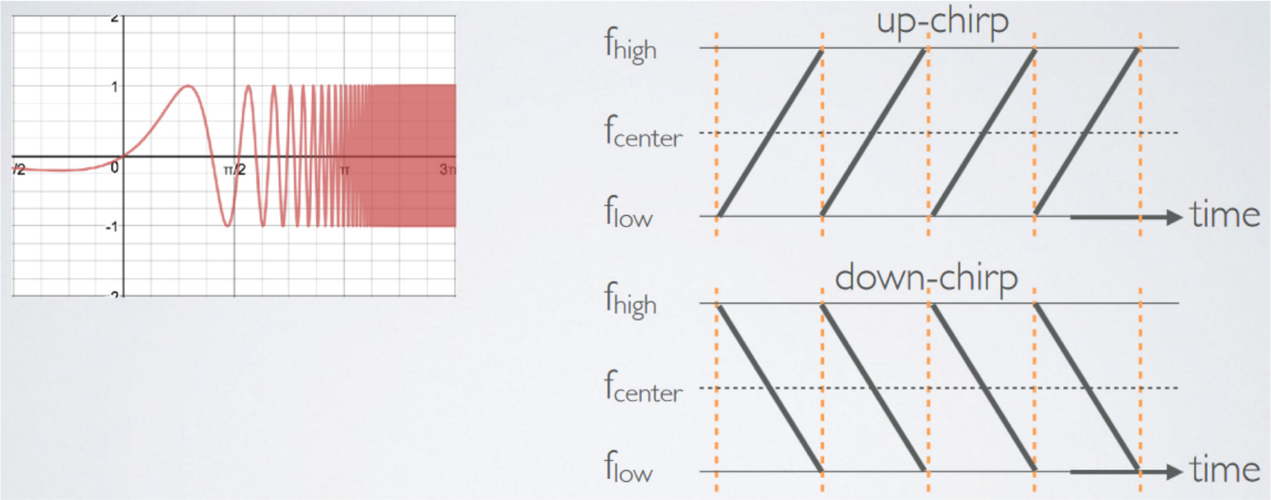
- Open communication standard built with proprietary LoRa PHY

- Low rate (1-20 kbps) and long range (~5 km)
  - Shorter range than Sigfox but much higher bit rate

- Most popular LPWAN protocol
  - Target of academic research
  - Industry involvement in hardware and deployments

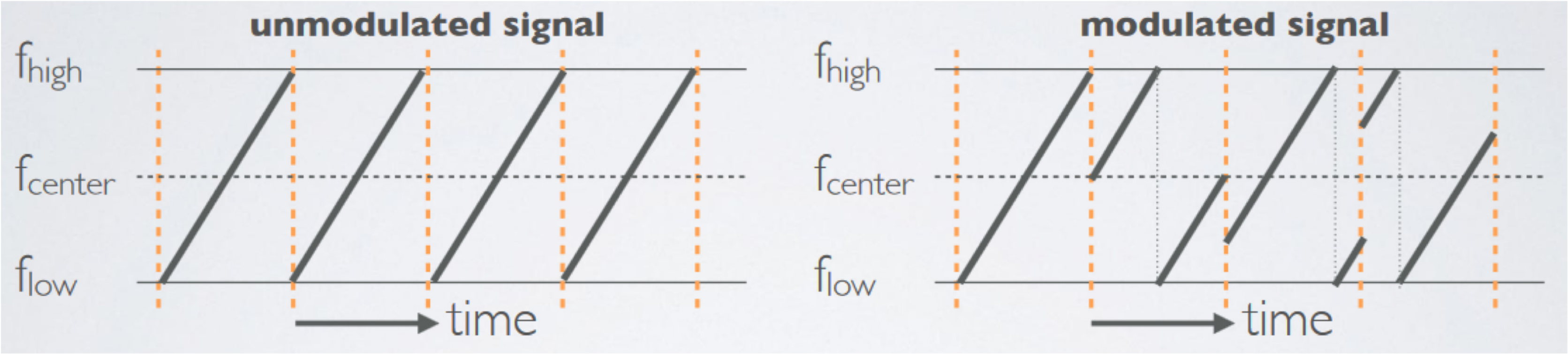
LoRa PHY uses a different modulation

- Chirp Spread Spectrum (CSS)
  - Modulation technique where frequency is varied linearly from lowest to highest within a channel



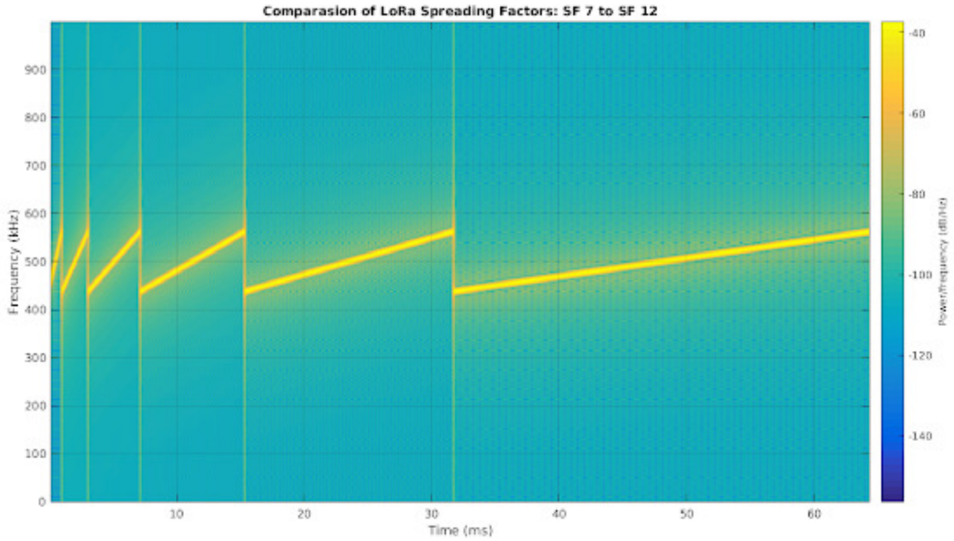
Chirp Spread Spectrum

- Data is modulated in the starting and ending points of chirp
  - Frequency increases linearly, modulo bounds of the channel

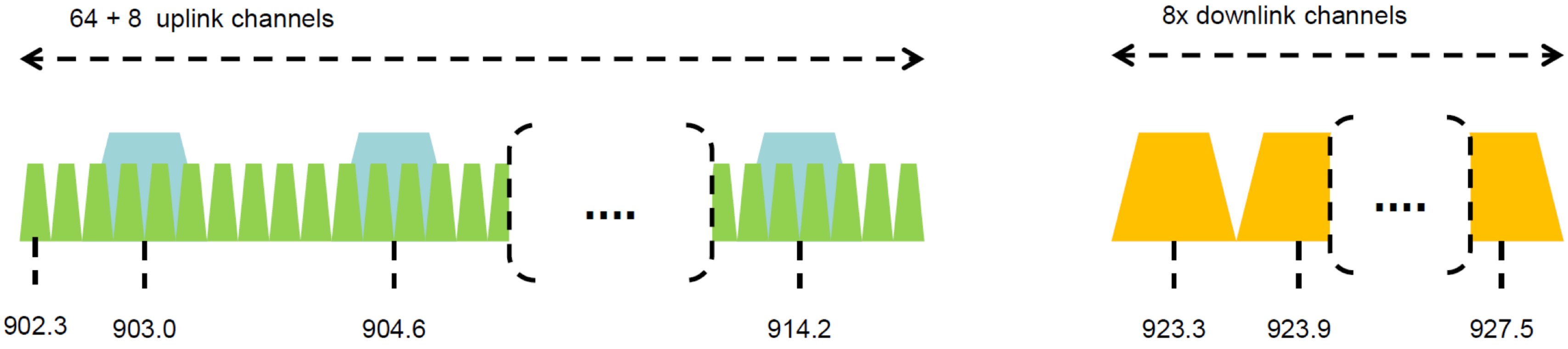


CSS has a Spreading Factor which determines bit rate

- Spreading Factor is essentially the rate-of-change of frequency
  - Slope of the line
  - Lower values of spreading factor (steeper slope) are faster data rate
- Important: different spreading factors are (mostly) orthogonal!
  - Two can overlap in time, space, and channel without a collision



LoRa channels



- Sixty-four, 125 kHz uplink channels
  - Frequency Hopping over the 64 uplink channels
  - Plus eight, 500 kHz overlapping uplink channels (not well used in practice)
- Eight, 500 kHz downlink channels

LoRa gateways

- No synchronization with end devices

- Instead listen to entire bandwidth simultaneously
  - Only 12 MHz total
  - Recognize preambles and allocate a hardware to decode packet
    - Normal gateways: 8 decoders
    - Good gateways: 64 decoders

LoRa data rates

- Data rate options depend on channel in use
  - Unbalanced uplink and downlink

- 64-channel uplink
  - 1-5 kbps data rate

- Allowable rates based on dwell time restriction (400 ms)

Data Rate Index	Spreading Factor	Bit Rate
125 kHz Uplink Rates		
0	SF10, 125 kHz	980 bps
1	SF9, 125 kHz	1760 bps
2	SF8, 125 kHz	3125 bps
3	SF7, 125 kHz	5470 bps
500 kHz Uplink Rates		
4	SF8, 500 kHz	12500 bps
500 kHz Downlink Rates		
8	SF12, 500 kHz	980 bps
9	SF11, 500 kHz	1760 bps
10	SF10, 500 kHz	3900 bps
11	SF9, 500 kHz	7000 bps
12	SF8, 500 kHz	12500 bps
13	SF7, 500 kHz	21900 bps

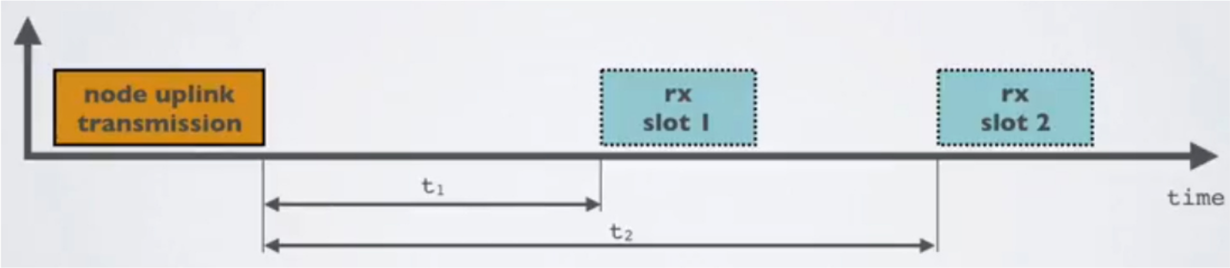
LoRa link budget

- Typical TX power 20 dBm
  - Up to 30 dBm for 64-channel hopping
  - Up to 26 dBm for 8-channel hopping
- Receive sensitivity -119 dBm
  - Compare to -100 dBm for 802.15.4 and -95 dBm for BLE
- Resulting range is about a kilometer in urban environments

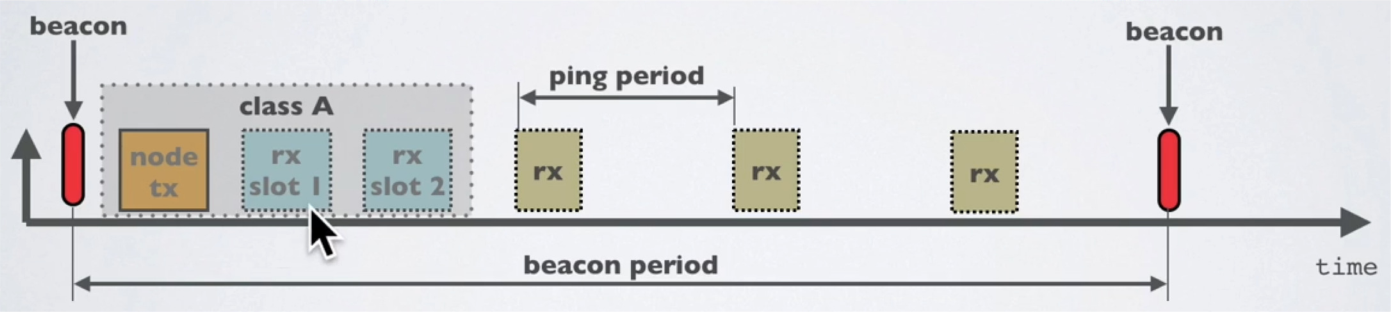
LoRaWAN MAC

- Uplink: Aloha - transmit whenever
  - Randomly split across 64 uplink channels (reduced odds of collision)
  - Devices a different spreading factors also do not collide
  - Packets are very long though: up to 400 ms in duration

- Downlink: listen-after-send (class A device)
  - Two windows for RX on different channels

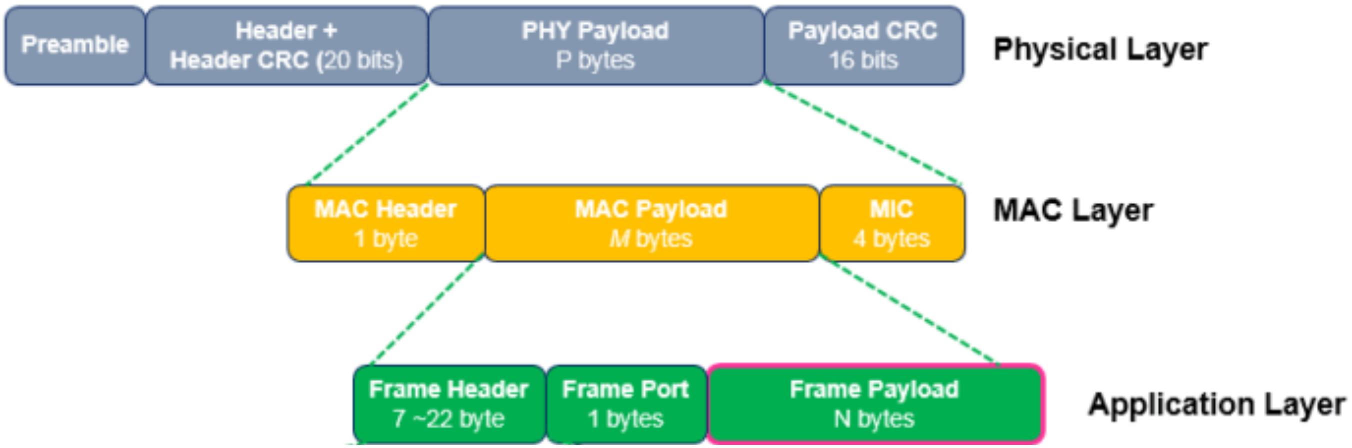


Optional downlink mechanisms

- Periodic listening (class B device)
  - Synchronized with periodic beacons
    - TX still unsynchronized Aloha
  - 

- Continuous listening (class C device)
  - Always-on receivers

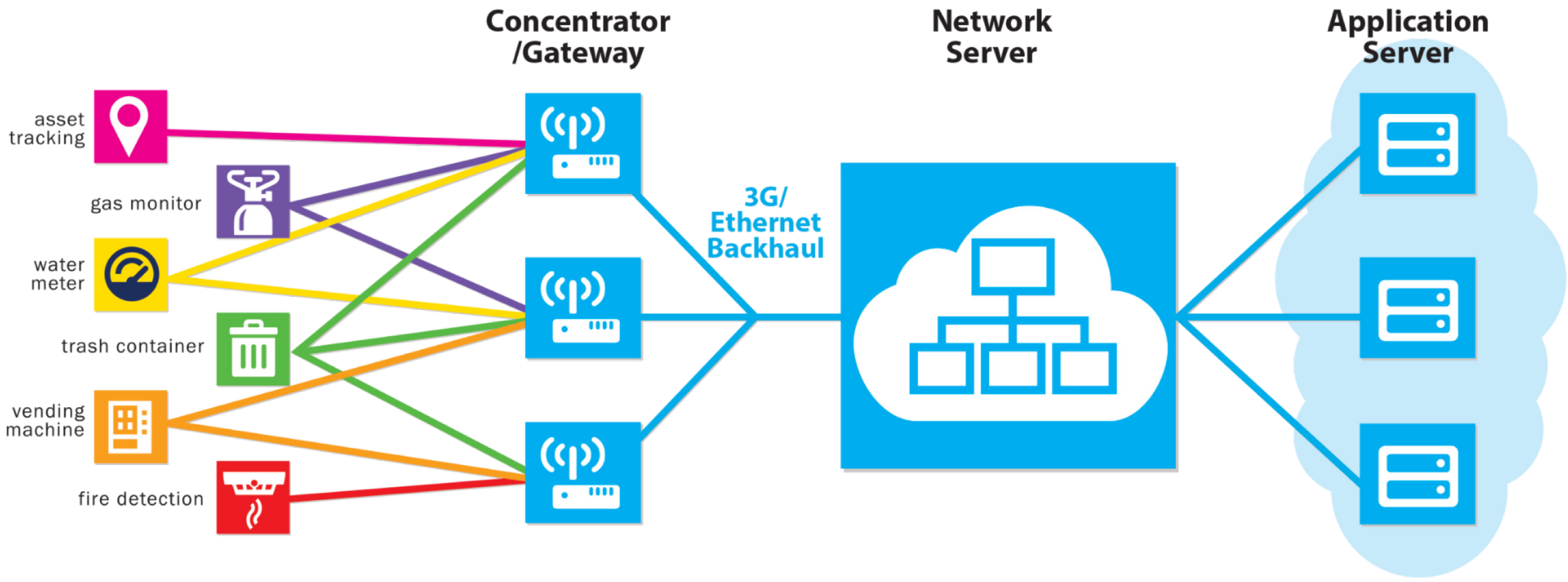
LoRaWAN packet format



- Frame header includes device address
- MAC Payload maximum size depends on data rate
  - Based on dwell time in the US

Data Rate Index	MAC Payload Size
0	19 bytes
1	61 bytes
2	133 bytes
3	250 bytes
4	250 bytes

LoRaWAN network details



LoRaWAN hardware

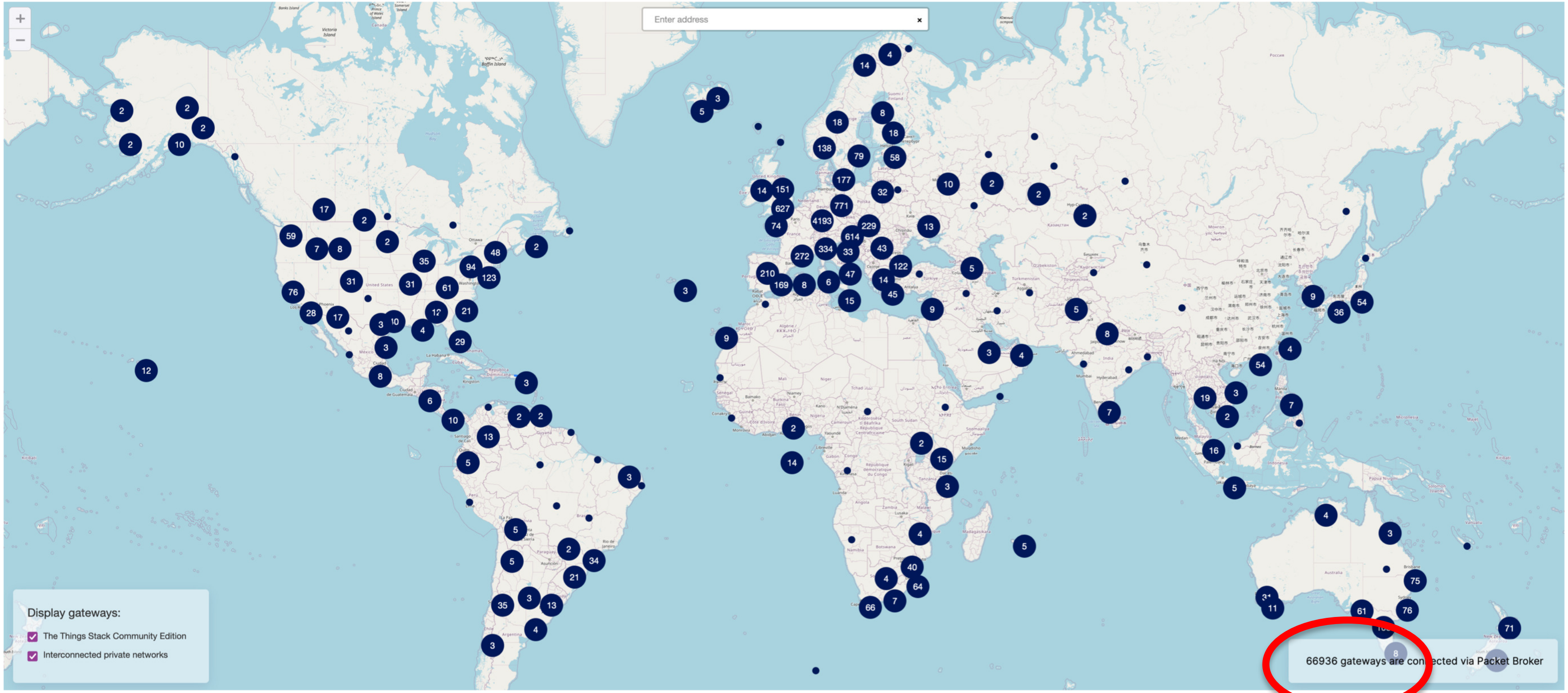
- Numerous hardware modules and development kits
  - Almost all use Semtech radio chips (Semtech owns LoRa PHY)

- Recent addition: STM32WLE5 LoRa SoC
  - Cortex-M4 + LoRa radio (analogous to nRF52840)

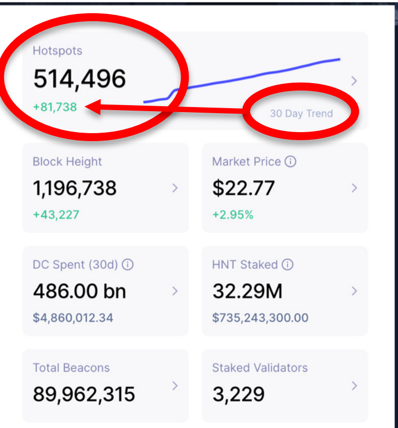
LoRaWAN network providers

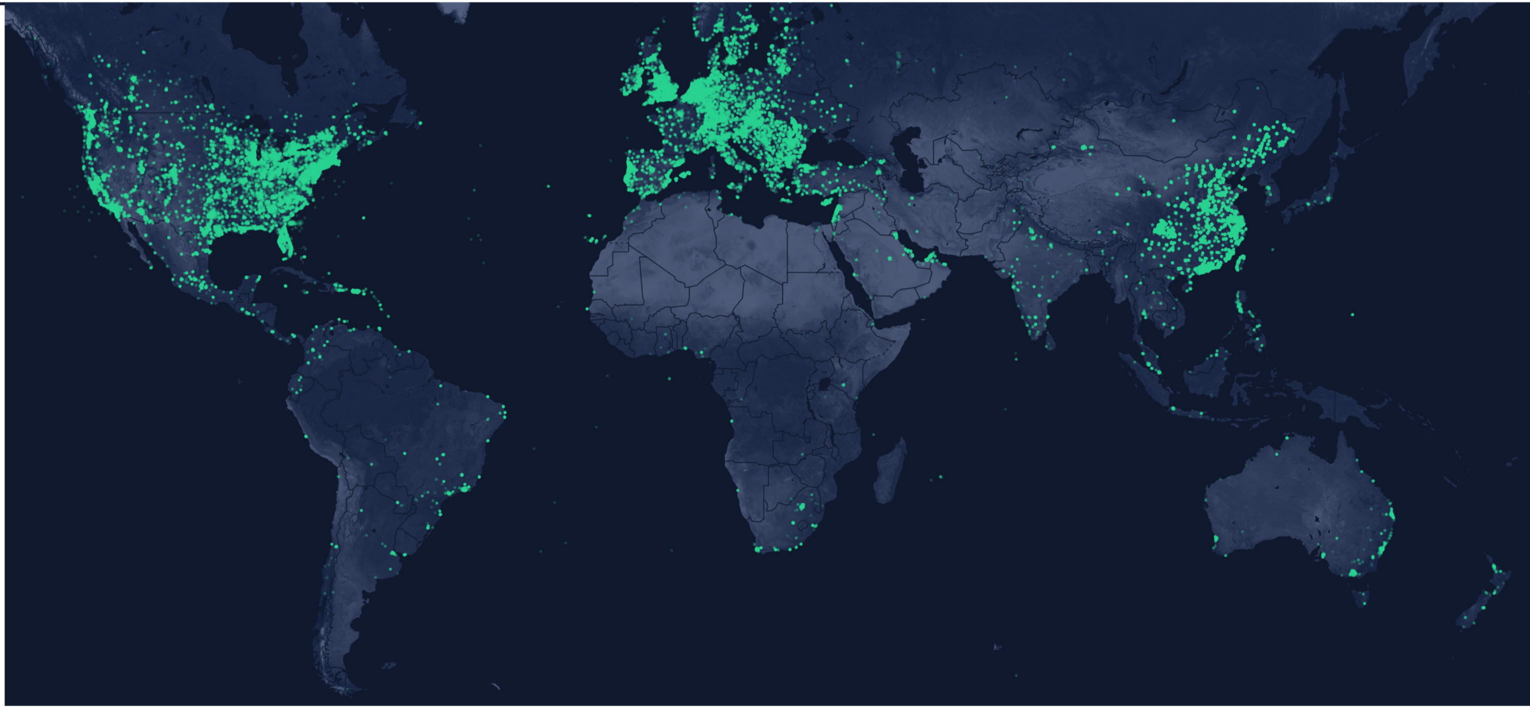
- Somewhat-managed network providers
  - The Things Network (predominantly in Europe)
  - Helium
    - Any can buy and install their own gateway, which serves everyone
    - Microtransactions to pay for communication

TTN Scale [Jan 2022]



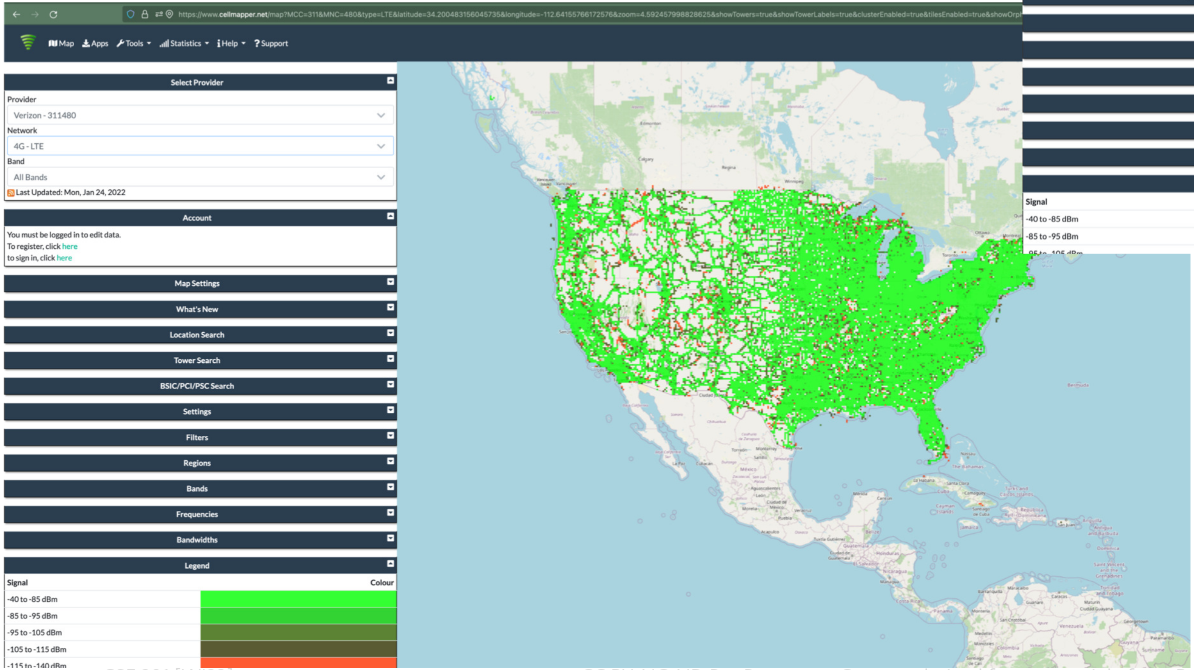
Helium Scale [Jan 2022]

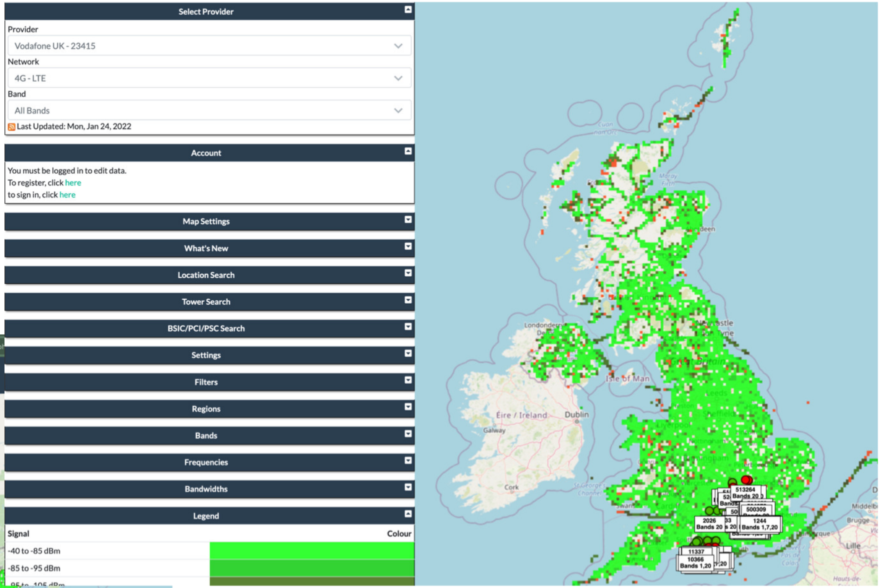


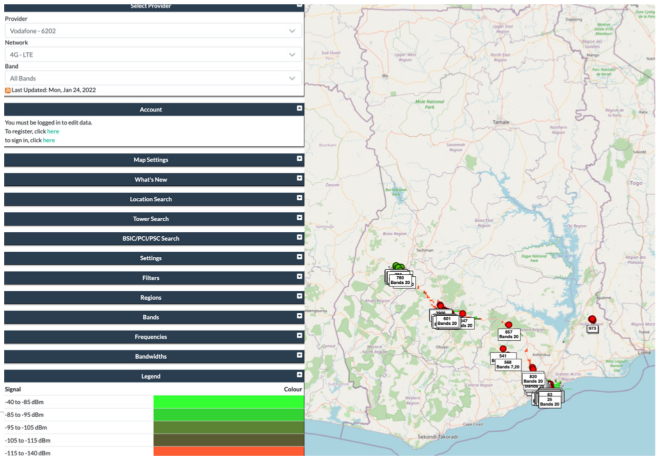


Quick reality check: Verizon?

- And this is just crowd-sourced data…







LoRaWAN interested parties

- ~~MachineQ is a subsidiary of Comcast providing LoRaWAN networks~~

- ~~Long-term goal~~
  - ~~Indoor-to-outdoor LoRaWAN gateways combined with WiFi~~
  - ~~Tune down power for 100-200 meter range~~

- Since ~Summer 2021: IoT Platform-as-a-service
  - Maybe with some LoRa, but they stopped rollout

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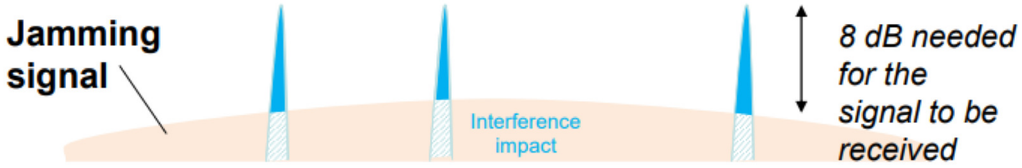
Sigfox

- Very low-rate (600 bps), very long-range (10+ km) communication
- Star-topology networks, with always-listening gateways
  - Any number of low-power end devices
- Uplink-focused communication
- Applications: very low-rate metering

Sigfox PHY

- Unlicensed-band communication
  - Europe 868 MHz. US 902-928 MHz (915 MHz band)

- Ultra-narrowband 600 Hz (100 Hz Europe) channel bandwidth
  - Detection only needs to occur at very specific frequency
  - Helps improve signal-to-noise ratio



Sigfox unbalanced uplink and downlink

- Uplink
  - 600 Hz bandwidth, 600 bps, DBPSK
- Downlink
  - 1.5 kHz bandwidth, 600 bps, GFSK

- Particularly optimized for Europe
  - Uplink on 1% duty cycle channel, up to 14 dBm
  - Downlink on 10% duty cycle channel, up to 27 dBm

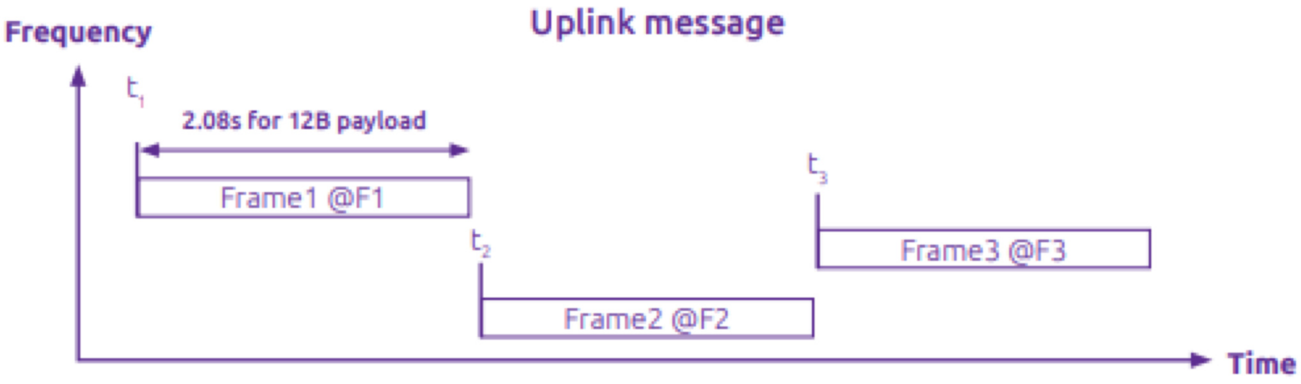
- Works fine in US too
  - Gets more power (24 dBm up is typical, up to 32 dBm down) and more range

Sigfox link budget

- Why transmit at 100-600 bps?
  - For greatly increased link budget
- Link budget: 150-160 dBm
  - Assuming Tx at ~20 dBm
  - Means Rx Sensitivity of -130 dBm (10 dBm better than LoRaWAN)
- Resulting range: 10-15 km in urban environments
  - Except that buildings lead to dead spots in range

Sigfox MAC

- Aloha-style access control (send whenever)
  - No acknowledgements!
- Send message three times for increased reliability
  - Then listen for downlink at a set period later on a known frequency



Sigfox uplink packet

```
+---------+---------+---------+-------------+---------------+------+
|Preamble |Frame    | Dev ID  |   Payload   |Msg Auth Code  | FCS  |
|  (19)   |Sync(29) |  (32)   |   (0-96)    |   (16-40)     | (16) |
+---------+---------+---------+-------------+---------------+------+
                    Uplink Frame Format
```

- Up to 29 bytes total per packet
  - Payload: up to **12 bytes** 😱
- Other fields
  - Preamble + Frame Sync are really a 6 byte field for radio sync
  - Authentication: 2-5 bytes
  - Frame Check Sequence: 16-bit CRC

Aside: why faster bitrate in the US?

- Packet size up to 29 bytes (232 bits)
  - At 100 bps: 2.32 seconds on air
  - At 600 bps: 0.387 seconds on air

- Maximum dwell time for 915 MHz band: 400 ms

Sigfox downlink packet

```
+------------+--------+-----+---------+-------------+-----+
|  Preamble  |Frame   | ECC | Payload |Msg Auth Code| FCS |
|    (91)    |Sync(13)| (32)|  (0-64) |     (16)    | (8) |
+------------+--------+-----+---------+-------------+-----+
                 Downlink Frame Format
```

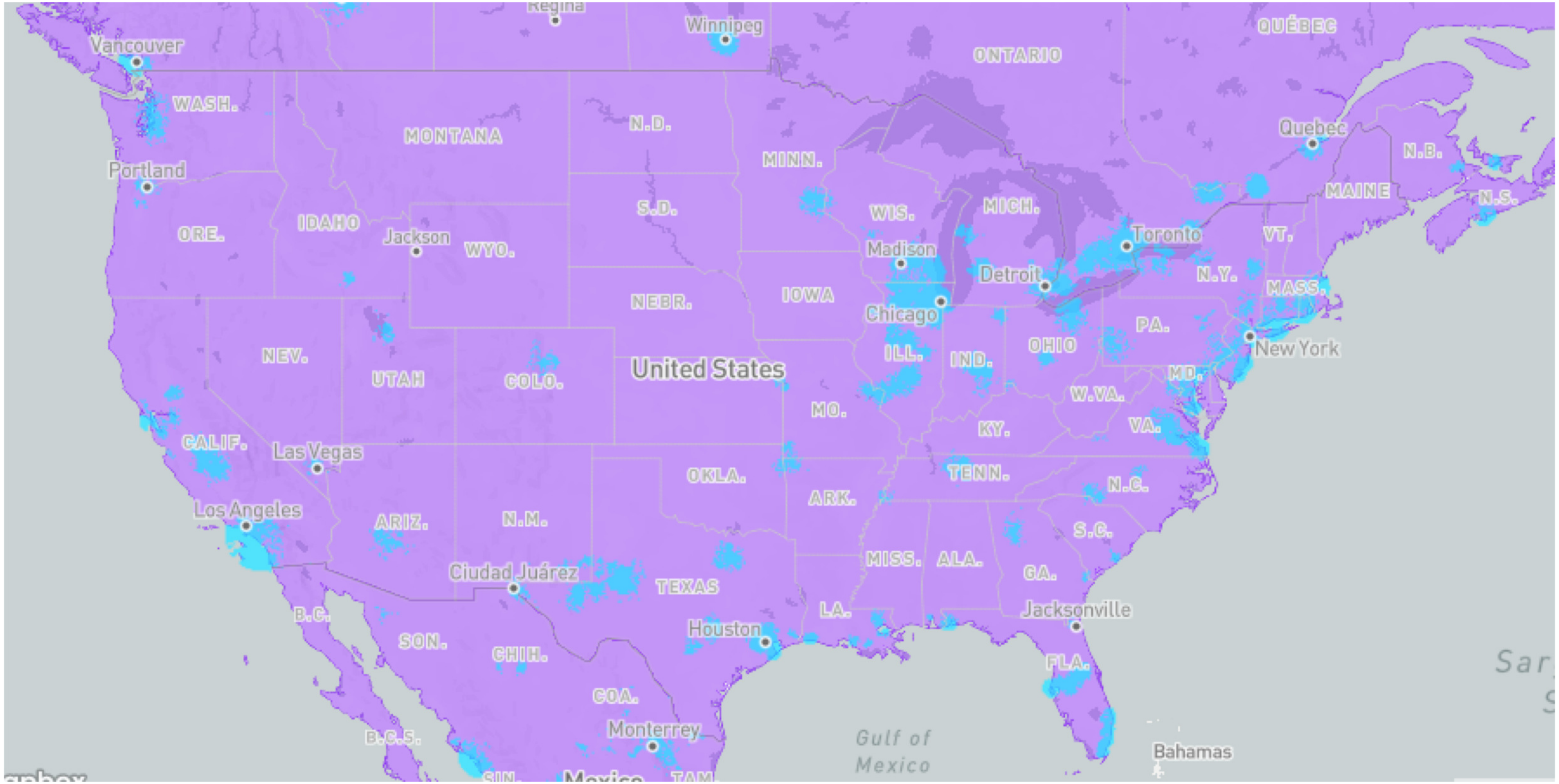
- Similar structure, 28 bytes total
  - Payload: up to 8 bytes
- Larger preamble + frame sync of 13 bytes
- Error Correcting Code for increased reliability

Sigfox deployments

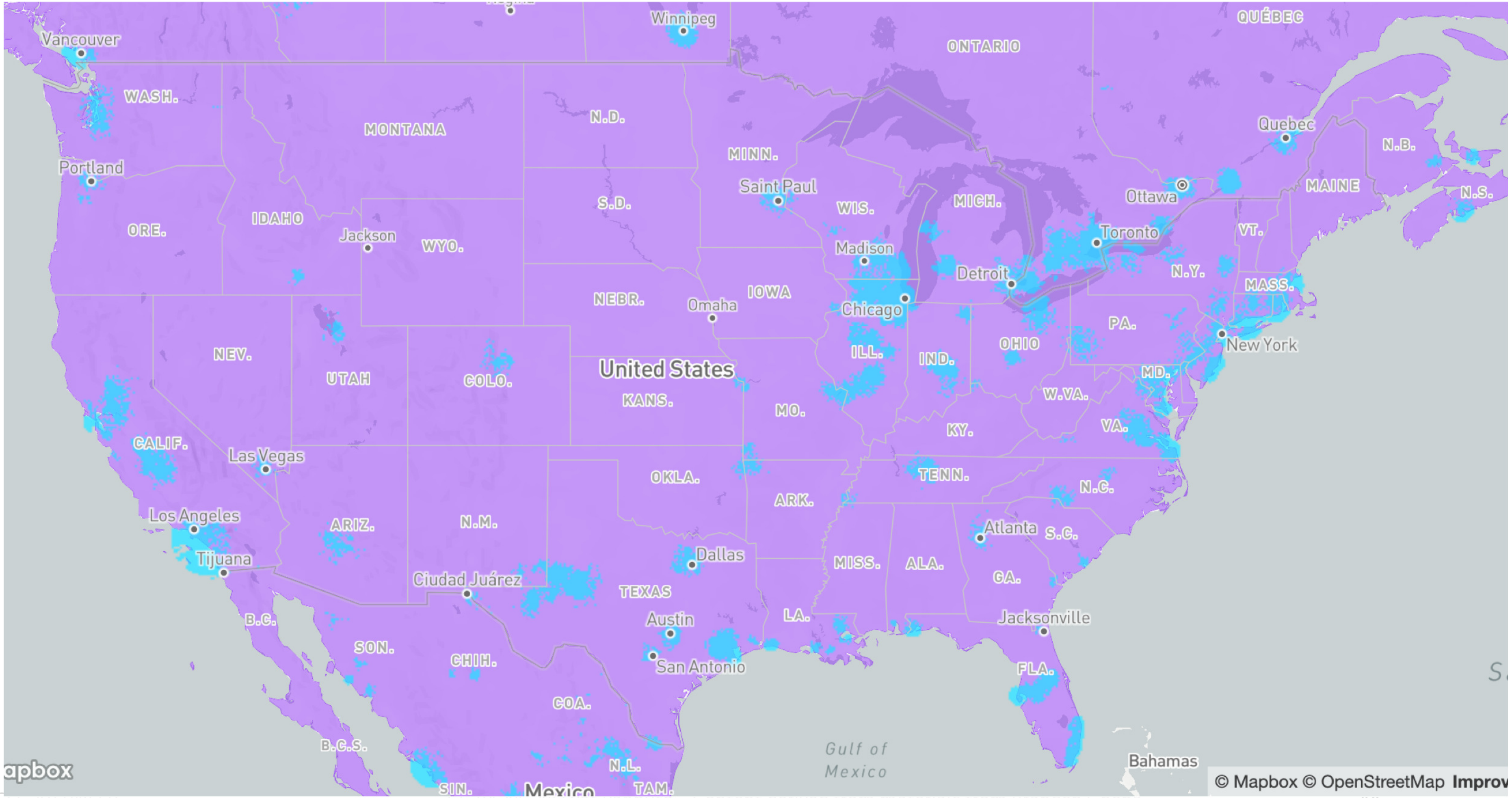
- Proprietary network with managed deployment
  - Like cellular networks
  - Sigfox deploys networks and transports data
  - 140 uplink messages plus 4 downlink message per day

- Connectionless communication
  - Devices are registered with the networks
  - Keys are provided in the software image
  - Any deployed Sigfox gateway can collect transmitted data
    - Enables mobile applications

Sigfox coverage (Winter 2021)

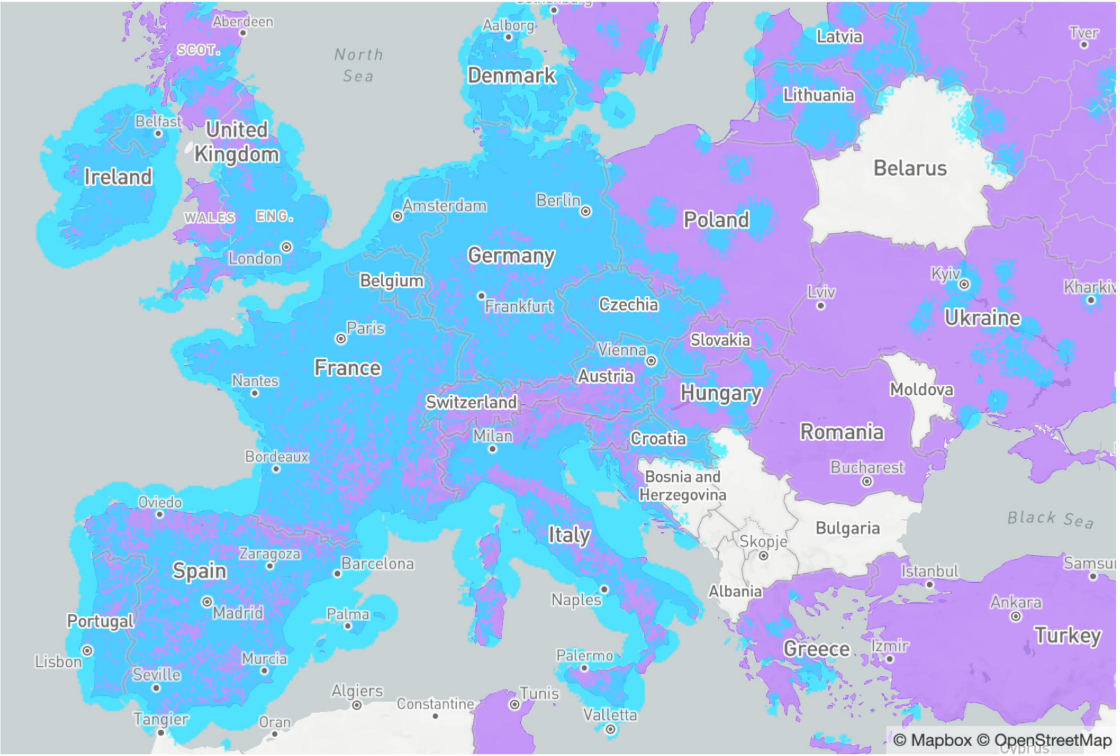


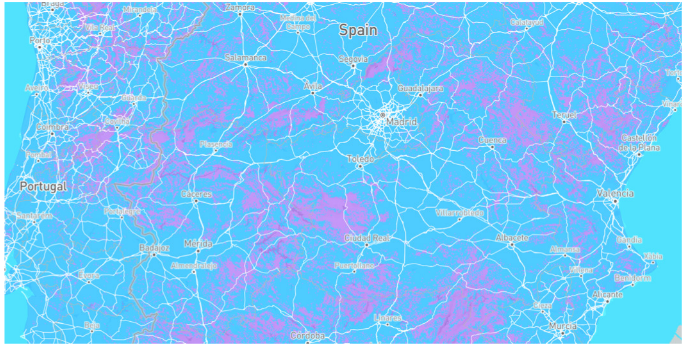
Sigfox coverage (Winter 2022)



(c.f. Europe, Winter 2022)

Things do get pinker ('planned rollout') as you zoom in though…





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IEEE standard for LPWANs

```
n.b.
  802       = “area networking”
      .3    = “LANs”
      .11 = “Wireless LANs”
      .15 = “PANs”
```

- 802.11ah (HaLow) standard in 2016
  - First real hardware in 2020
  - Still not in real-world use yet

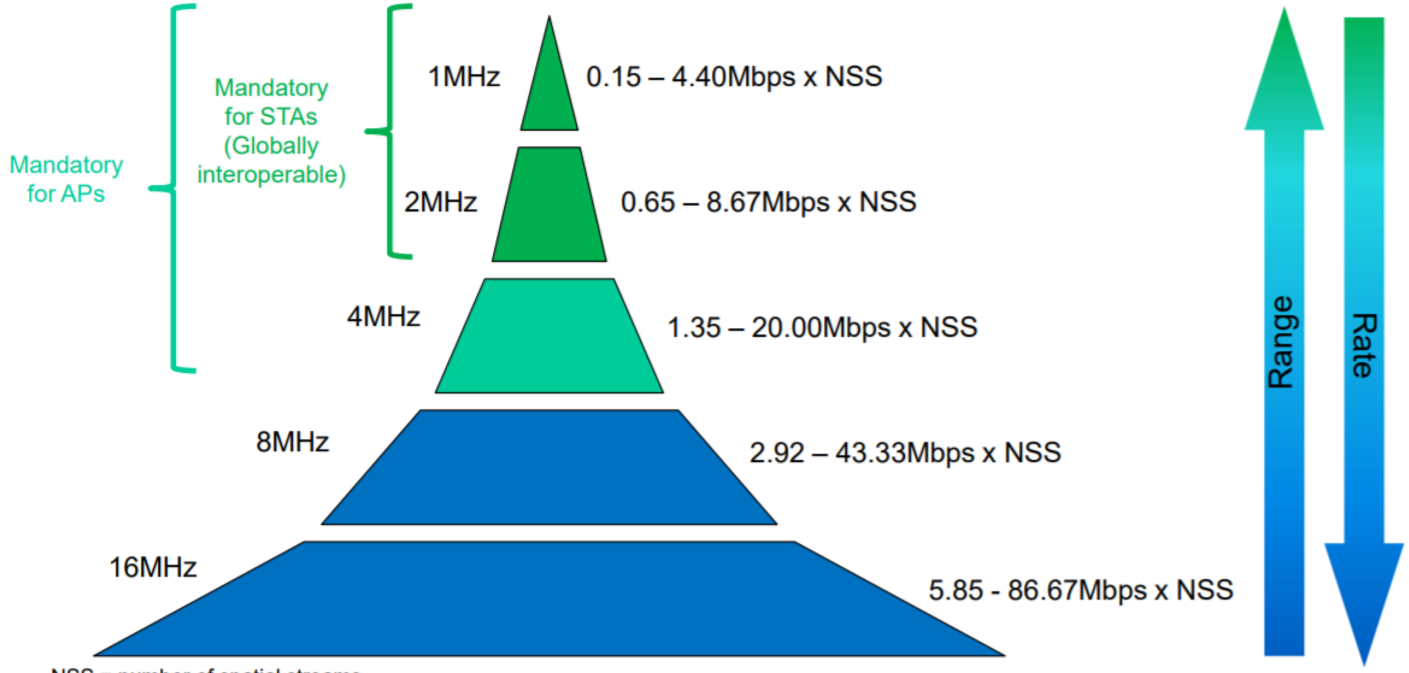
- Focus on the indoor-to-outdoor scenario
  - Medium range (maximum 1 km)

- 915 MHz communication
  - NOT interoperable with other 802.11 access points and devices

- Theoretically up to 356 Mbps
  - Practically, most devices are expected to implement 150 kbps to 8 Mbps

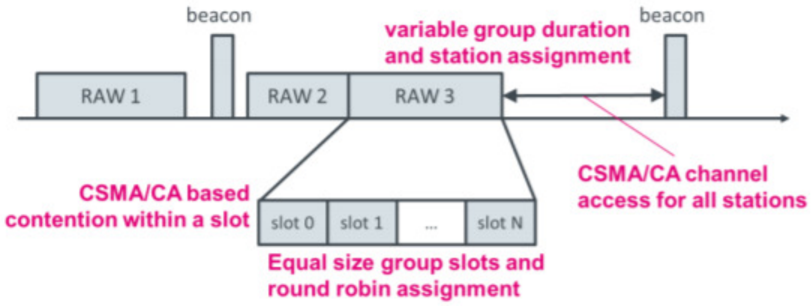
802.11ah allows multiple bandwidth allocations

- Expected throughput vs. coverage



NSS = number of spatial streams

802.11ah architecture



- Star topology
  - Up to 8191 devices per access point
- Devices are assigned to a group
  - Groups are scheduled slots with TDMA
  - Within a slot CSMA/CA is used for contention among devices
  - Devices not in the group can sleep until their slot
- Traditional IP communication on top of that
  - And traditional 802.11 security mechanisms (WPA2/TLS)

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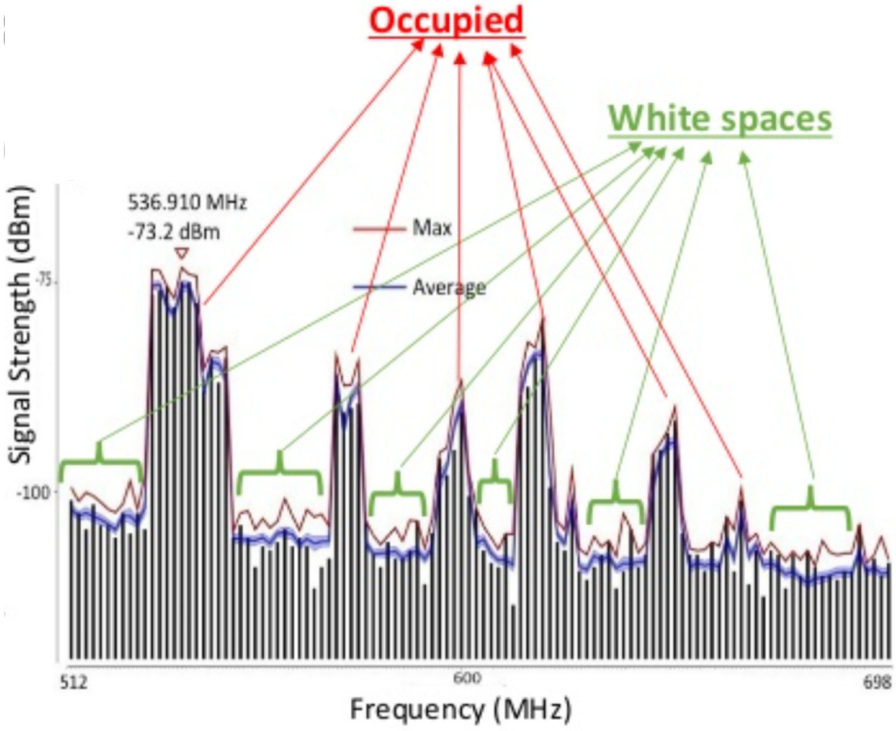
TV whitespaces

- Unused TV channels between 54
  - VHF (54-216 MHz)
  - UHF (470-698 MHz)
  - 6 MHz channel width

- Allocated but unused
  - FCC allows unlicensed use
  - IF you do not interfere with primary users



Sensing channel use

- Variation in use
  - Spatial: Cannot assume same channel will be free everywhere
  - Temporal: Cannot assume channel will be free at all times

- Cognitive radio approach
  - Dynamically identify unused portions of spectrum

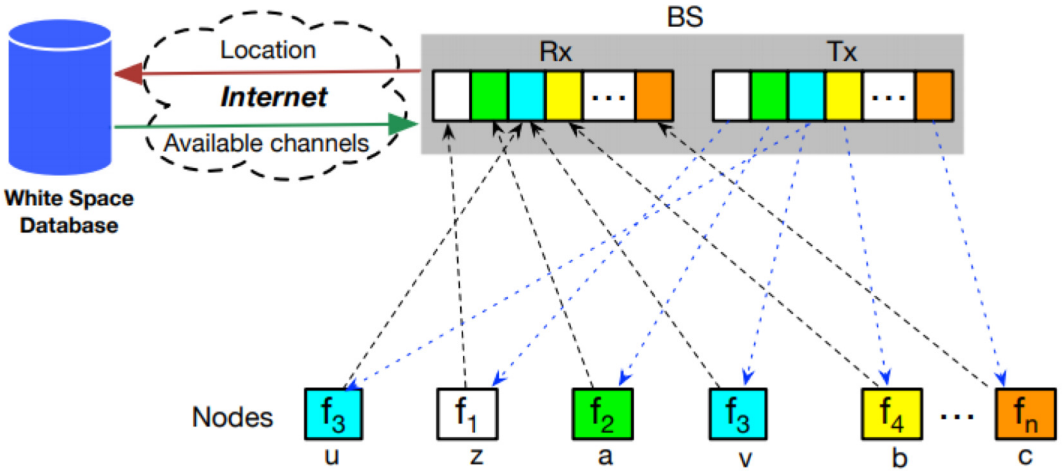
- Database approach
  - Let someone else do the scanning. Consult database based on location and time

802.11af

- IEEE standard for whitespaces circa 2014
  - Not much (any?) use to date
- US/Canada-specific
  - Limits general purpose product appeal
- Requires infrastructure about whitespace availability
  - People are figuring this out, but not really available yet
  - [n.b. very active area of research; including here]

Sensor Networks Over tv Whitespaces (SNOW)

- A design for sensor networks over whitespaces
  - Base Station manages channel for deployment
  - Frequency division for devices. Each uplinks on separate subcarrier
  - Downl ency



Resources

- LoRaWAN
  - LoRaWAN Specification version 1.1
  - LoRaWAN Regional Parameters version 1.0.2

- Sigfox
  - Sigfox Technical Overview
  - IETF Descriptions
    - https://www.ietf.org/proceedings/97/slides/slides-97-lpwan-25-sigfox-system-description-00.pdf
    - https://tools.ietf.org/html/draft-zuniga-lpwan-sigfox-system-description-04

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Do novel networks meet application needs?

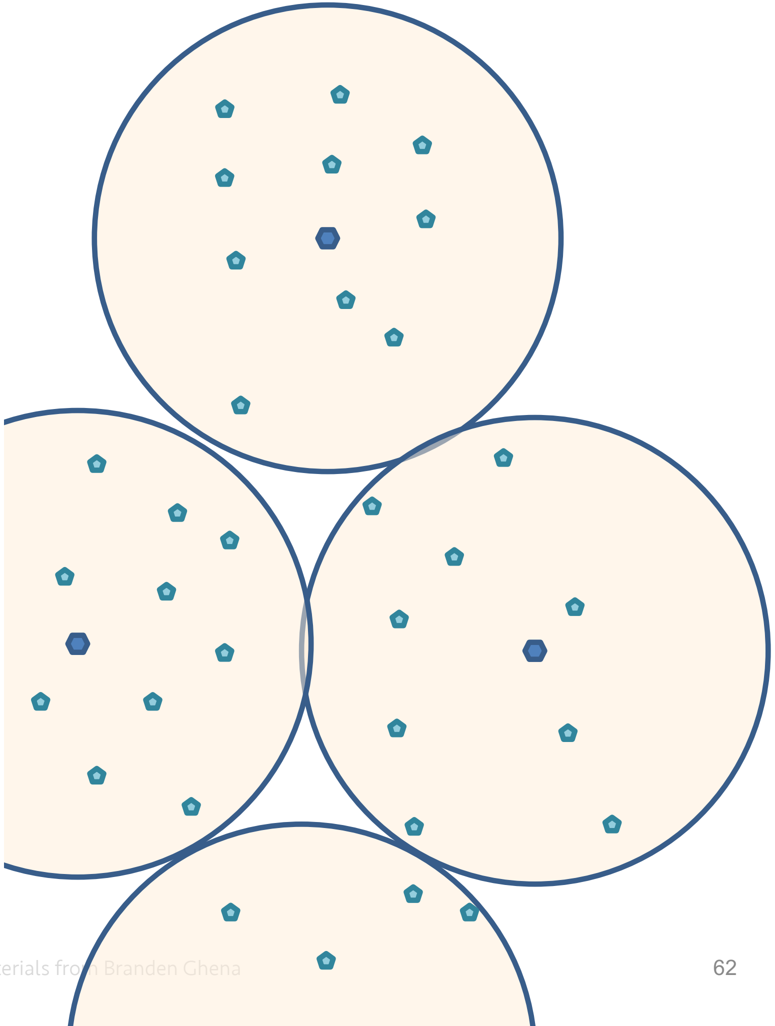
- How do we compare varied requirements and capabilities?
  - Networks have throughput per gateway and range of gateway.
  - Applications have throughput per device and deployment area.
- Each gateway must support throughput for all devices in its coverage area.
  - Deployment areas are often wider than 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**

- $bit\ flux = \dfrac{network\ throughput}{coverage\ area}$
- 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*

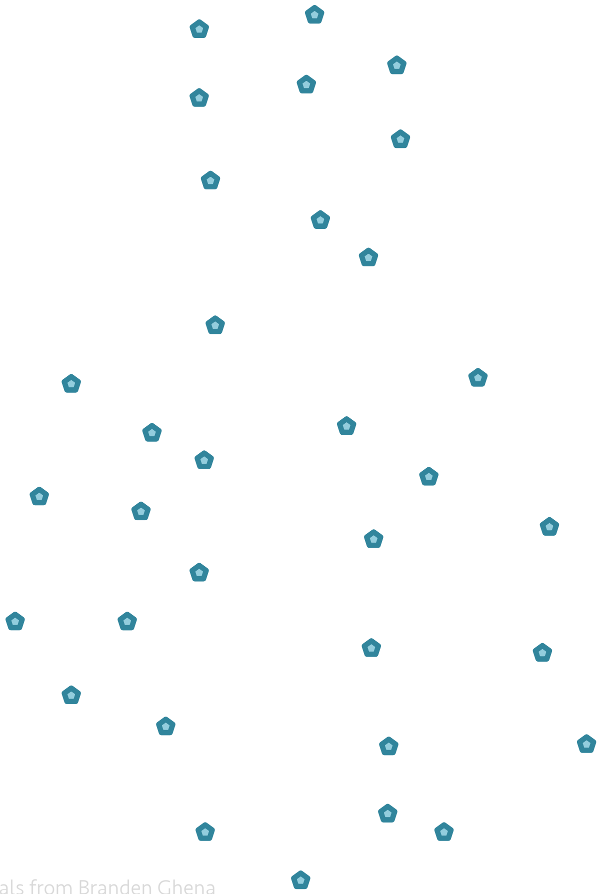


Bit flux can measure application needs.

For an application:

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

- Assumes a relatively homogeneous distribution.

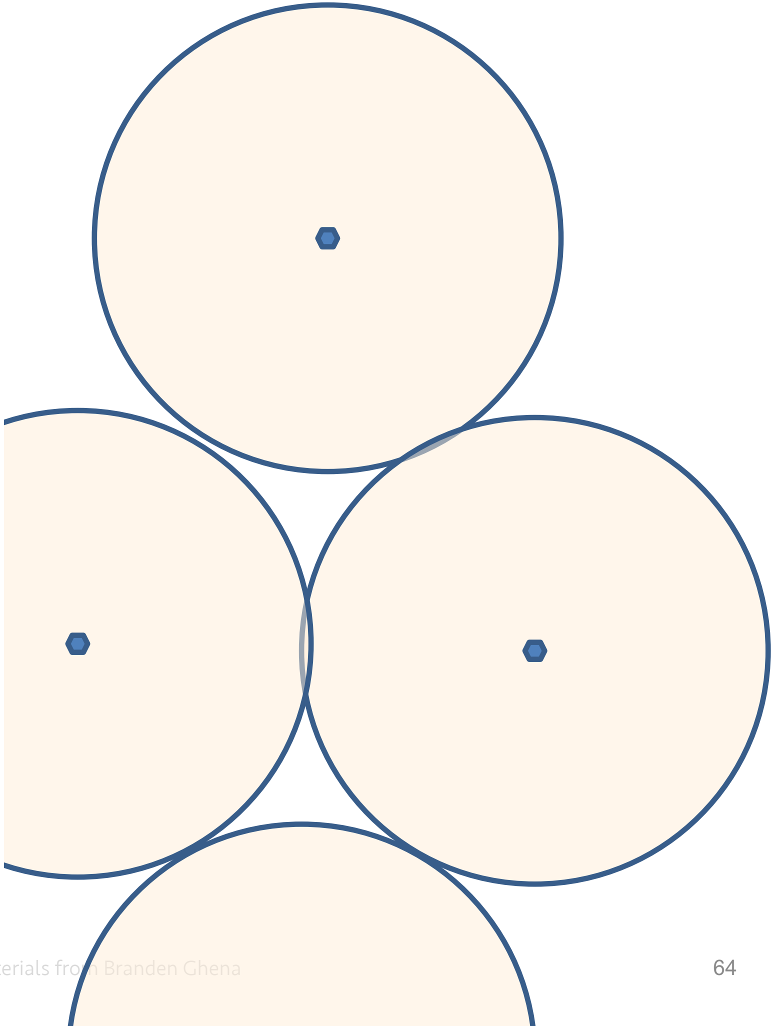


Bit flux can measure network capabilities.

For a network:

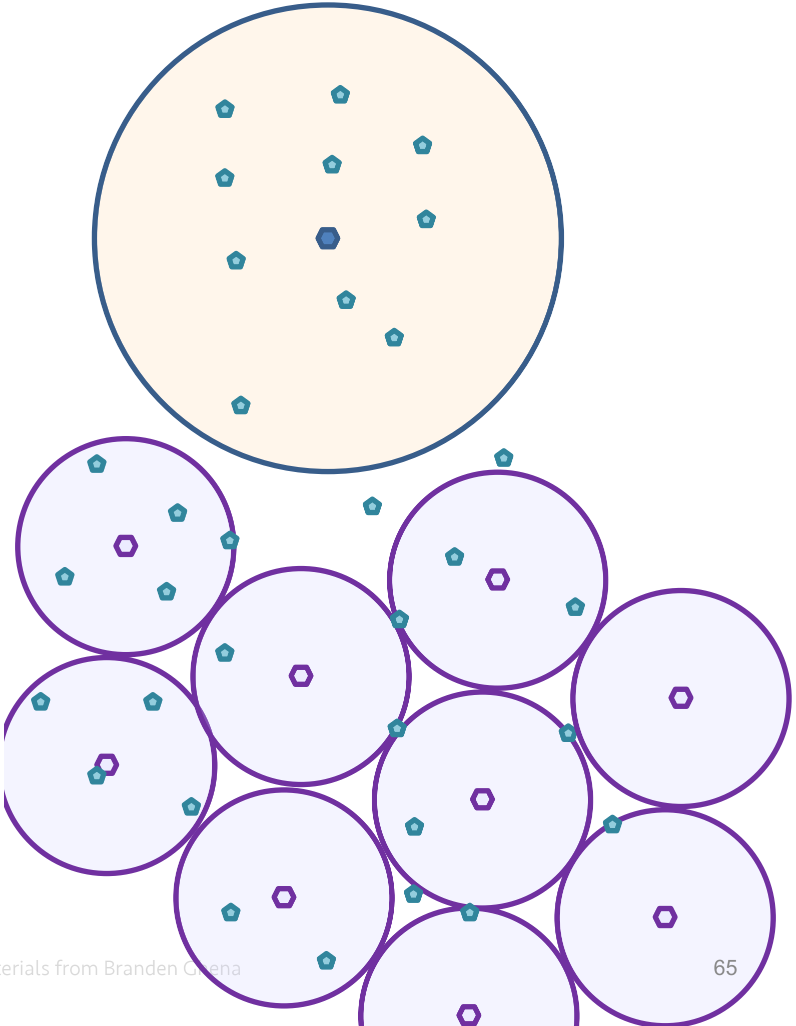
$$bit\ flux = \frac{gateway\ goodput}{gateway\ coverage\ area}$$

- 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.
- $bit\ flux \uparrow = \dfrac{gateway\ goodput}{coverage\ area \downarrow}$

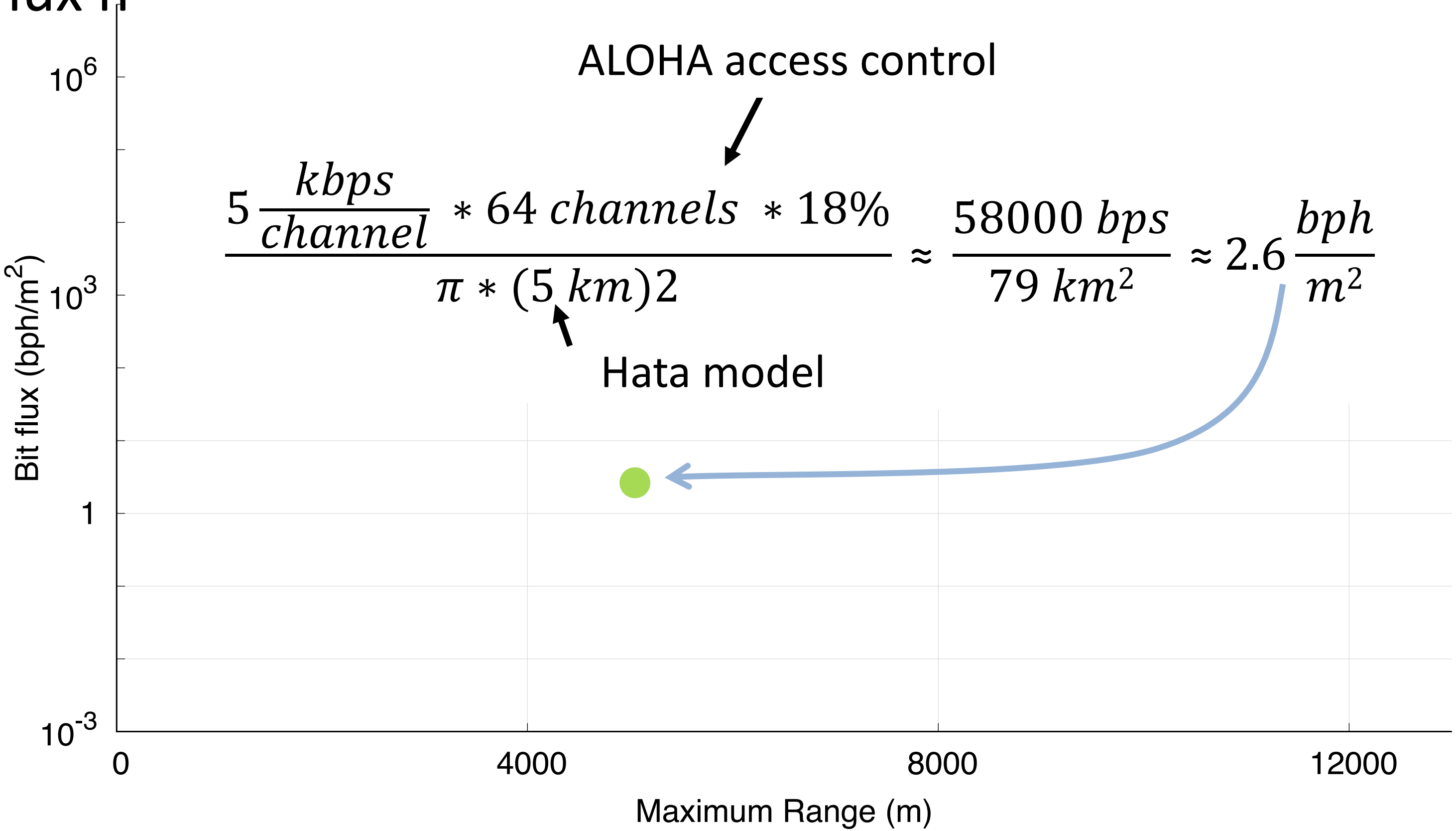


Bit flux measurement for LoRaWAN

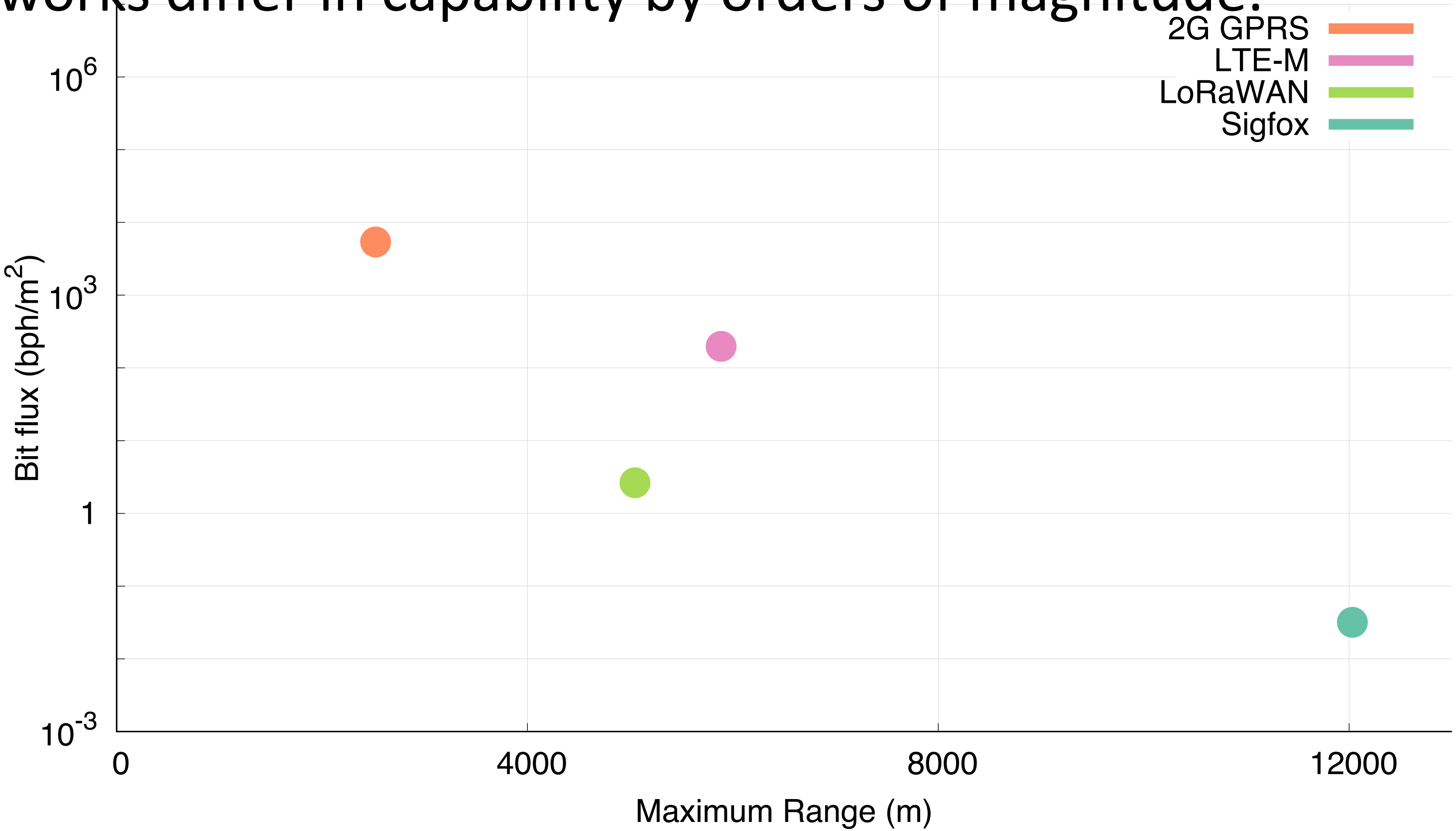
$$\frac{5\,\frac{kbps}{channel} * 64\ channels * 18\%}{\pi * (5\ km)2} \approx \frac{58000\ bps}{79\ km^2} \approx 2.6\,\frac{bph}{m^2}$$

ALOHA access control

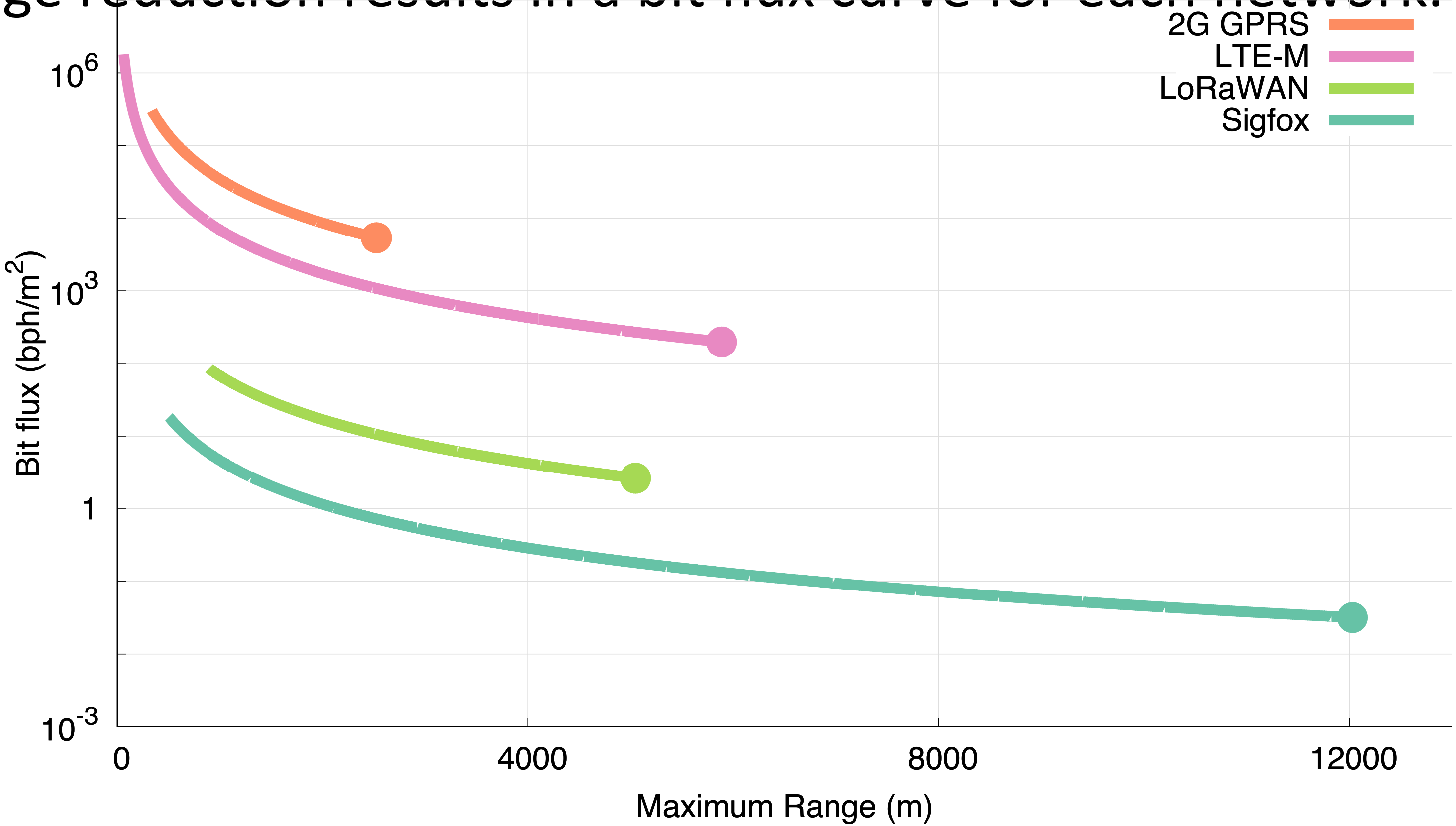
Hata model



Networks differ in capability by orders of magnitude.



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



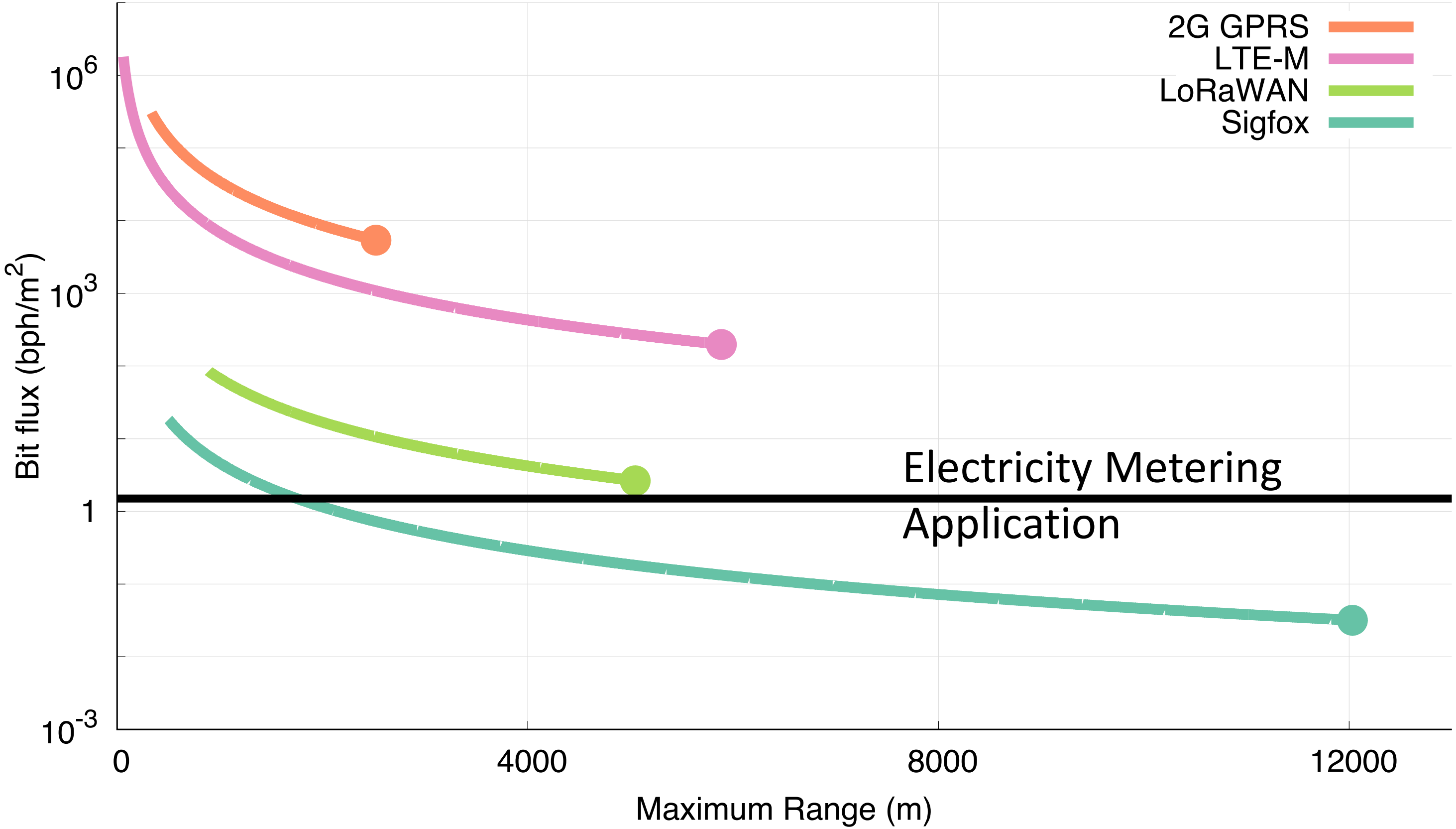
Let’s compare network capabilities to a real-world application.

Smart household electric meters.

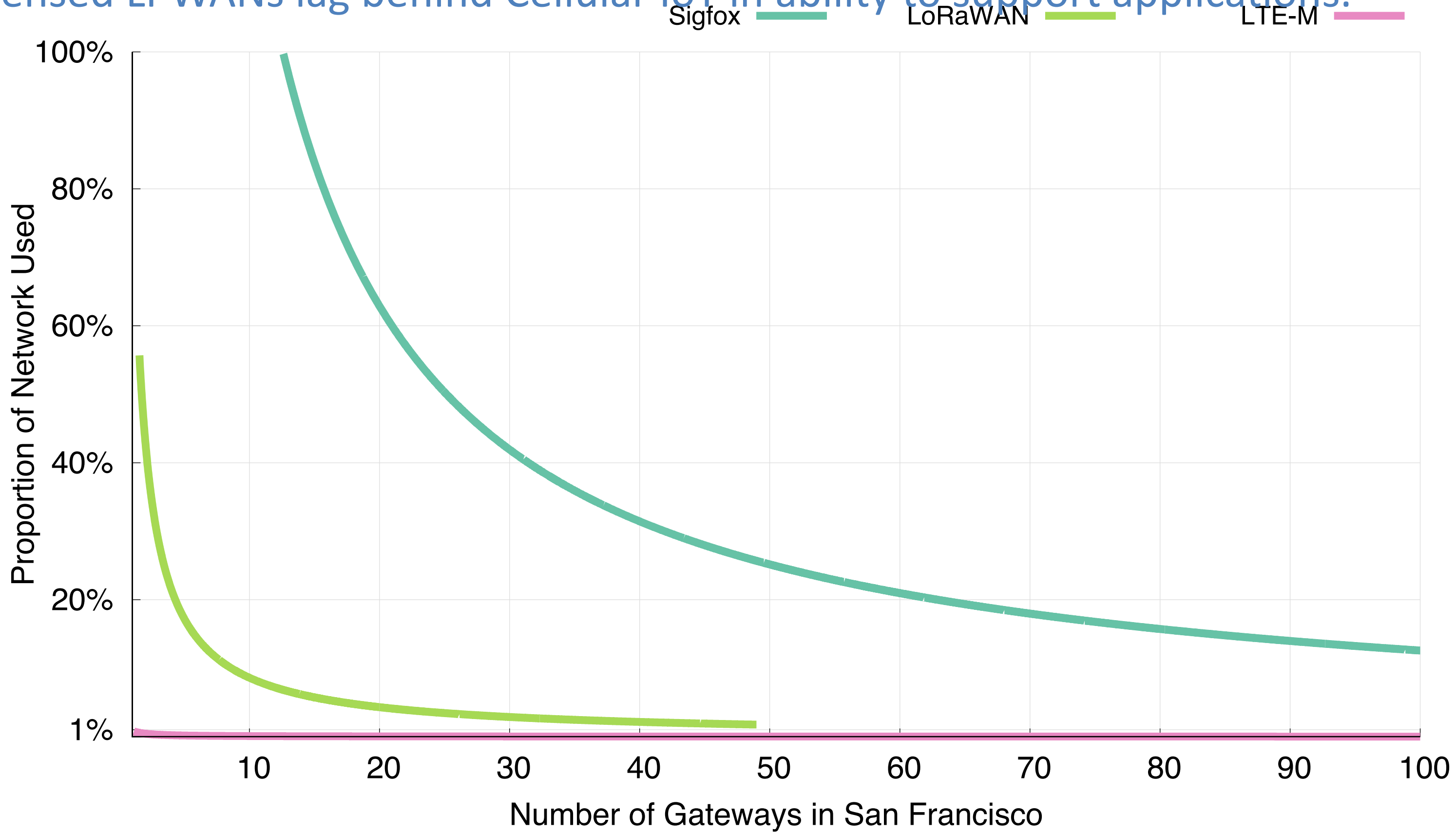
- ~250 bytes of data every 4 hours
- ~370000 electric customers in San Francisco

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

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

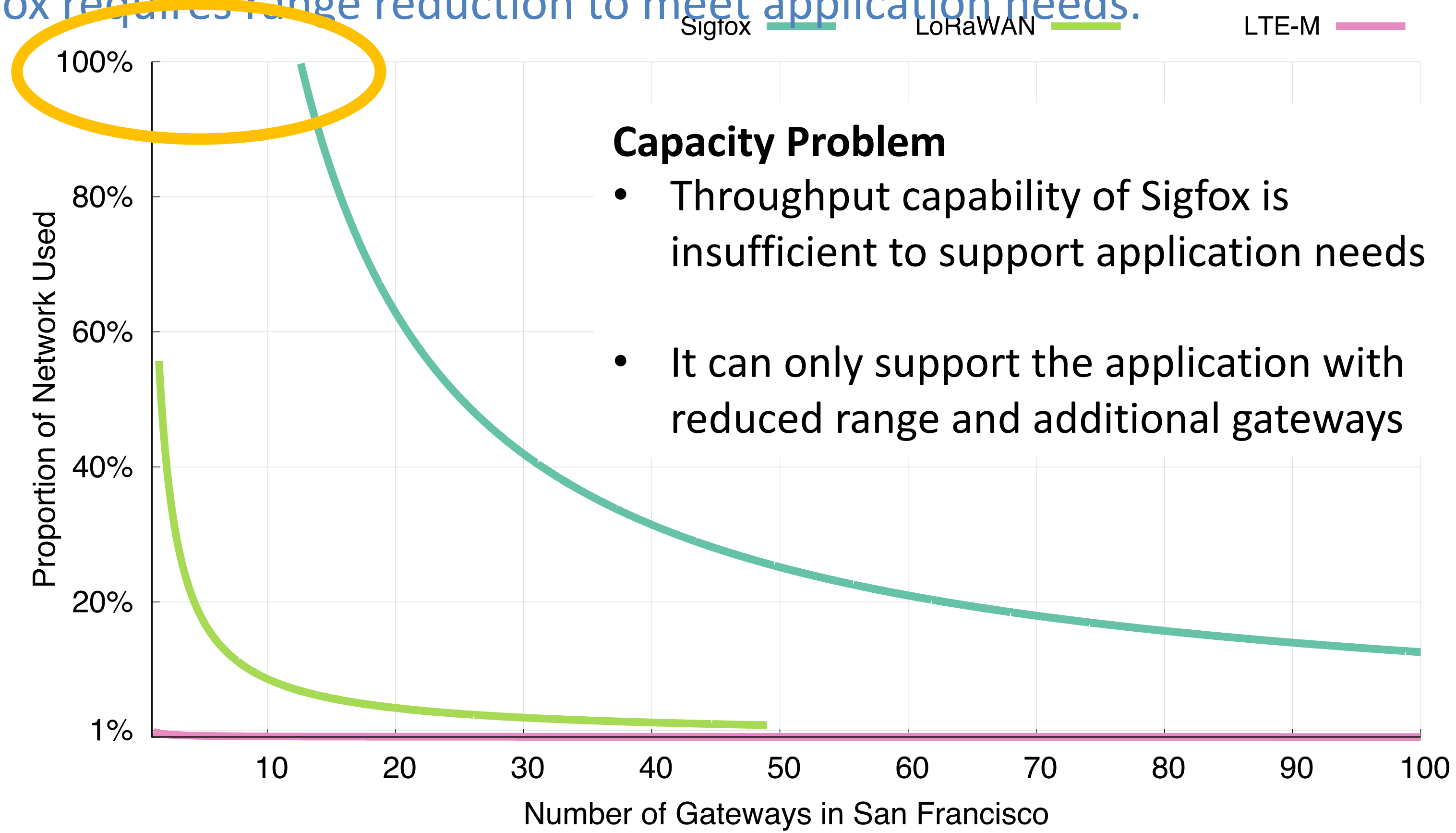


Unlicensed LPWANs lag behind Cellular IoT in ability to support applications.



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

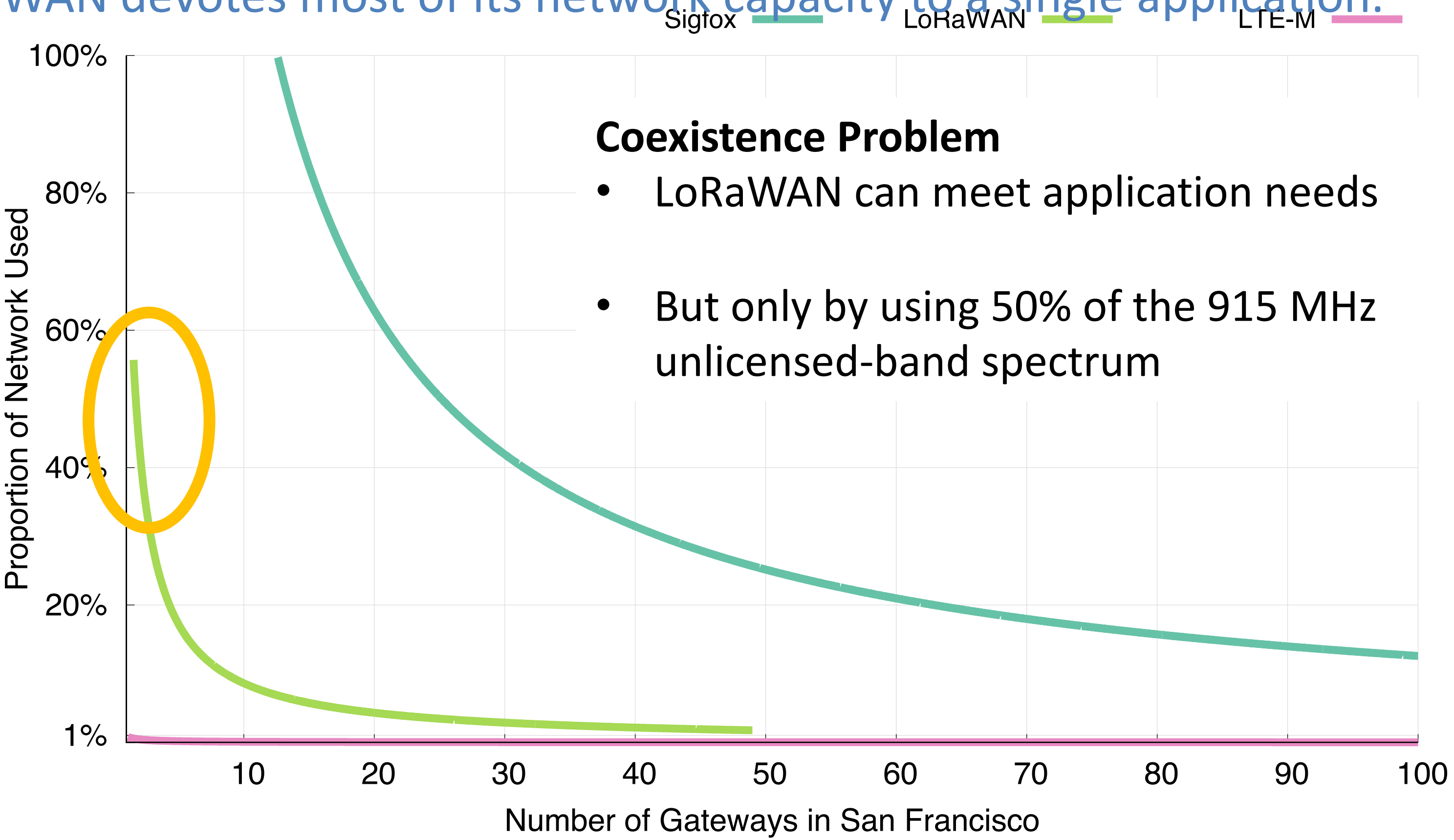
Capacity solutions are relatively straightforward.

- Better access control mechanisms.
- 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.

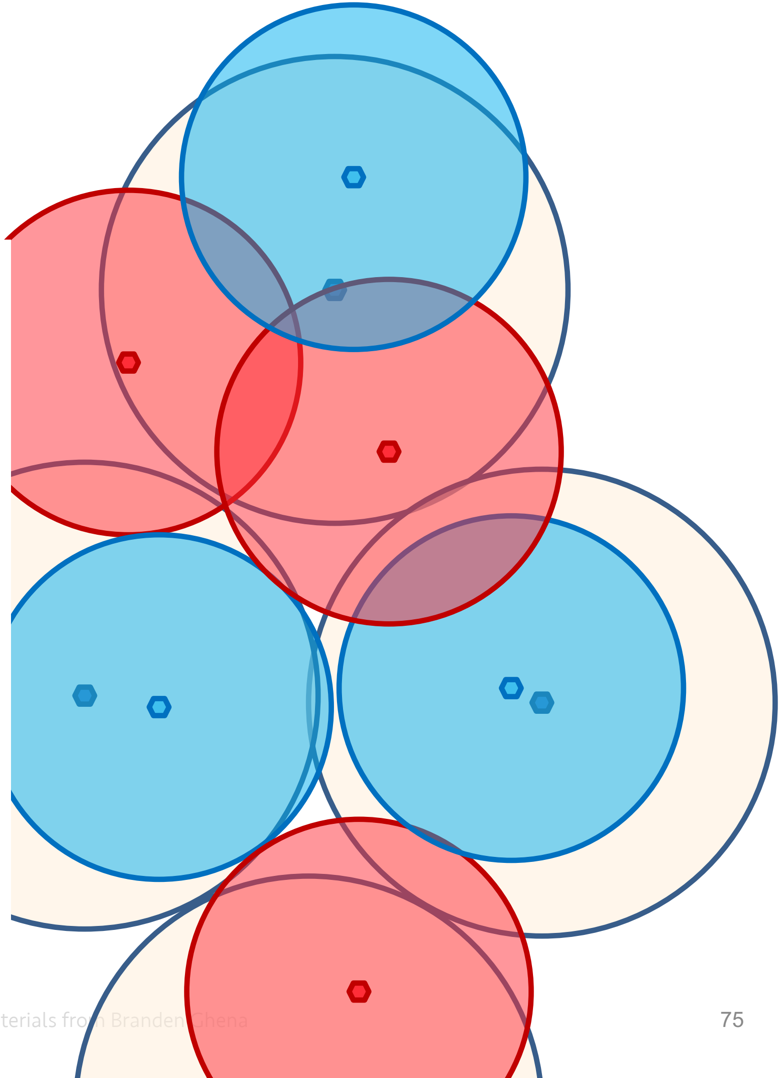


Coexistence Problem

- 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…



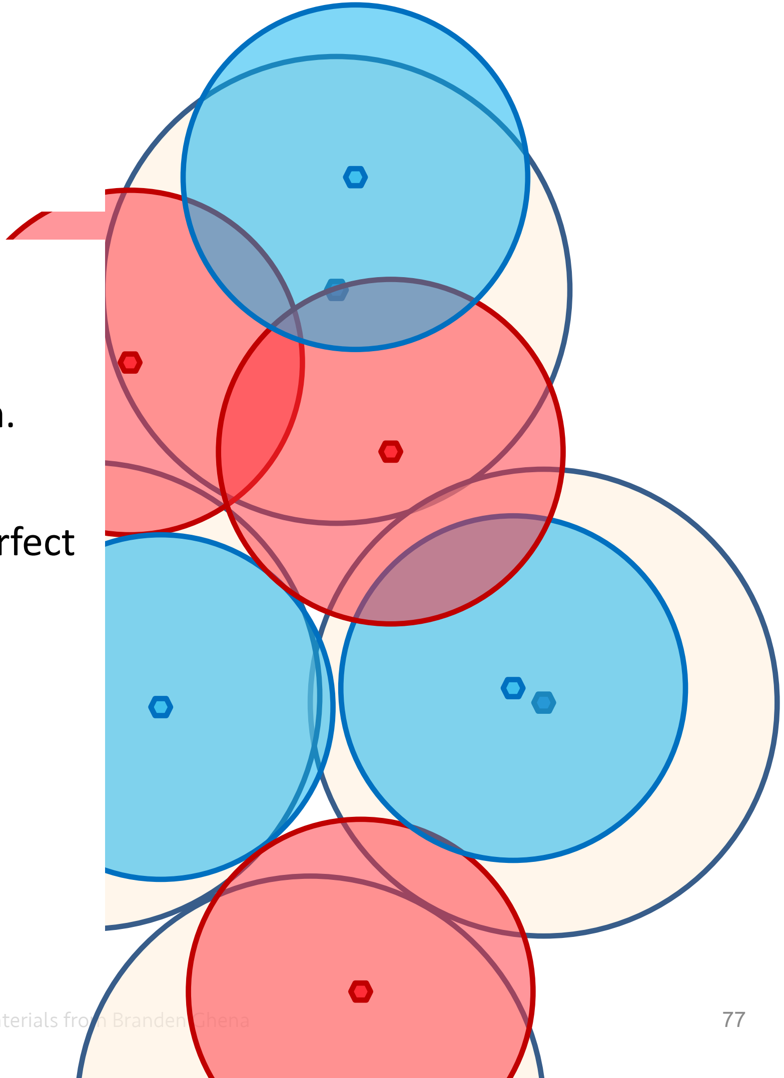
Coexistence in unlicensed bands is a more difficult problem.

- 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.

Friday's "Lab": Licensed vs. Unlicensed LPWANs