CSE 291: Wireless and Communication in the Internet of Things

Upcoming Cellular IoT

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Today's Goals

- Understand how modern "Cellular for IoT" fit in to the existing cellular infrastructure, and what they do at a technical level to suit IoT needs

- Preview LPWANs more generally

Aside: One last bit on emerging new G's
aka: What's up with this 5G / airplane kerfuffle?

- aka: when FDMA doesn't do the "D" part so great

January 18, 2022
9:40 PM PST
Last Updated 12 hours ago

Aerospace & Defense

AT&T, Verizon pause 5G rollout near U.S airports to avoid flight disruptions

Emirates, Air India, and others cancel flights due to AT&T and Verizon's 5G rollout

Airlines have dropped flights or switched planes to certain US cities, with emphasis on 777 aircraft

By Mitchell Clark | Jan 18, 2022, 5:43pm EST

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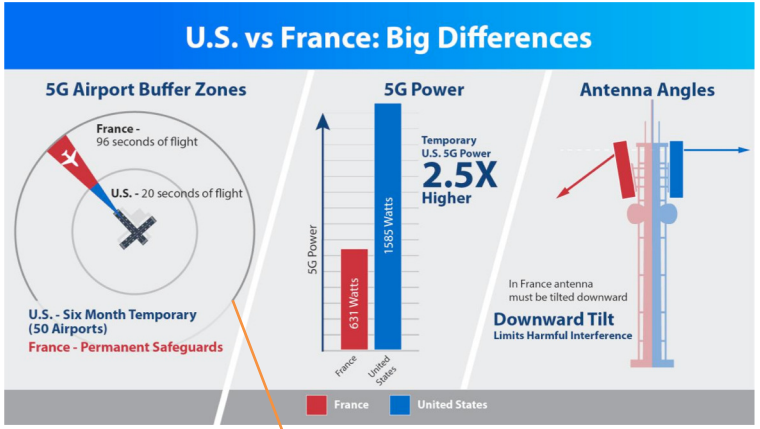
Emirates, Air India, ANA, and Japan Airlines have all announced they're canceling some flights to the US due to this week's rollout of C-band 5G over concerns it could potentially interfere with some instruments, particularly on Boeing 777 aircraft. This comes as cell carriers, federal agencies, airlines, and airplane manufacturers struggle to reach an agreement on policies regarding how the rollout should be handled.

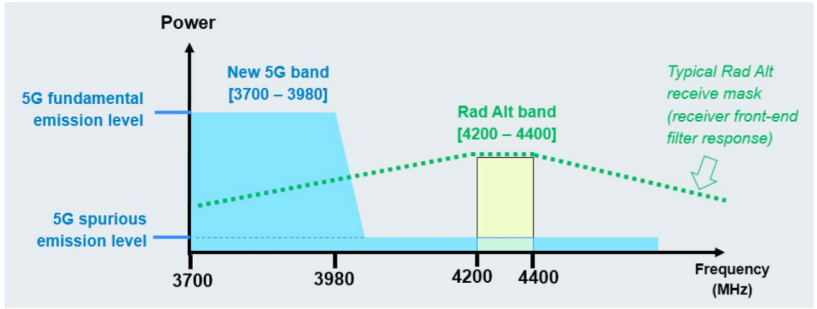
verge deals

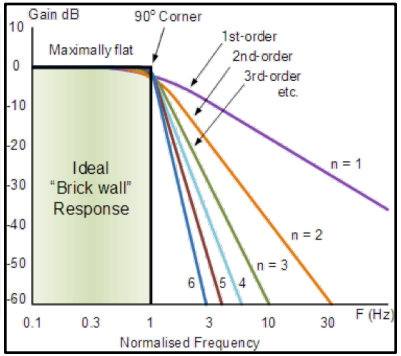
n.b. The FAA site on this is actually pretty good, and both accessible / technical

- https://www.faa.gov/5g

Filter design is hard ($$), a touch on the EE black magic side (especially equations vs practice)







160 mph (~landing speed)
*96s ~= 4.25 mi
*20s ~= 0.9 mi

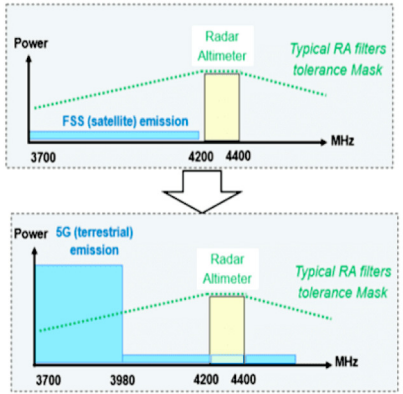
Graphics stolen from https://www.5gtechnologyworld.com/5g-altimeter-interference-aviation-versus-telecoms/ , the FAA site, and a quick google image for 'higher order filter cutoff'

Resource: Some of the best technical details I could find

- National Business Aviation Association (NBAA) webinar
  - https://www.bigmarker.com/nbaa/NBAA-News-Hour-What-the-Looming-Threat-From-5G-Interference-Could-Mean-for-Your-Flight?show_live_page=true&add_to_calendar=true&bmid=859a33fdec7a
  - One takeaway from webinar: Airports *aren't* the problem; helos, emergency, etc

Radar Altimeter Performance

- Radar altimeter performance defined by ED-30 (FAA TSO) and DO-155
  - Does not specify adjacent band performance
- In 2016 ICAO initiated job card to develop SARPs for radar altimeters
  - Recognized potential interference and lack of aviation data
- AVSI began developing testing methodology and equipment to define current performance
  - Supported by all main altimeter manufacturers and airframers



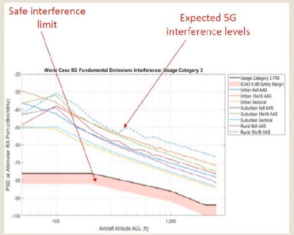
Highlights from the webinar [n.b. recorded Dec 7, 2021]

RTCA MSG Report

Usage Category 2: Business aviation, general aviation, and regional transport airplanes

Usage Category 3: Both transport and general aviation helicopters

- For RAs studied in these categories, large discrepancy between analyzed 5G emissions and capability to tolerate those emissions
- Worst-case results shown; not all RAs have same susceptibility

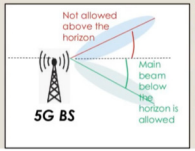


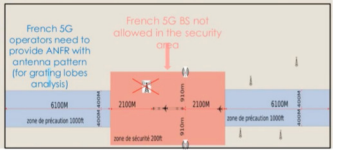
Other Events thru Dec 2020

- **Nov 19, 2020** – RTCA and AVSI file response to telecom critique of RTCA MSG Report
- Multiple calls for 5G auction delay
  - **Dec 1, 2020** – DOT/FAA letter to NTIA requesting engagement with FCC to defer 5G auction
  - **Dec 7, 2020** – US House Transportation & Infrastructure Committee Chair and Ranking Member letter to FCC Chair requesting 5G auction postponement
  - **Dec 7, 2020** – Aviation coalition files request with FCC to suspend 5G auction
- **Dec 8, 2020** – FCC proceeds with 5G auction

Aviation Proposed Mitigations

- Dec 7, 2020 – Aviation coalition files proposed 5G mitigations that would provide some protection for aviation safety and flying public
  - Aviation/aerospace unable to take timely technical mitigations to protect itself with high power 5G operational as soon as Dec 2021
  - RTCA has begun work on an updated RA minimum performance standard, but will not be ready until 2022 at earliest
  - Filter options being investigated, but uncertainty on feasibility or implementation questions. Filters will not help emissions that could occur directly into RA protected spectrum.
  - Proposed protection area around runways and limitation of base station tower antenna power above the horizon
  - However still an issue for helicopters and UAS
- Increasing international recognition that an issue exists, e.g., France, Canada





2021 Events

- **May 25, 2021** – AIA presents on behalf of industry at the DoD's JI-FRAI efforts to test potential interference
  - JI-FRAI findings won't be published until early 2022
- **Jul 1, 2021** – Industry Day with FAA
  - Conversation focused on the need for information from telecom.
- **Jul 14, 2021** – Aviation coalition sends letter to Departments of Transportation & Commerce asking to bring both aviation and telecom industries to the table
- **Oct 14, 2021** – Aviation coalition had a technical interchange meeting with FAA

2021 Events

- **Nov 2, 2021** – Aviation coalition files questions to FCC on needed 5G parameters
- **Nov 2, 2021** – FAA publishes Special Airworthiness Information Bulletin requesting voluntarily submitted data from RA and aircraft manufacturers and aircraft operations
- **Nov 3, 2021** – AVSI completed filing sharing its test data with FCC
- **Nov 3, 2021** – Industry coalition met with National Economic Council (NEC)
- **Nov 5, 2021** – Industry letter to NEC requesting joint aviation/telecom industry working group meeting with FCC and FAA

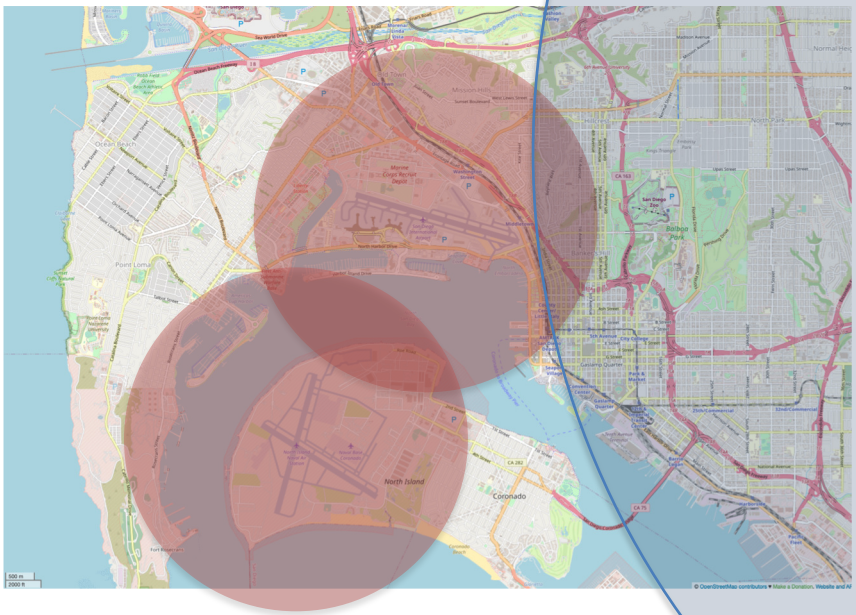
2021 Events

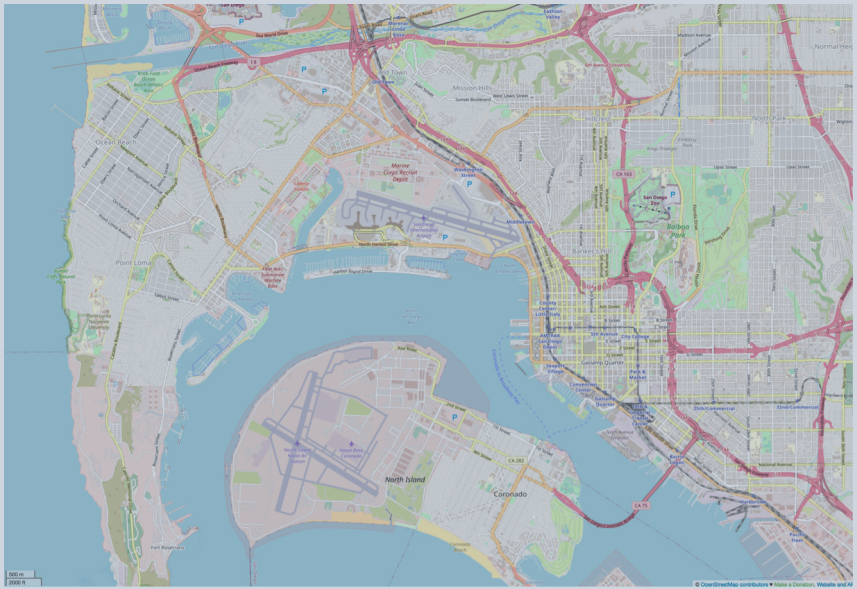
- **Nov 24, 2021** – Telecoms share their six months mitigation proposal publicly and not within NEC forum
  - Aviation assesses proposed mitigations as insufficient to protect safety-of-life RA usage in and around airport/heliport areas and helicopter operations outside of heliport areas
- **Dec 2 , 2021** – Aviation coalition shares mitigation counterproposal via NEC forum
  - Retains some aspects of telecom mitigation proposal; replaces others
  - Intended to allow flexibility in 5G deployment that should benefit telecoms
  - No response yet from telecoms

Just because I was curious…

160 mph (~landing speed)
*96s ~= 4.25 mi
*20s ~= 0.9 mi

- n.b. “SoCal TRACON” is the **busiest ATC in the world** [SD based; incl LA]





Outline

- Cellular IoT
  - LTE-M
  - NB-IoT
- Preview of other LPWANs

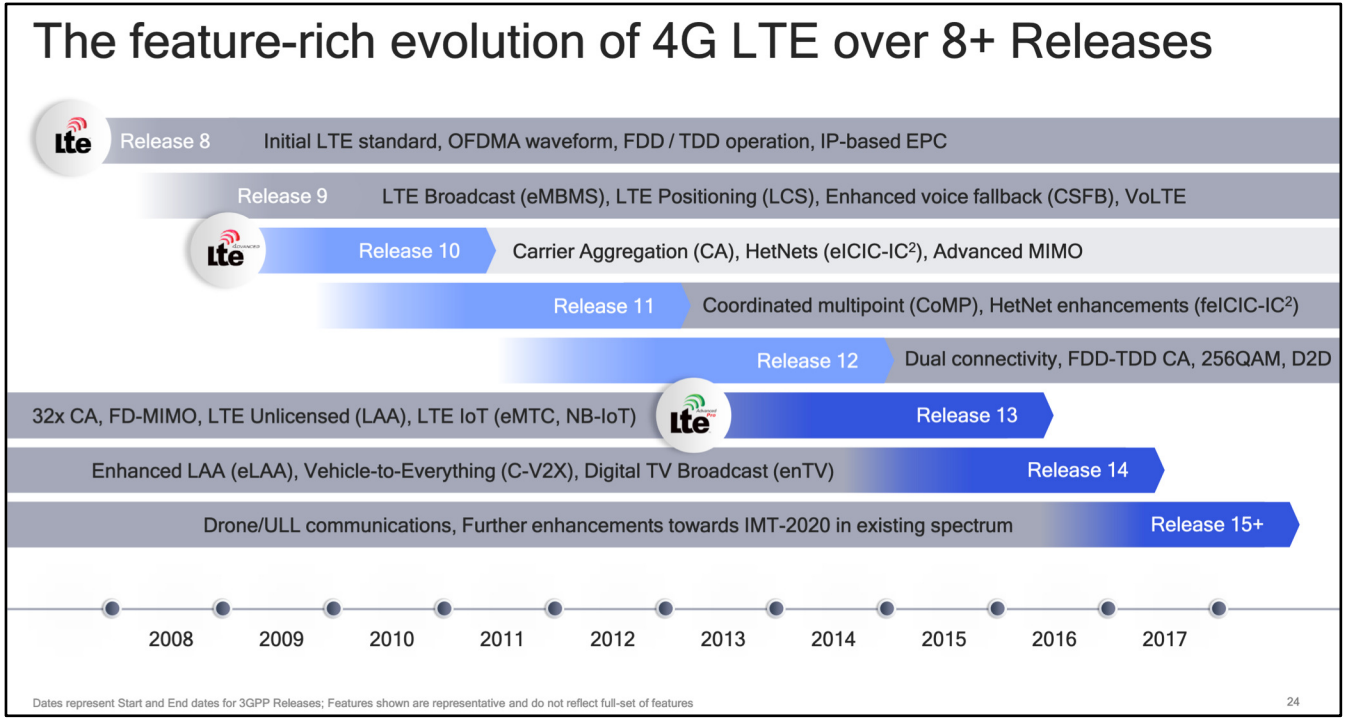
3GPP
aka: the actual answer for what stuff is really doing

- 3rd Generation Partnership Project (3GPP)

- Industry alliance for development of telecoms standards
  - Established around 1998
  - Makes "Releases" which are roughly analogous to IEEE standards/versions
    - Release 8 (2008) LTE ~4G
    - Release 15 (2018) NR (New Radio) ~5G

- Focused on the practical
  - ITU post-hoc defined "4G", 3GPP defined LTE and LTE_____

Mapping "4G", "LTE", "LTE Advanced", etc onto actual technologies



This Qualcomm presentation is great: https://www.qualcomm.com/media/documents/files/demystifying-3gpp-and-the-essential-role-of-qualcomm-in-leading-the-expansion-of-the-mobile-ecosystem.pdf

LTE Categories

- Different equipment supports different "categories" of LTE
  - Maximum MCS index supported
- Examples
  - iPhone 6 (2015): Cat 4
  - Pixel 3 (2018): Cat 16
- Aside: Hey look, *some* LTE is "ITU 4G"!

User equipment Category	Max. L1 data rate Downlink (Mbit/s)	Max. number of DL MIMO layers	Max. L1 data rate Uplink (Mbit/s)	3GPP Release
1	10.3	1	5.2	Rel 8
2	51.0	2	25.5	
3	102.0	2	51.0	
4	150.8	2	51.0	
5	299.6	4	75.4	
6	301.5	2 or 4	51.0	Rel 10
7	301.5	2 or 4	102.0	
8	2,998.6	8	1,497.8	
9	452.2	2 or 4	51.0	Rel 11
10	452.2	2 or 4	102.0	
11	603.0	2 or 4	51.0	
12	603.0	2 or 4	102.0	
13	391.7	2 or 4	150.8	Rel 12
14	391.7	8	9,585	
15	750	2 or 4	226	
16	979	2 or 4	n/a	
17	25,065	8	n/a	Rel 13
18	1,174	2 or 4 or 8	n/a	
19	1,566	2 or 4 or 8	n/a	
20	2,000	2 or 4 or 8	315	Rel 14
21	1,400	2 or 4	300	Rel 14

Additional low-end categories for IoT

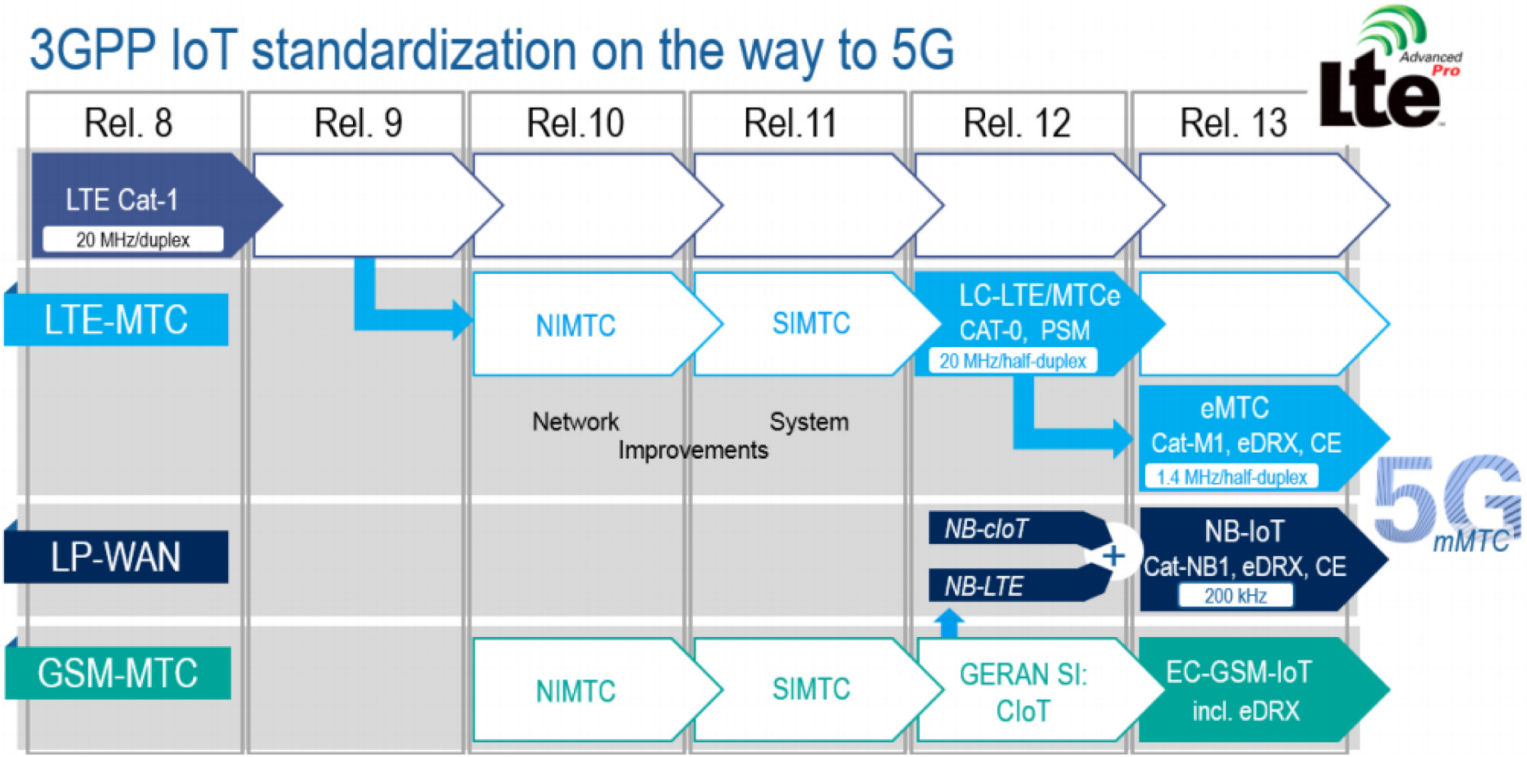
- LTE Cat 0
  - Traditional LTE, but focused on the really low end
- LTE-M (LTE Cat M1)
  - 375 kbps uplink, 300 kbps downlink (for the actually implemented mode)
  - Reduced power and maximum bandwidth
  - Increased range
- NB-IoT (LTE Cat NB1)
  - 65 kbps uplink, 26 kbps downlink
  - Reduced power and greatly reduced bandwidth
  - Greatly increased range

Why do we need “special categories” for IoT on cell?

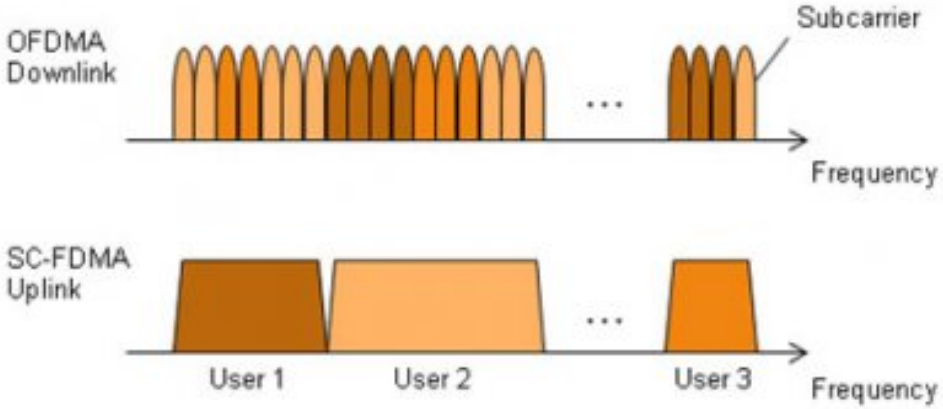
- Pragmatic for the end device
  - Lower power
  - Allow for long-off periods
- Pragmatic for network operators
  - *Allows for scale*– network no longer needs to assume that devices could always be on in each cell

Country	Carrier	sim card cost (1000 devices)	data cost (1000 devices, 6 month)	total cost
Dominican Republic	Claro RD			
Samoa	Vodafone Samoa			
China	China Telecom	$160-500 (based on the deal)	<$756	$916-1256
Kenya	Safaricom			
India	Jio			
Australia	Vodafone			
Egypt	Vodafone			
Brazil	Telefónica Brasil	Vivo		
Tajiikistan	MegaFon			
Colombia	Avantel	$1,250	$3,770.88	$5,020.88
Switzerland	Swisscom	$0	$32,820	$32,820
Ireland	Three	$0	$40,740	$40,740
England	Sky	$0	$48,900	$48,900
China	China Unicom			
Singapore	Singtel			
Taiwan	Chunghwa Telecom			
South Korea	SK telecom			
Canada	Bell Mobility			
UK	EE (Everything Everywhere)			

LTE-M and NB-IoT were developed in parallel



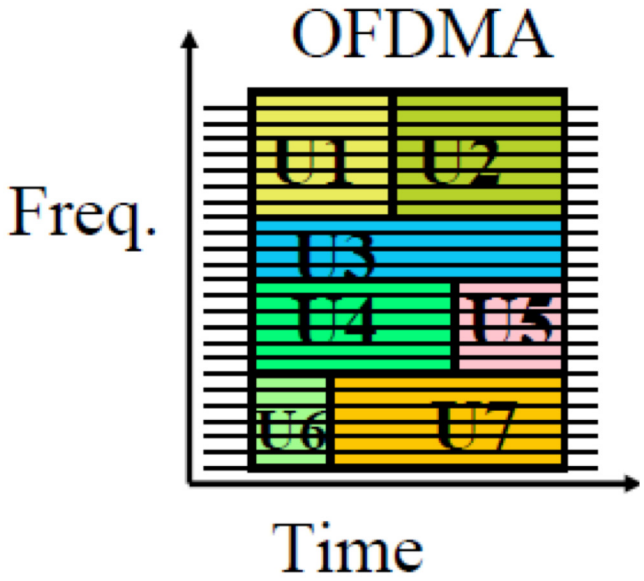
LTE-M and NB-IoT downlink and uplink



- OFDMA downlink
  - Put the more complicated hardware in the cell tower [simple FFT demodulator]

- SC-FDMA (single carrier FDMA) uplink
  - Blocks of subchannels combined into one signal
  - Similar concept, but simpler for end devices to implement

LTE resource allocation

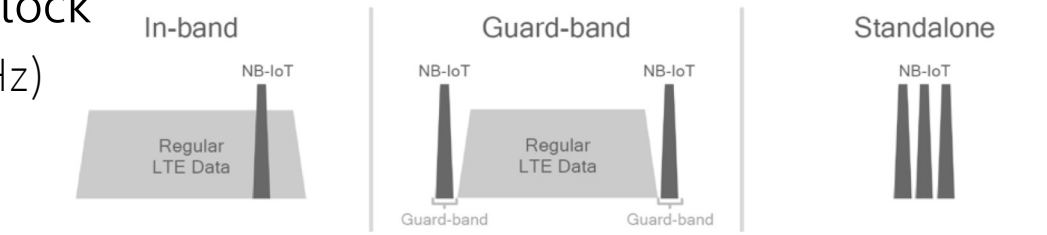


- Cellular uses OFDMA to schedule
  - Time + Frequency -> "2D Scheduling"
- Cellular uses single channels up to 20 MHz
  - Further divides these into 100 Resource Blocks
- Resource Block
  - 12 subcarriers for OFDM in frequency (15 kHz each)
  - 7 symbols in time (0.5 ms)
- Devices are allocated frequency and time based on what they are sending
  - Allocated in units of Resource Blocks

Resources used by LTE-M and NB-IoT

- LTE-M uses up to 6 resource blocks
  - 1.4 MHz of bandwidth (1.080 MHz)
  - Can co-exist with other normal LTE traffic, scheduled by cell tower
  - Limited to only some capability of LTE

- NB-IoT uses up to 1 resource block
  - 200 kHz of bandwidth (180 kHz)
  - Multiple deployment options
    - Guard-band in practice



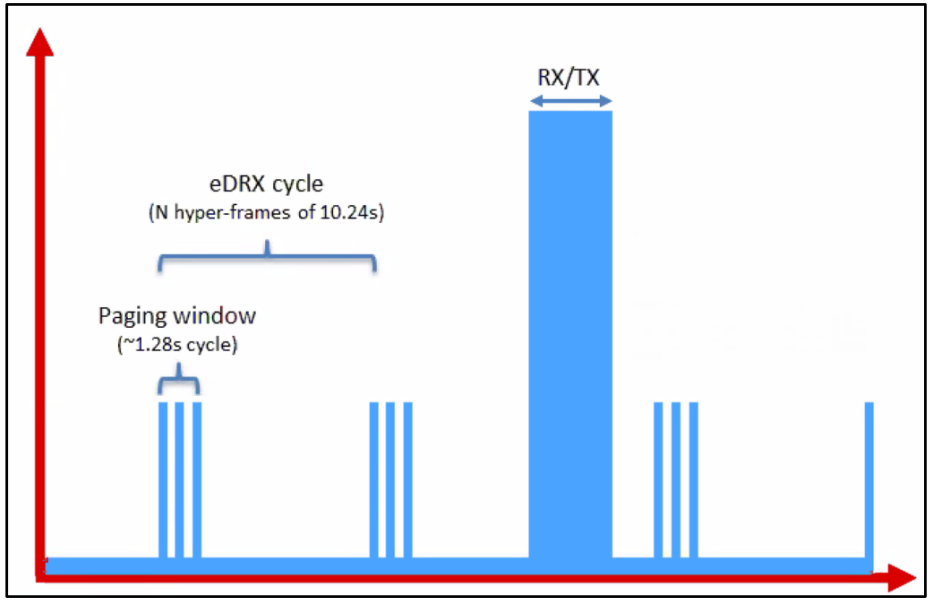
Utilizing single resource block (180kHz) within an LTE carrier

Utilizing unused resource blocks within an LTE carrier guard-band

Utilizing stand-alone 200 kHz carrier

Reducing power for IoT devices

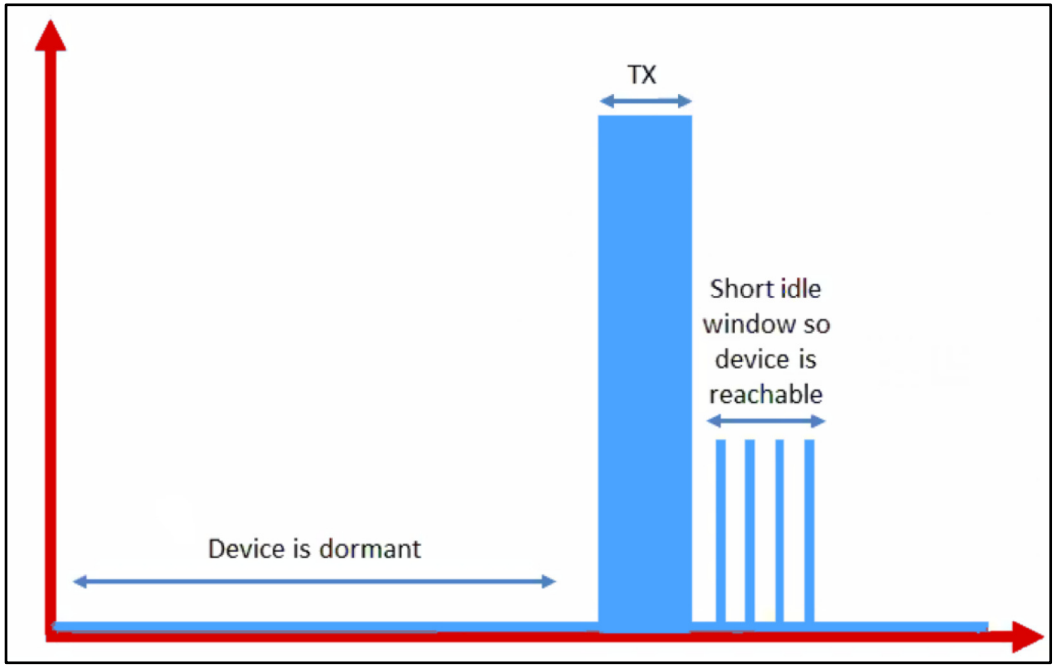
- Reduce max Tx power to 20 dBm
  - Increased receive sensitivity at tower will cover it
- Extended Discontinuous Reception (eDRX)
  - Allow devices to reduce paging period and still stay on network
  - Cell tower will hold messages
- What does this get to?
  - "For a LTE-M1 device that transmits data once per day, and wakes up every 60 hyper frames to check for commands (this would be about every 10 minutes), a life of 4.7 years is achievable on 2 AA batteries."



Graphics, quote from https://www.link-labs.com/blog/lte-e-drx-psm-explained-for-lte-m1

Further power reduction for simple devices

- Power Saving Mode (PSM)
  - For very simple, uplink-focused devices, allow them to turn off entirely but stay connected
  - Minutes to *days* in duration
  - Notify tower before sleeping, listen for packets after each transmission



Graphics from https://www.link-labs.com/blog/lte-e-drx-psm-explained-for-lte-m1

Some numbers from an actual telecom: Aeris
[n.b. Aeris has been a leader in cellular M2M since the 90's]

- PSM has two timers, devices *request* values, *tower chooses* actual:
  - Extended Timer ("sleep" timer)
    - 3GPP max is 35,712,00s [413.33 days]
    - Aeris timer range: Min 240m [4h]; Max 413 days
    - "Aeris Fusion" timer range: Max: 12.9 days
  - Active Timer (how long will the device stay in idle after communication?)

Active Timer – T3324

The requested active timer value is a single binary string byte value defined by octet 3 of the GPS Timer 2 specification (see section 10.5.7.4 of 3GPP TS 24.008) as follows:

- Bits 5 to 1 represent the binary coded timer value.
- Bits 6 to 8 define the timer value unit (table):

Timer 3 Value	Timer Value Incremented
000xxxxx	2 seconds
001xxxxx	1 minute
010xxxxx	1 decihour (6 minutes)
111xxxxx	Timer is deactivated

Numbers from https://aeriscom.zendesk.com/hc/en-us/articles/360049848254-Understanding-LTE-M-Power-Management-Modes

Improved range for LTE-M and NB-IoT

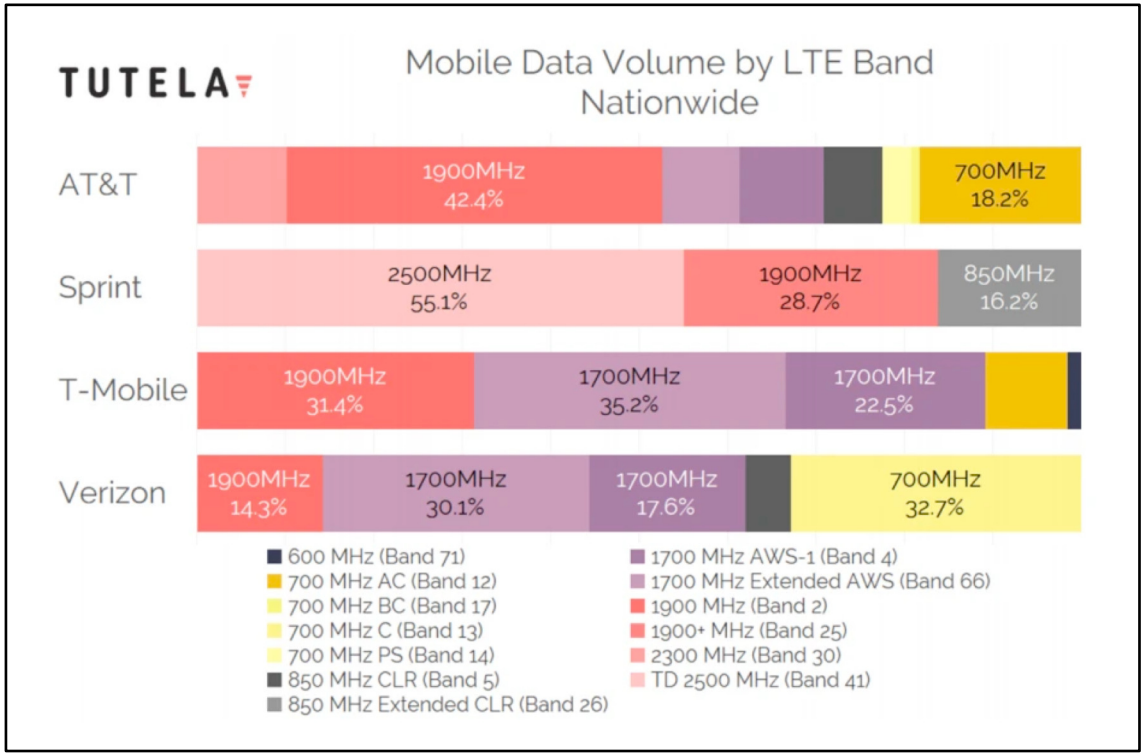
- LTE defines a Maximum Coupling Loss (MCL) a.k.a Link Budget
  - Traditional cellular: 144 dB (~2.5 km)
  - LTE-M: 160 dB (~5 km)
  - NB-IoT: 164 dB (~10 km)

  - Sigfox: ~155 dB
  - LoRaWAN: ~143 dB

- Note that many cellular bands are often on higher frequencies
  - Example: 1900 GHz

Coarsely, lower frequency -> longer range

- This was the picture circa 2019
- Why else might T-Mobile have *really* wanted to buy Sprint…



Cellular deployments

- Originally unclear which would be dominant
  - Verizon and AT&T focused on LTE-M
  - T-Mobile focused on NB-IoT
  - All rolled out services nationwide in the 2018-2019 timeframe

- Networks are expanding to provide both capabilities
  - LTE-M: AT&T, T-Mobile, US Cellular, Verizon
  - NB-IoT: AT&T, T-Mobile

- Pricing models still very uncertain
  - NB-IoT example: $5 per device per year up to 12 MB, 10 packets per hour
  - Future adoption will greatly depend on these

Outline

- Cellular IoT
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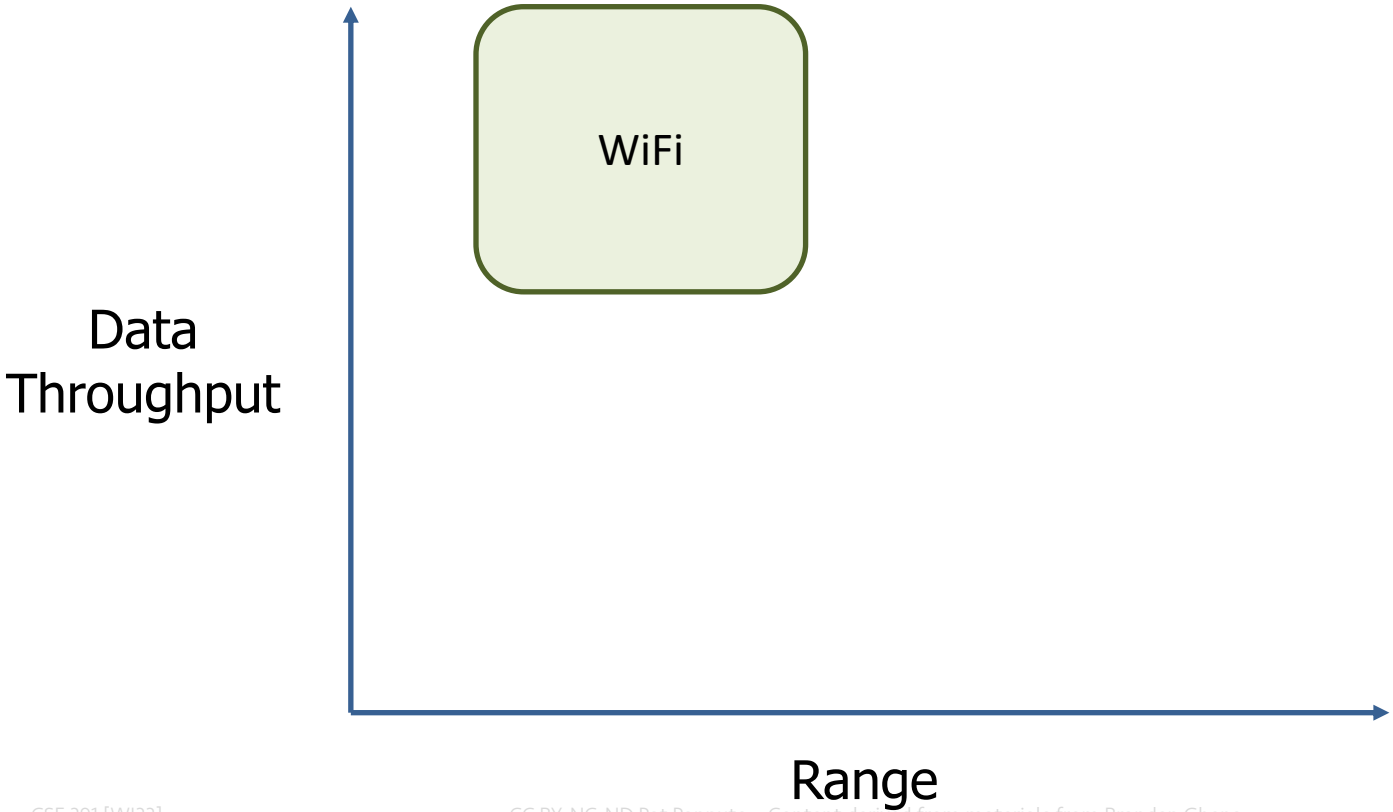
  - NB-IoT
- Preview of other LPWANs

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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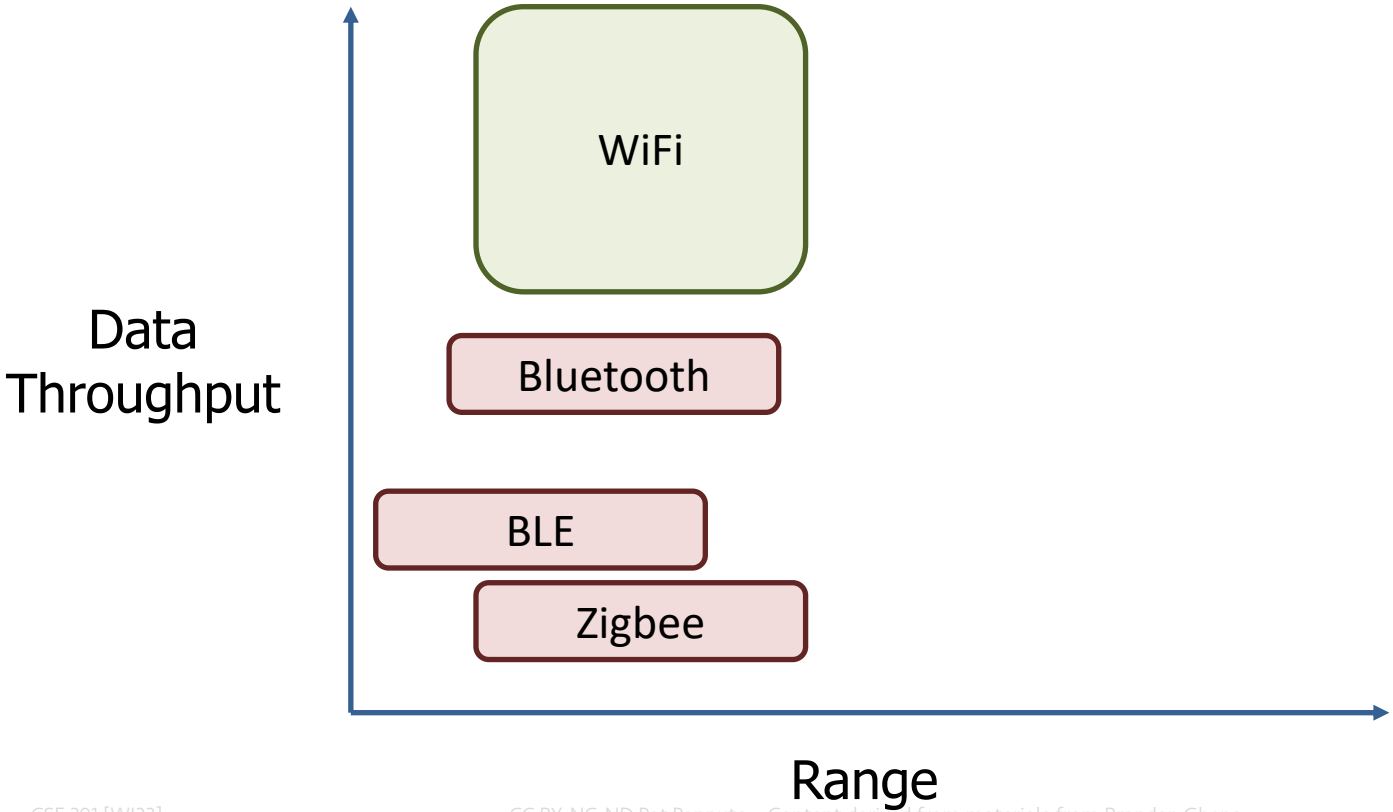

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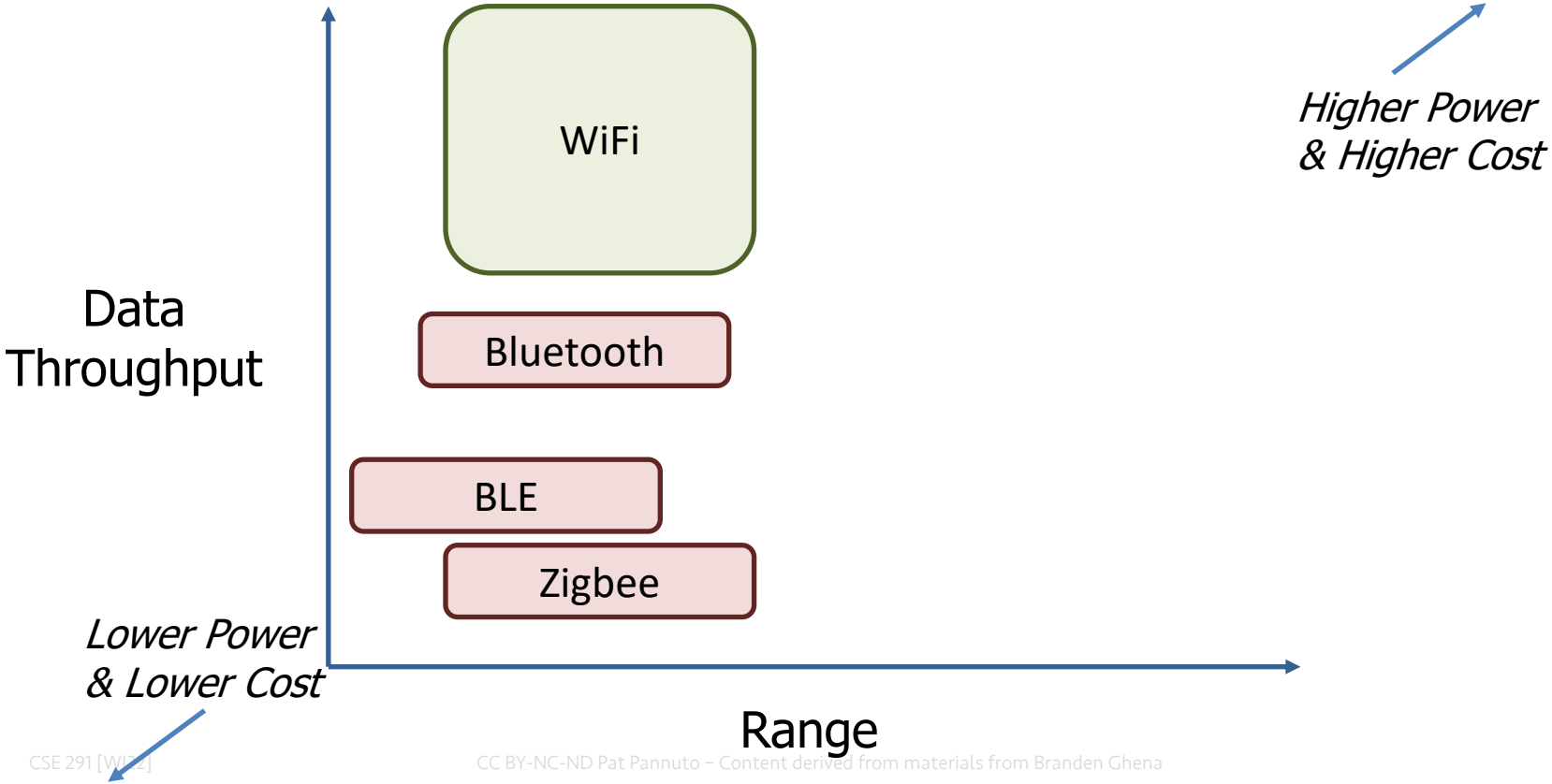

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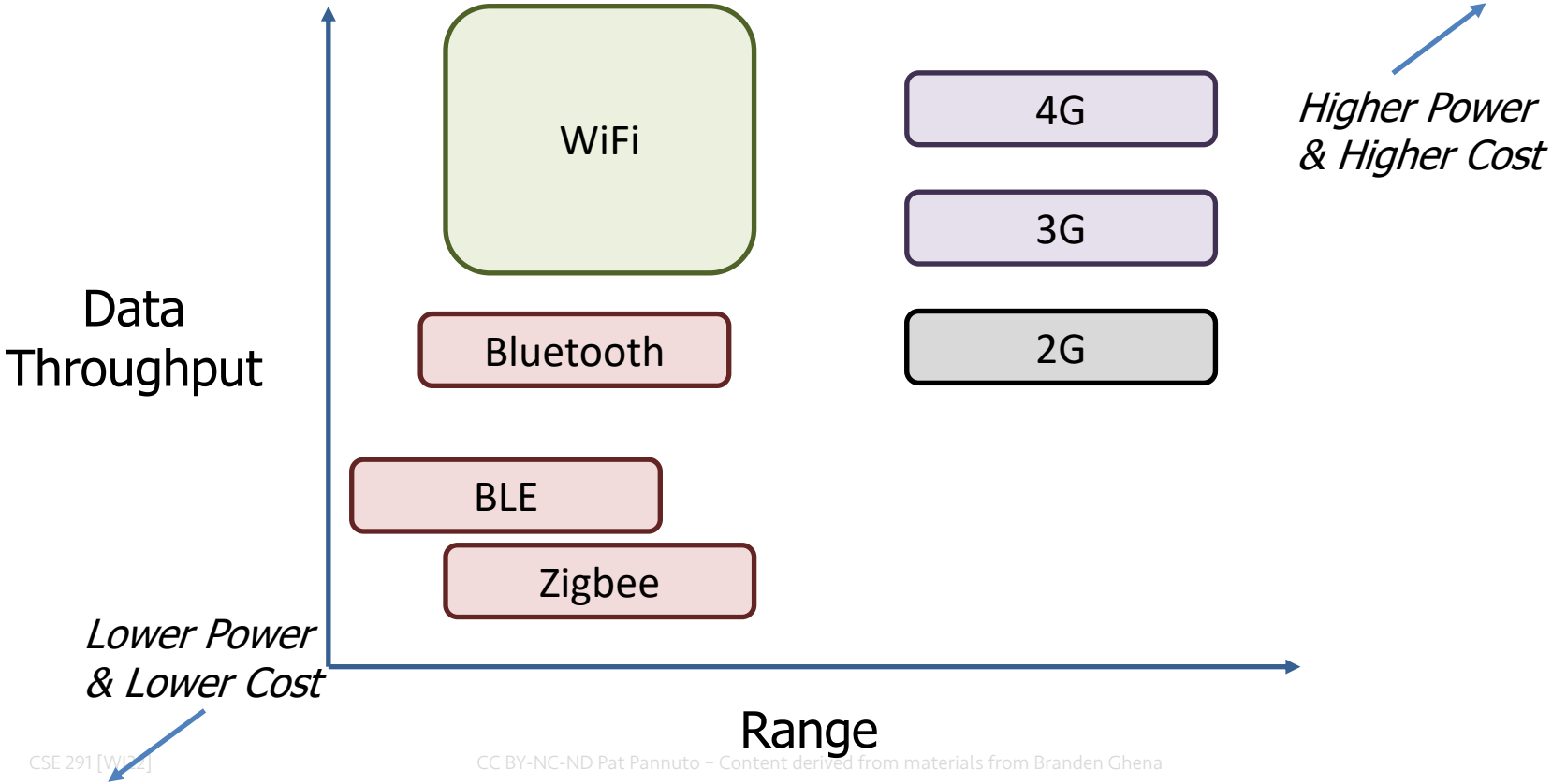

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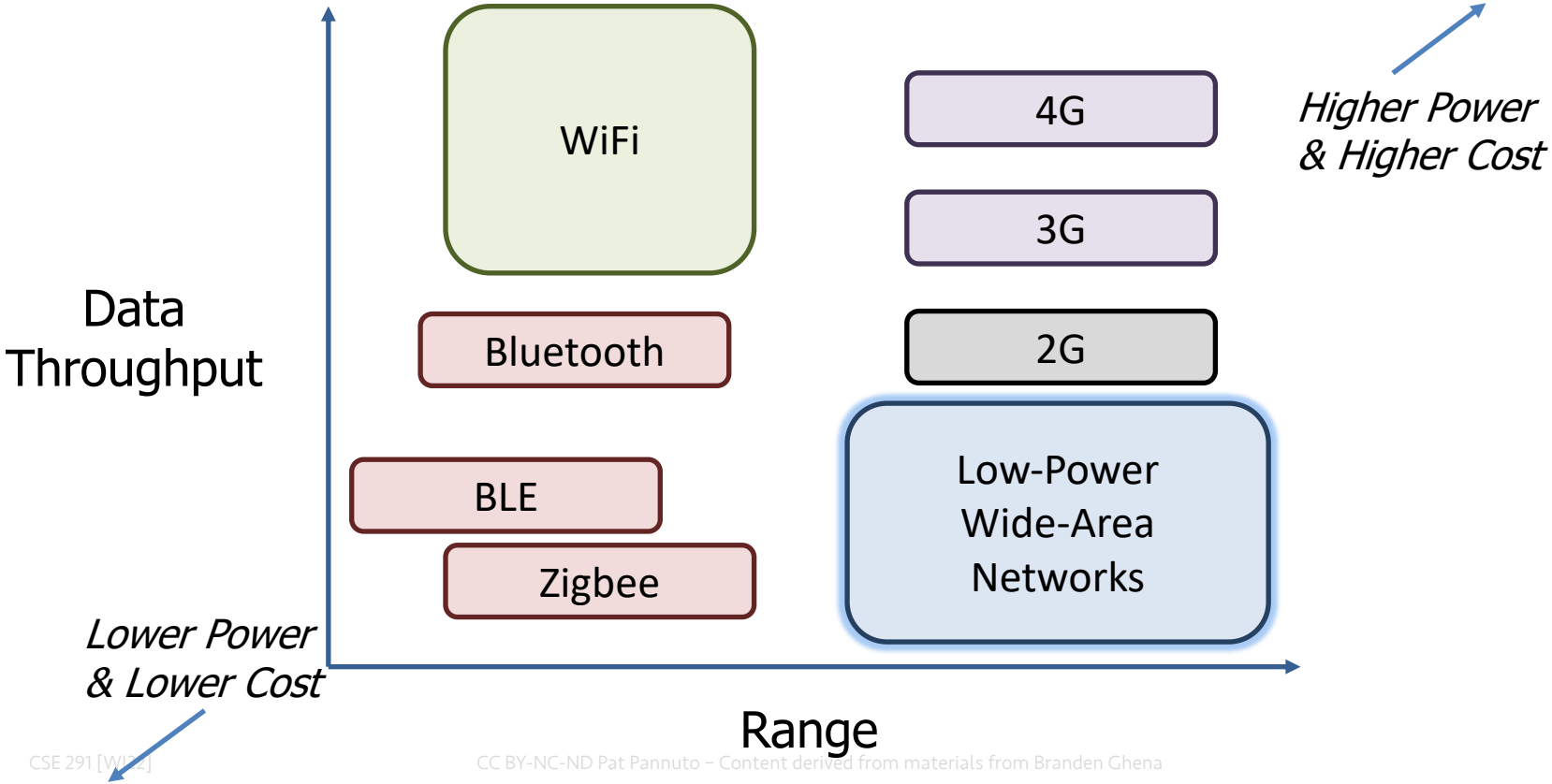

LTE-M and NB-IoT design constrained by fitting within existing cellular ecosystem

- 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

Next Week: Non-Cellular LPWANs [LoRa, Sigfoxx, etc]

Friday's "Lab": Specs aren't scary!

- Plan A: Empirical measurements of power
- Plan B: …
- Plan C: Datasheet & specification measurements of power, lifetime
  - Yes, the C is for Plan "C"OVID
  - Continues theme of last week, "so you are building a device…"