WIRELESS COMMUNICATION SYSTEMS-LECTURE 1

AARHUS
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DEPARTMENT OF ELECTRICAL AND COMPUTER ENGINEERING

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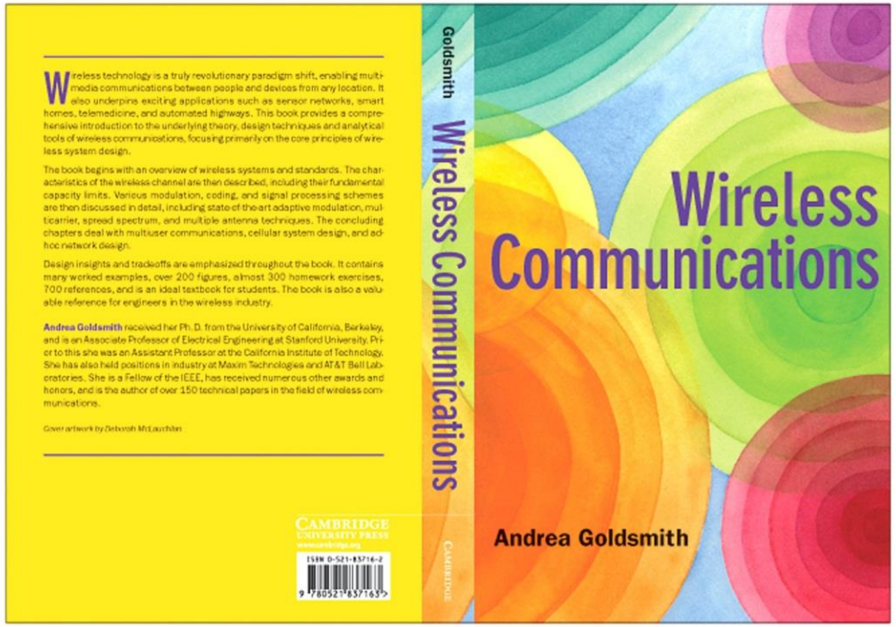
MATERIALS

- Andrea Goldsmith, Wireless Communications, 2nd Edition, Cambridge University Press., ISBN:9780511841224



- Notes from lectures

COURSE OBJECTIVES

Wireless communication systems support a wide range of applications, ranging from conventional voice call, messaging, multimedia services in smartphone, to emerging virtual reality (VR), autonomous driving, drones, and medical implants. Wireless communication systems play a crucial role in digitalization. This course introduces **founding principles, architecture, protocols, and algorithms** behind the next generation wireless systems designed to tackle the growing demand. Topics include state of the art wireless **PHY layer concepts, MAC layer protocols, existing wireless standards**, etc. Overall, the course would teach basic wireless communication and **theoretical concepts** necessary to **critically analyze modern wireless systems** such as WiFi, BLE (Bluetooth Low Energy), 4G LTE (Long Term Evolution) and 5G NR (New Radio). A **mini-project** would be designed to help develop hands-on skills in wireless system design.

LEARNING OUTCOMES

- **Develop** the concept of **systems thinking** in the context of wireless systems
- **Describe** the **interplay of concepts** and multiple sub-disciplines in wireless systems
- **Evaluate performance** of different systems through simulations
- **Compare different systems** under specific environments and distinguish the design ideas behind the differences

EXAMINATION & EVALUATION

- Require hand-in of Programming Exercises
- Quizzes
- Individual written examination (3 hours)
- Mini-Project
- Grade – an overall grade by use of 7-scale
  - Internal censor
- Dates : To be announced

MAIN CONTENT-THEORY

- Overview of Wireless Communications
- Path Loss, Shadowing, and Fading Models
- Capacity of Wireless Channels
- Digital Modulation and its Performance
- Adaptive Modulation
- Diversity
- MIMO Systems
- Multicarrier Systems: OFDM and other waveforms
- Multiuser and Cellular Systems

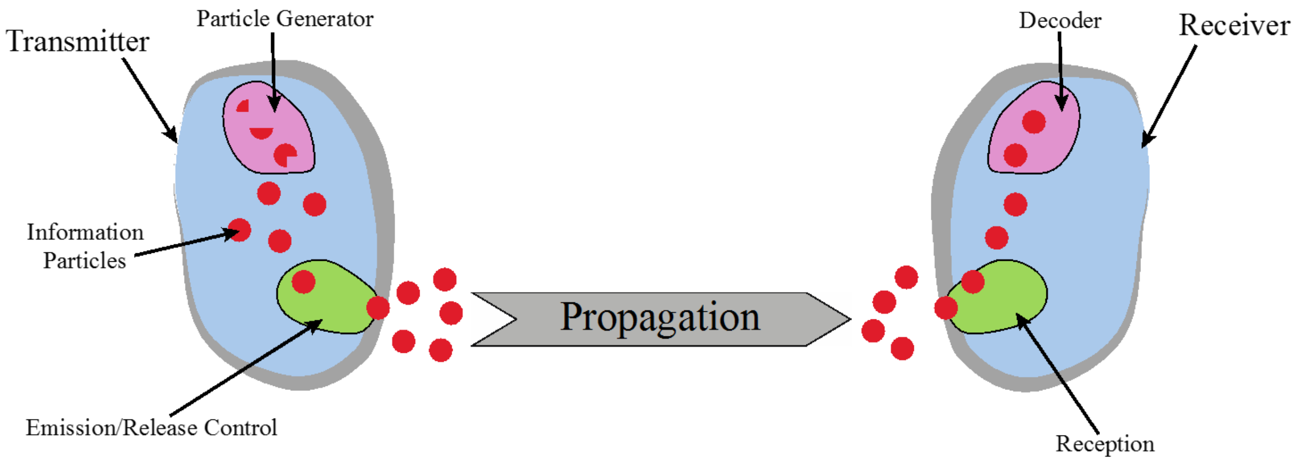
MAIN CONTENT-SYSTEMS

- WIFI Systems (WLAN)
- Cellular Systems (1G-5G)
- Satellite Communication
- Underwater Communication
- Beyond 5G/6G researches
  - Reconfigurable Intelligent Surface
  - Semantic Communications

HIGH LEVEL GOALS

- As engineers we aim for an :
- increase in the bit rate as much as possible
- increase in the spectral efficiency (bits/s/Hz) as much as possible
- increase in the power efficiency as much as possible
- minimize in the cost/power implementation

WIRELESS COMMUNICATION SYSTEMS?

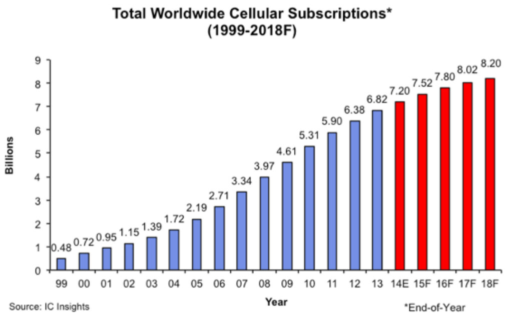


WIRELESS HISTORY

- Ancient Systems: Smoke Signals, Carrier Pigeons, …

Radio invented in the 1880s by Marconi

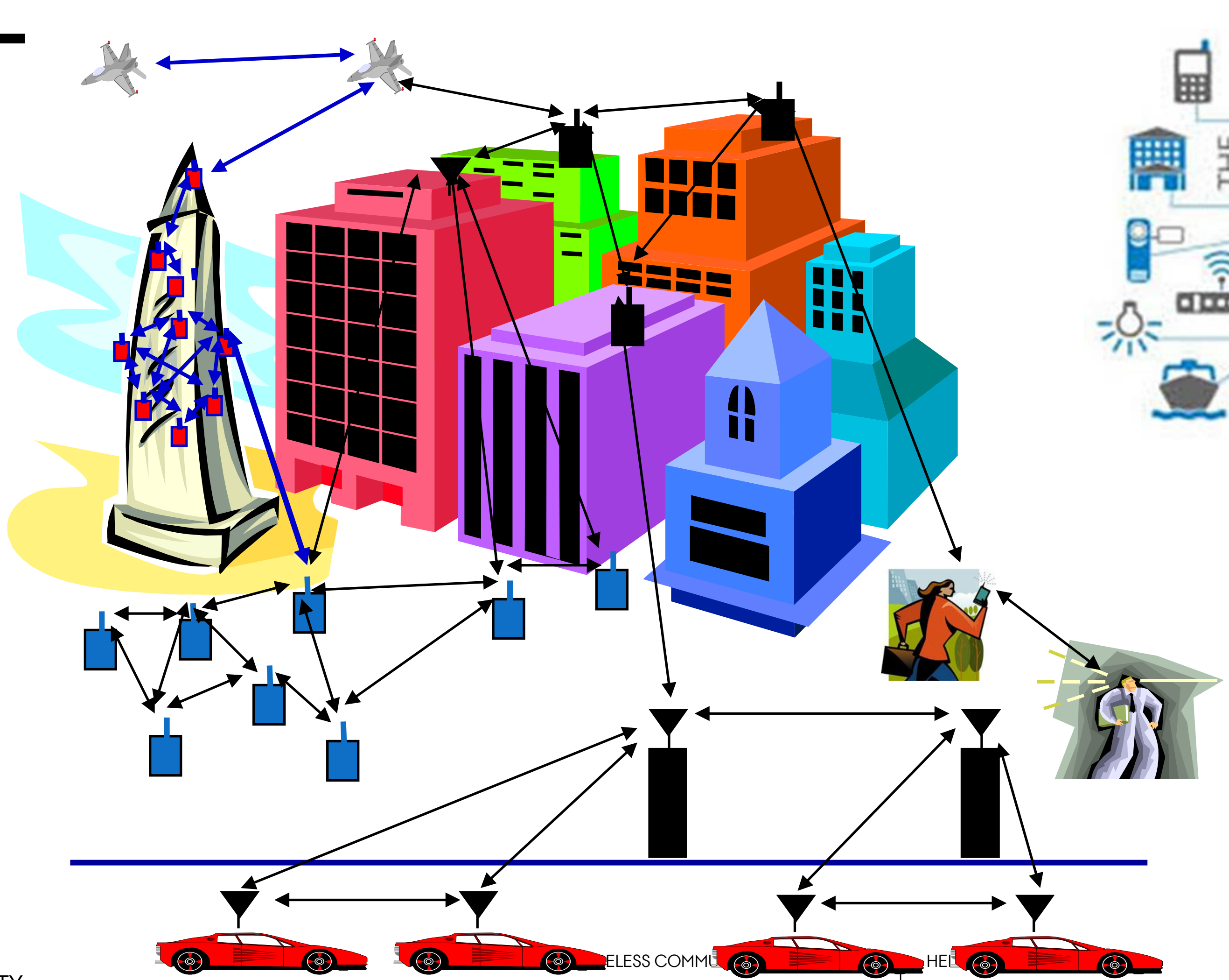
- Many sophisticated military radio systems were developed during and after WW2
- Exponential growth in cellular use since 1988: approx. 8B worldwide users today
  - Ignited the wireless revolution
  - Voice, data, and multimedia ubiquitous
  - Use in 3rd world countries growing rapidly



- WIFI also enjoying tremendous success and growth
- Bluetooth pervasive, satellites also widespread

FUTURE WIRELESS NETWORKS

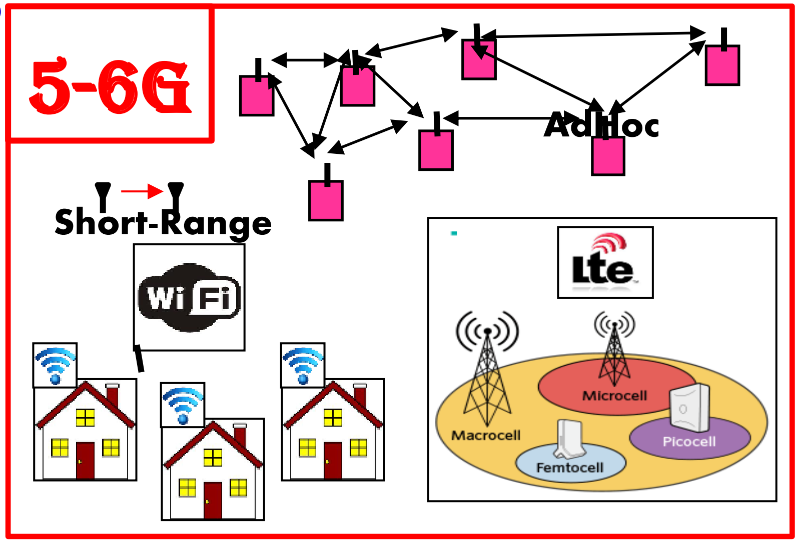
Ubiquitous Communication Among People and Devices



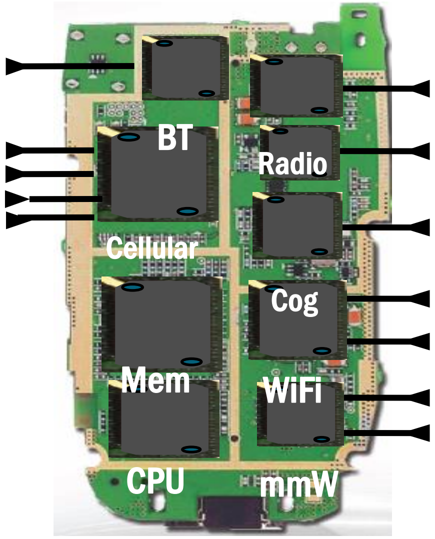
- Next-Gen Cellular/WiFi
- Smart Homes/Spaces
- Autonomous Cars
- Smart Cities
- Body-Area Networks
- Internet of Things
- All this and more …

CHALLENGES

- **Network/Radio Challenges**
  - Gbps data rates with “no” errors
  - Energy efficiency
  - Scarce/bifurcated spectrum
  - Reliability and coverage
  - Heterogeneous networks
  - Seamless internetwork handoff

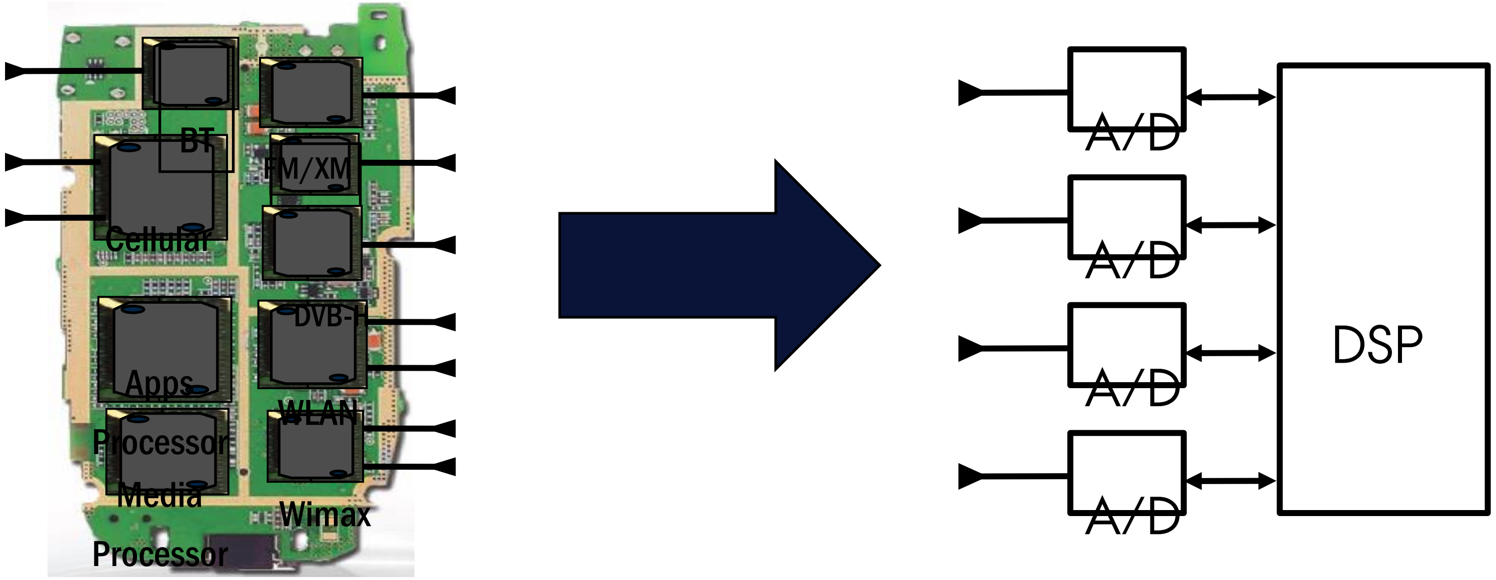


- **Device/SoC Challenges**
  - Performance
  - Complexity
  - Size, Power, Cost, Energy
  - High frequencies/mmWave
  - Multiple Antennas
  - Multiradio Integration
  - Coexistance



SOFTWARE-DEFINED (SD) RADIO:

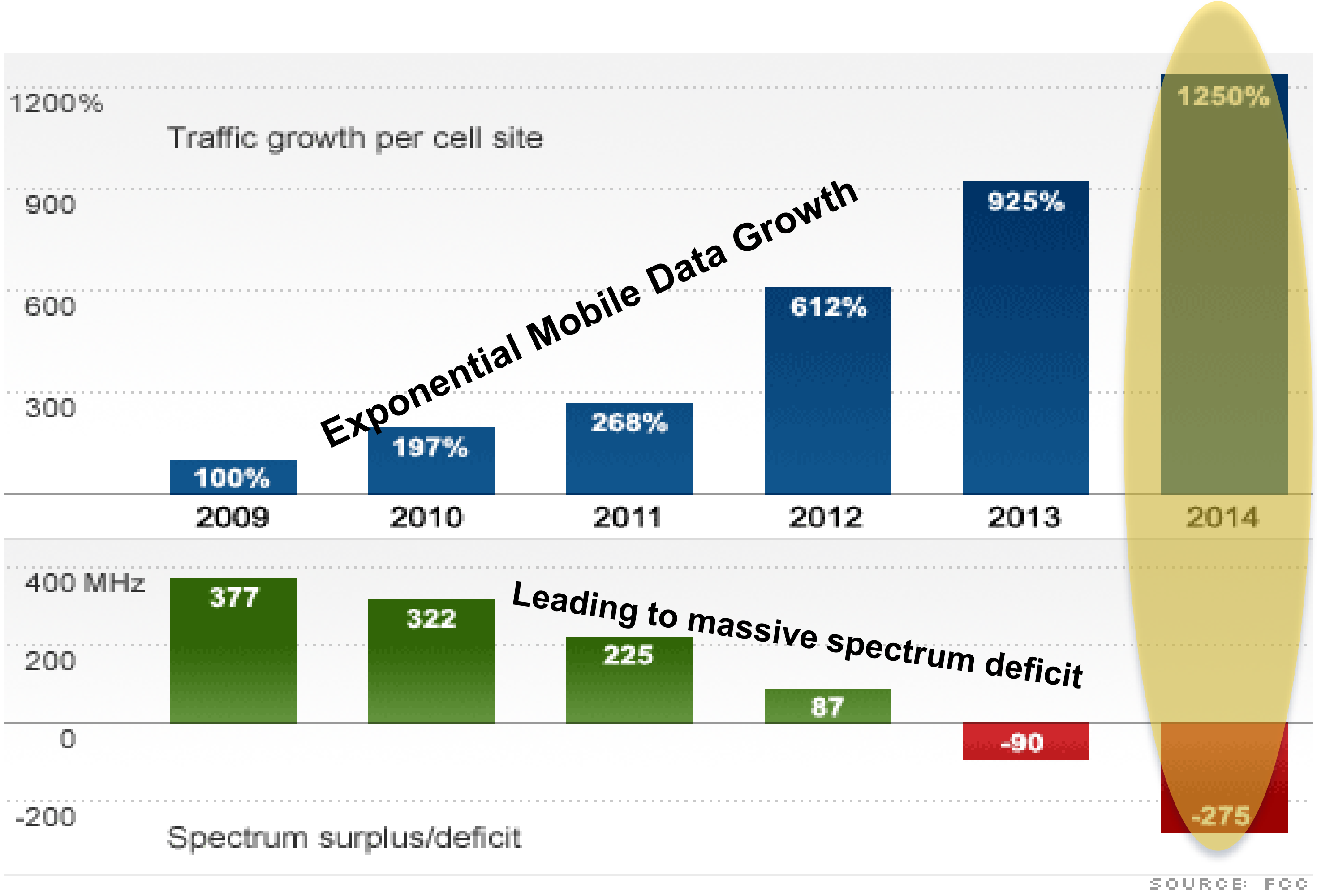
Is this the solution to the device challenges?



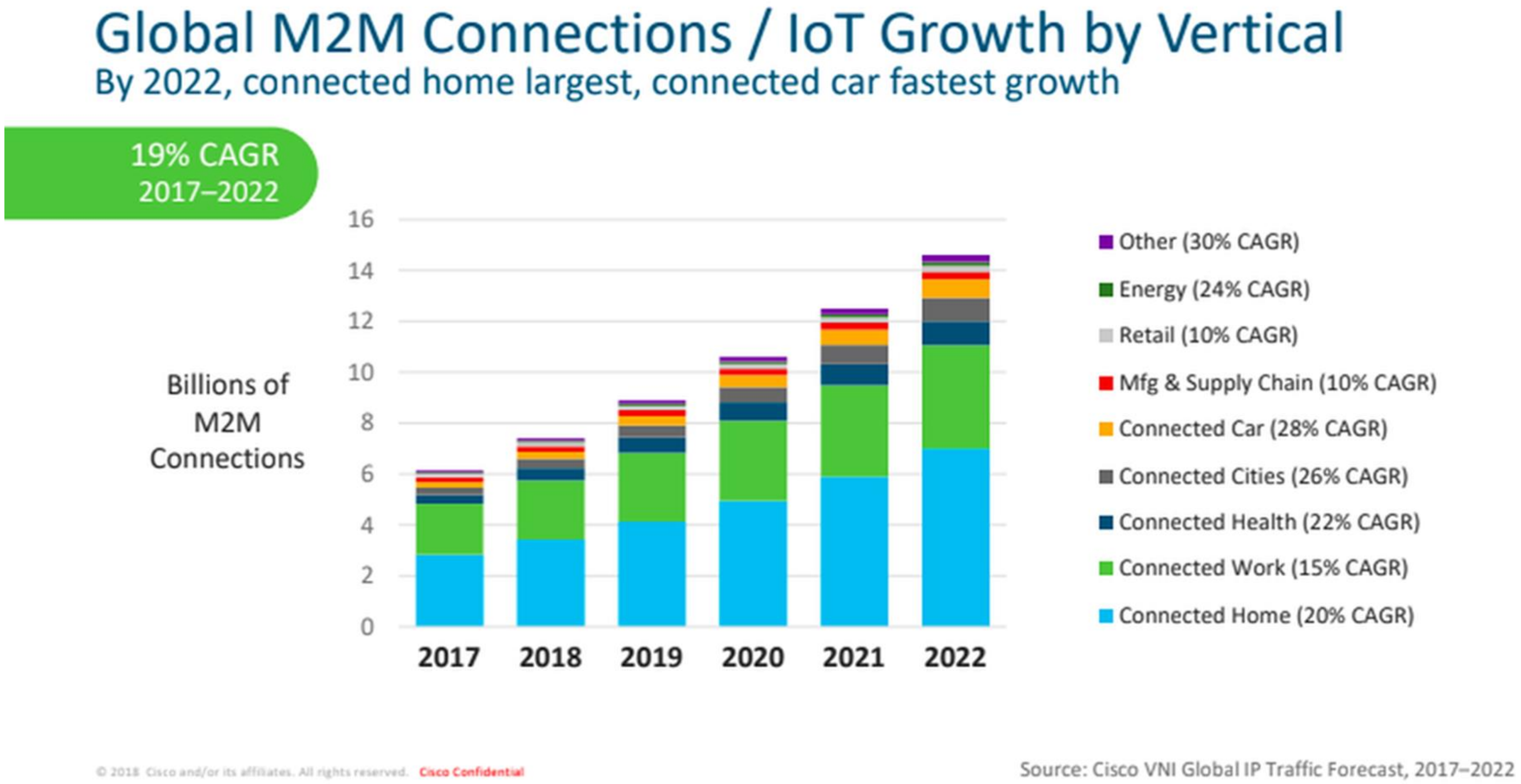
- Wideband antennas and A/Ds span BW of desired signals
- DSP programmed to process desired signal: no specialized HW

Today, this is not cost, size, or power efficient

AIRWAVES ARE FULL



THE INTERNET OF THINGS



What is the Internet of Things:

Enc
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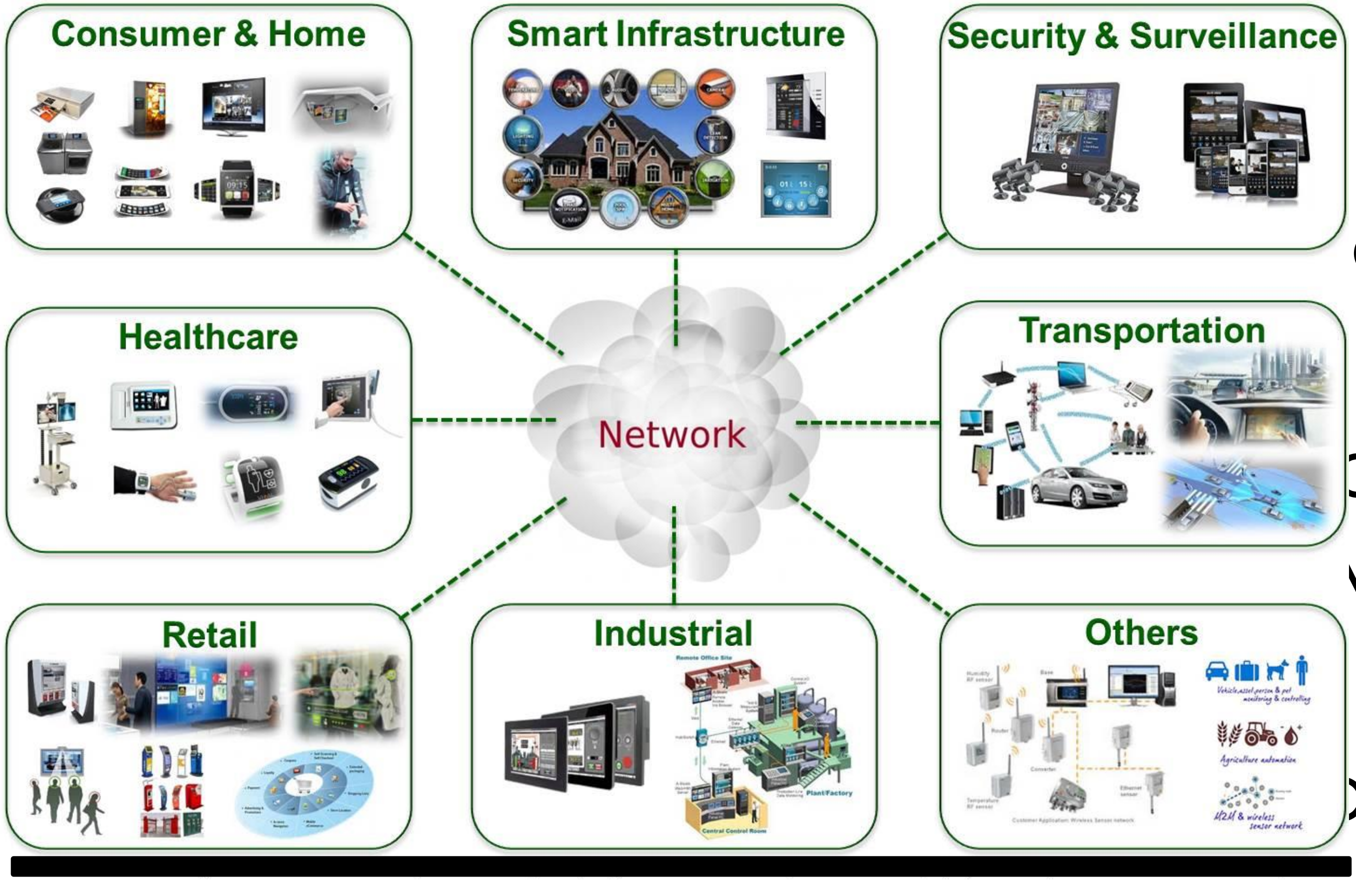


Different requirements than smartphones: low rates/energy consumption

Are we at the Shannon limit of the Physical Layer?

We are at the Shannon Limit

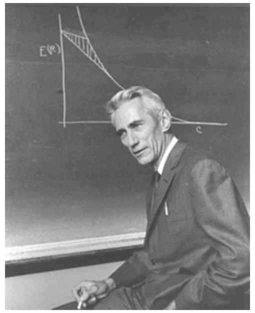
- "The wireless industry has reached the theoretical limit of how fast networks can go" *K. Fitcher, Connected Planet*
- "We're 99% of the way" to the "barrier known as Shannon's limit," *D. Warren, GSM Association Sr. Dir. of Tech.*

Shannon was wrong, there is no limit

- "There is no theoretical maximum to the amount of data that can be carried by a radio channel" *M. Gass, 802.11 Wireless Networks: The Definitive Guide*

WHAT WOULD SHANNON SAY?

We don’t know the Shannon capacity of most wireless channels



- Time-varying channels.
- Channels with interference or relays.
- Cellular systems
- Ad-hoc and sensor networks
- Channels with delay/energy/$$$ constraints.

Shannon theory provides design insights and system performance upper bounds

CURRENT/NEXT-GEN WIRELESS SYSTEMS

Current:

- 4G Cellular Systems (LTE-Advanced)
- 6G Wireless LANs/WiFi (802.11ax)
- mmWave massive MIMO systems
- Satellite Systems
- Bluetooth
- Zigbee
- WiGig

Emerging

- 5G Cellular and 7G WiFi Systems
- Ad/hoc and Cognitive Radio Networks
- Energy-Harvesting Systems
- Chemical/Molecular

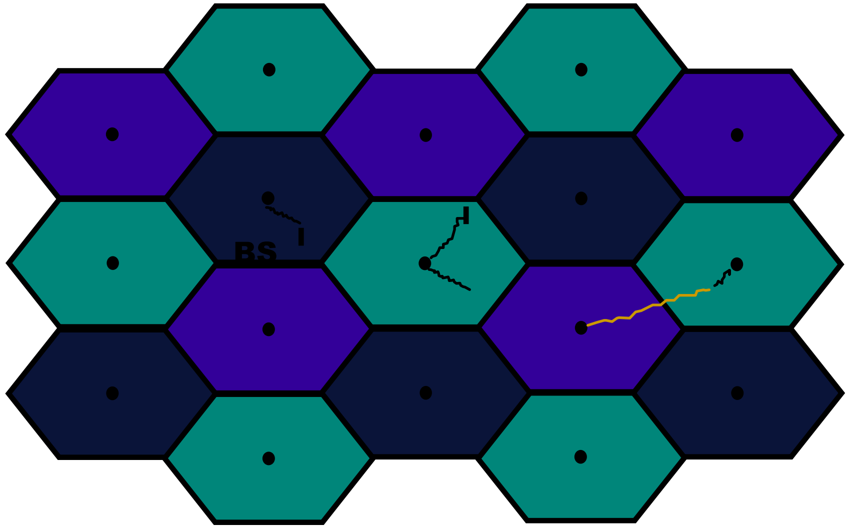
Much room For innovation

Time for a Break

SPECTRAL REUSE

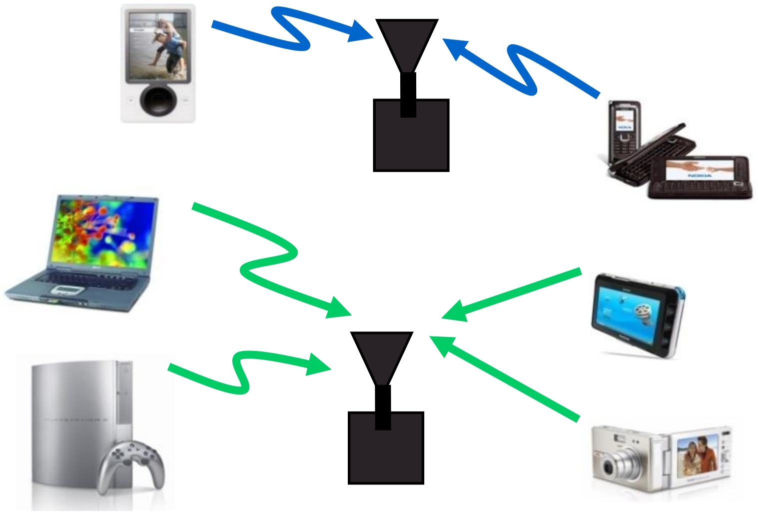
— Due to its scarcity, spectrum is *reused*

In licensed bands



Cellular

and unlicensed bands



WiFi, BT, UWB,...

Reuse introduces interference

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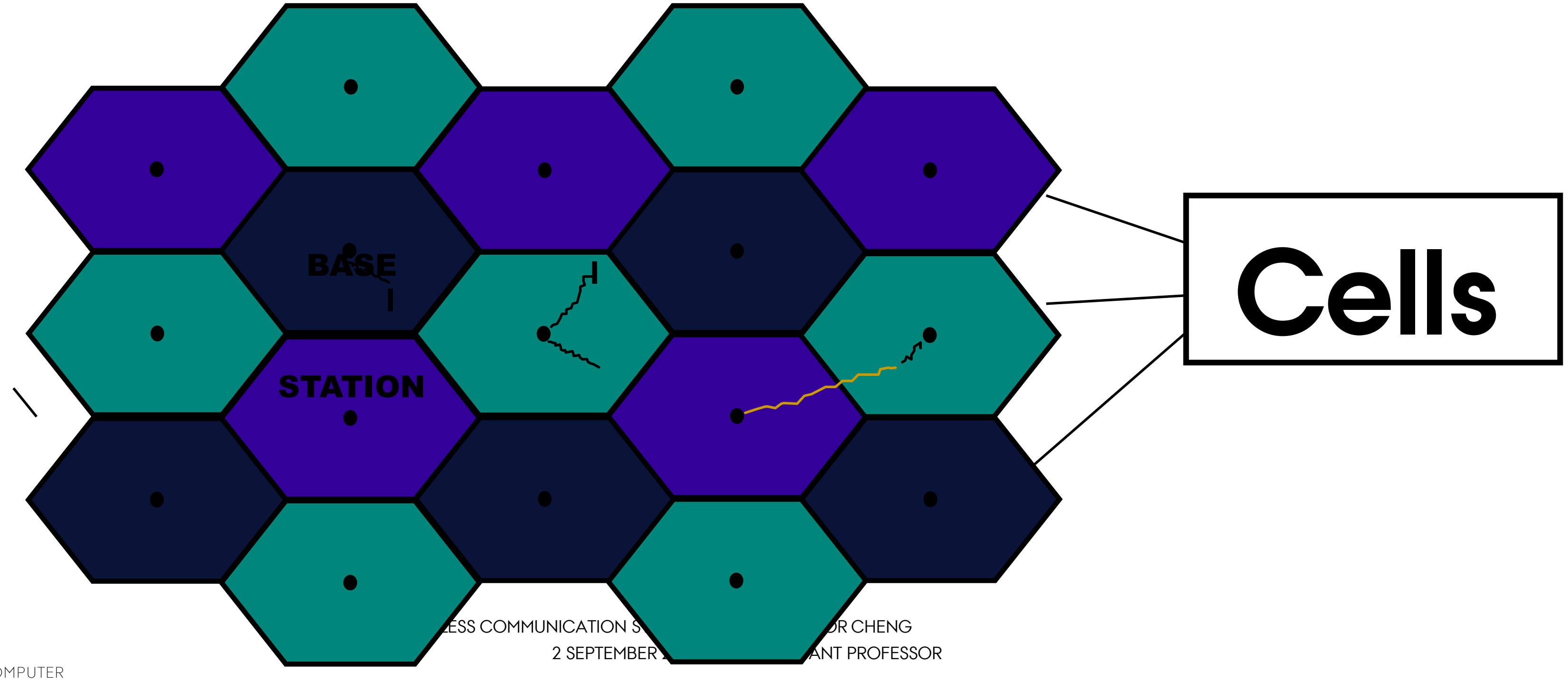
CELLULAR SYSTEMS:
REUSE CHANNELS TO MAXIMIZE CAPACITY

Geographic region divided into cells
Freq./timeslots/codes/space reused in different cells (reuse 1 common).
Interference between cells using same channel: interference mitigation key
Base stations coordinate handoff and control functions
Shrinking cell size increases capacity, as well as complexity, handoff, …



4G/LTE CELLULAR

Much higher data rates than 3G (50-100 Mbps)

- 3G systems has 384 Kbps peak rates

Greater spectral efficiency (bits/s/Hz)

- More bandwidth, adaptive OFDM-MIMO, reduced interference

Flexible use of up to 100 MHz of spectrum

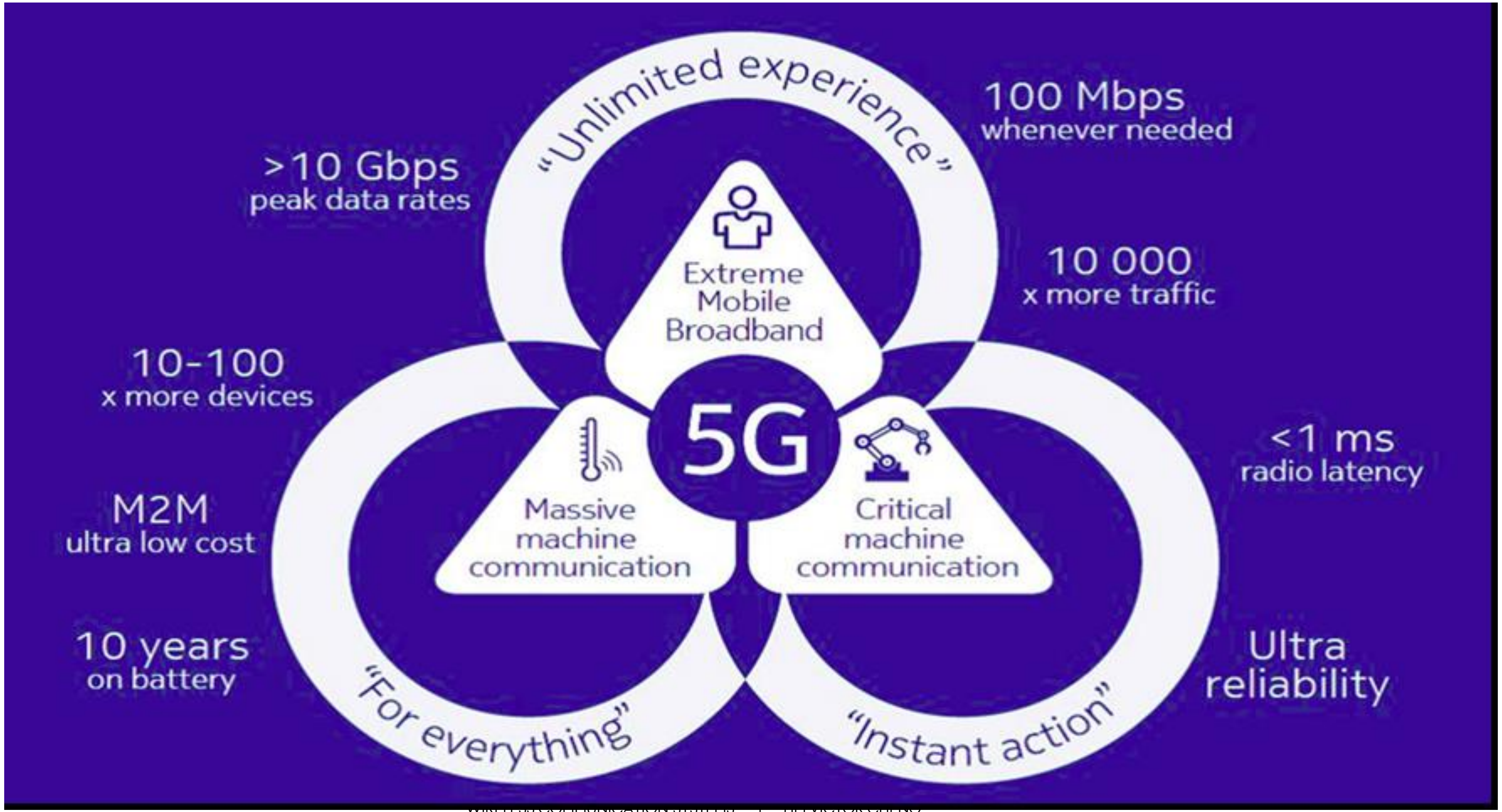
- 10-20 MHz spectrum allocation common

Low packet latency (<5ms).

Reduced cost-per-bit (not clear to customers)

All IP network

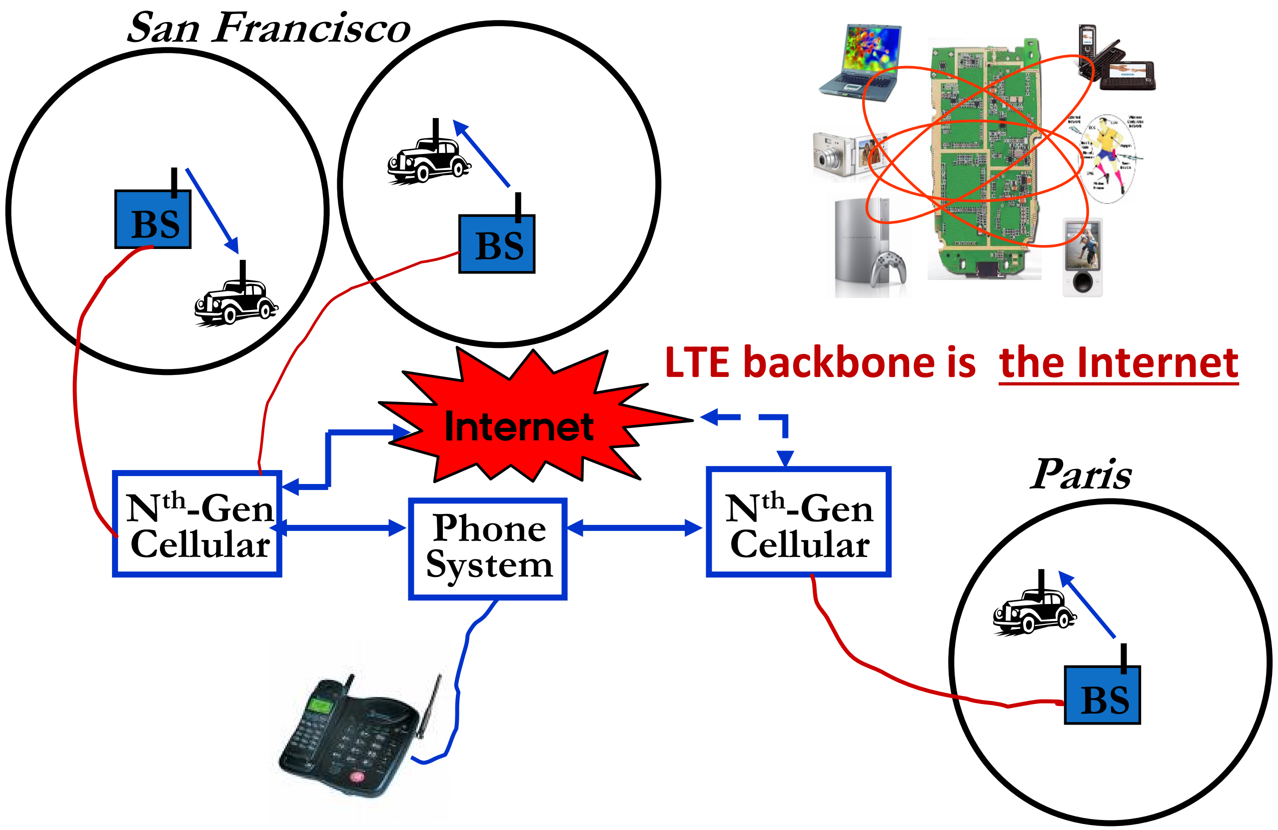
5G UPGRADES FROM 4G



FUTURE CELLULAR PHONES

Burden for this performance is on the backbone network

Everything wireless in one device



LTE backbone is the Internet

Much better performance and reliability than today

- *Gbps rates, low latency, 99% coverage, energy efficiency*

WIFI NETWORKS *MULTIMEDIA EVERYWHERE, WITHOUT WIRES*

Streaming Video
- Gbps data rates
- High reliability
- Coverage inside and out

Wireless HDTV and Gaming

WIRELESS LAN STANDARDS

802.11b (Old – 1990s)

- Standard for 2.4GHz ISM band (80 MHz)
- Direct sequence spread spectrum (DSSS)
- Speeds of 11 Mbps, approx. 500 ft range

802.11a/g (Middle Age– mid-late 1990s)

- Standard for 5GHz band (300 MHz)/also 2.4GHz
- OFDM in 20 MHz with adaptive rate/codes
- Speeds of 54 Mbps, approx. 100-200 ft range

802.11n/ac/ax or Wi-Fi 6 (current gen)

- Standard in 2.4 GHz and 5 GHz band
- Adaptive OFDM /MIMO in 20/40/80/160 MHz
- Antennas: 2-4, up to 8
- Speeds up to 1 Gbps (10 Gbps for ax), approx. 200 ft range
- Other advances in packetization, antenna use, multiuser MIMO

Many WLAN cards have many generations

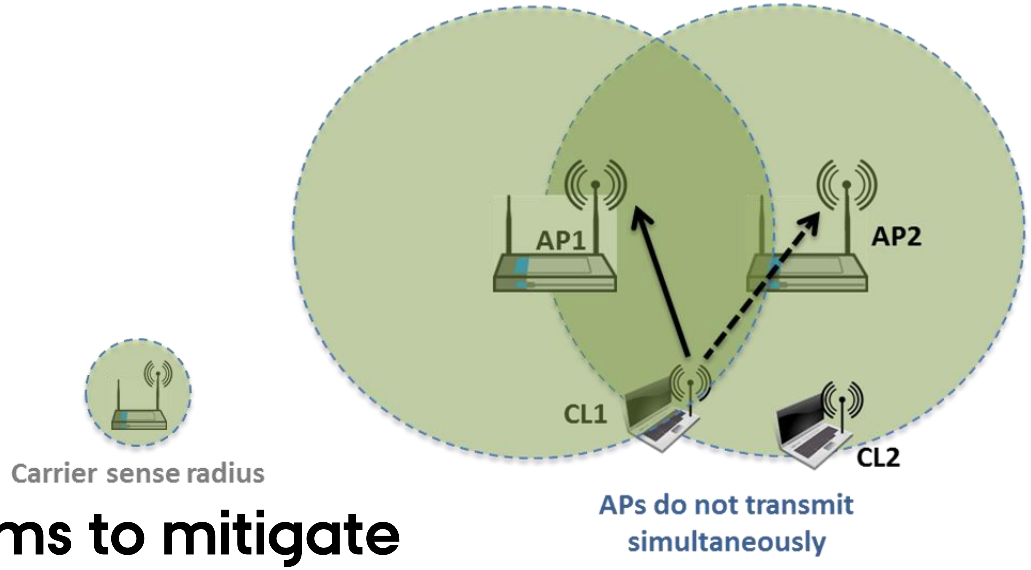
WHY DOES WIFI PERFORMANCE SUCK?

Carrier Sense Multiple Access:

if another WiFi signal

detected, random backoff

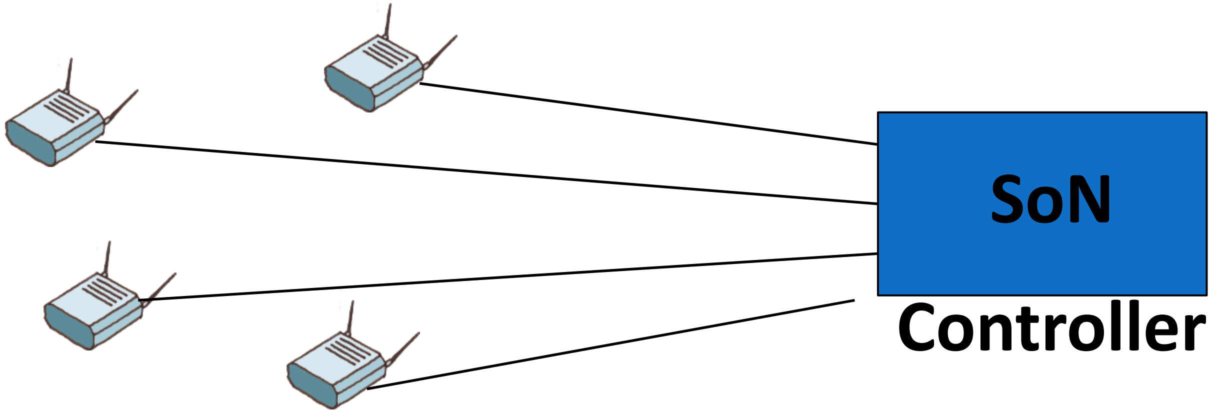
Collision Detection: if collision detected, resend



The WiFi standard lacks good mechanisms to mitigate interference, especially in dense AP deployments

- Multiple access protocol (CSMA/CD) from 1970s
- **Static channel assignment, power levels, and sensing thresholds**
- **In such deployments WiFi systems exhibit poor spectrum reuse and significant contention among APs and clients**
  - **Result is low throughput and a poor user experience**
- Multiuser MIMO will help each AP, but not interfering APs

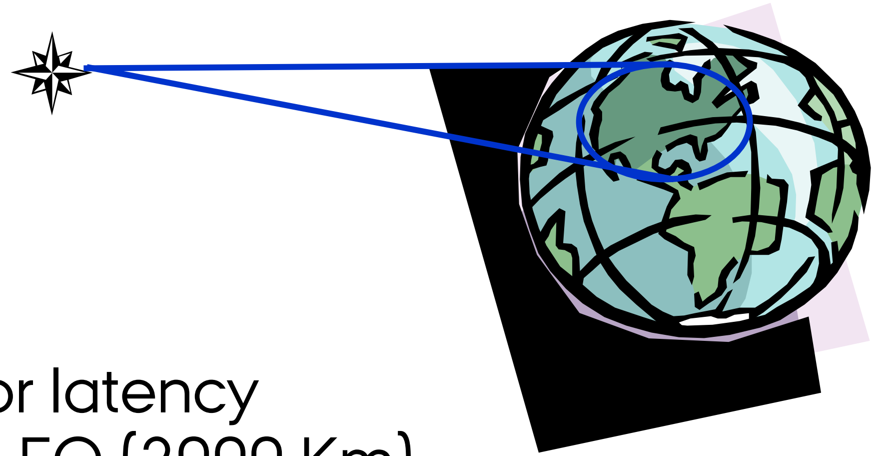
SELF-ORGANIZING NETWORKS FOR WIFI



- Channel Selection
- Power Control
- etc.

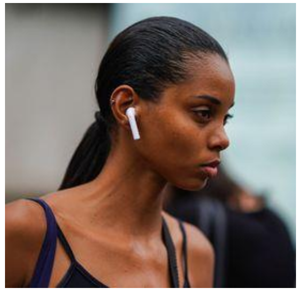
- SoN-for-WiFi: dynamic self-organization network software to manage of WiFi APs.
- Allows for capacity/coverage/interference mitigation tradeoffs.
- Also provides network analytics and planning.

SATELLITE SYSTEMS



- Cover very large areas
- Different orbit heights
  - Orbit height trades off coverage area for latency
  - GEO (39000 Km) vs MEO (9000 km) vs LEO (2000 Km)
- Optimized for one-way transmission
  - Radio (XM, Sirius) and movie (SatTV, DVB/S) broadcasts
  - Most two-way LEO systems went bankrupt in 1990s-2000s
  - LEOs have resurfaced with 4G to bridge digital divide
- Global Positioning System (GPS) ubiquitous
  - Satellite signals used to pinpoint location
  - Popular in cell phones, PDAs, and navigation devices

BLUET Bluetooth®



- Cable replacement RF technology (low cost)
- Short range (10m, extendable to 100m)
- 2.4 GHz band (crowded)
- 1 Data (700 Kbps) and 3 voice channels, up to 3 Mbps
- Widely supported by telecommunications, PC, and consumer electronics companies
- Few applications beyond cable replacement

IEEE 802.15.4/ZIGBEE RADIOS

Low-rate low-power low-cost secure radio

- Complementary to WiFi and Bluetooth

Frequency bands: 784, 868, 915 MHz, 2.4 GHz

Data rates: 20Kbps, 40Kbps, 250 Kbps

Range: 10-100m line-of-sight

Support for large mesh networking or star clusters

Support for low latency devices

CSMA-CA channel access

Applications: light switches, electricity meters, traffic management, and other low-power sensors.

SPECTRUM REGULATION

- Spectrum a scarce public resource, hence allocated
- Spectral allocation in US controlled by FCC (commercial) or OSM (defense)
- Auctions spectral blocks for set applications.
- Some spectrum set aside for universal use
- Worldwide spectrum controlled by ITU-R
- Regulation is a necessary evil.

Innovations in regulation being considered worldwide in multiple cognitive radio paradigms

STANDARDS

Interacting systems require standardization

Companies want their systems adopted as standard

- Alternatively try for de-facto standards

Standards determined by TIA/CTIA in US

- IEEE standards often adopted
- Process fraught with inefficiencies and conflicts

Worldwide standards determined by ITU-T

- In Europe, ETSI is equivalent of IEEE

EMERGING SYSTEMS

- New cellular system architectures
- mmWave/massive MIMO communications
- Software-defined network architectures
- Ad hoc/mesh wireless networks
- Cognitive radio networks
- Wireless sensor networks
- Applications of Communications in Health, Bio-medicine, and Neuroscience
- Many more…

MAIN POINTS

- The wireless vision encompasses many exciting applications
- Technical challenges transcend all system design layers
- 5G networks must support higher performance for some users, extreme energy efficiency and/or low latency for others
- Cloud-based software to dynamically control and optimize wireless networks needed (SDWN)
- Innovative wireless design needed for 5G cellular/WiFi, mmWave systems, massive MIMO, and IoT connectivity
- Standards and spectral allocation heavily impact the evolution of wireless technology

NEXT LECTURERE

- Main features of wireless communications (comparing with wired communications)
  - Fading
  - Muti-path
  - Mobility
  - Interference
- Path-loss Model (Chapter 2)

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