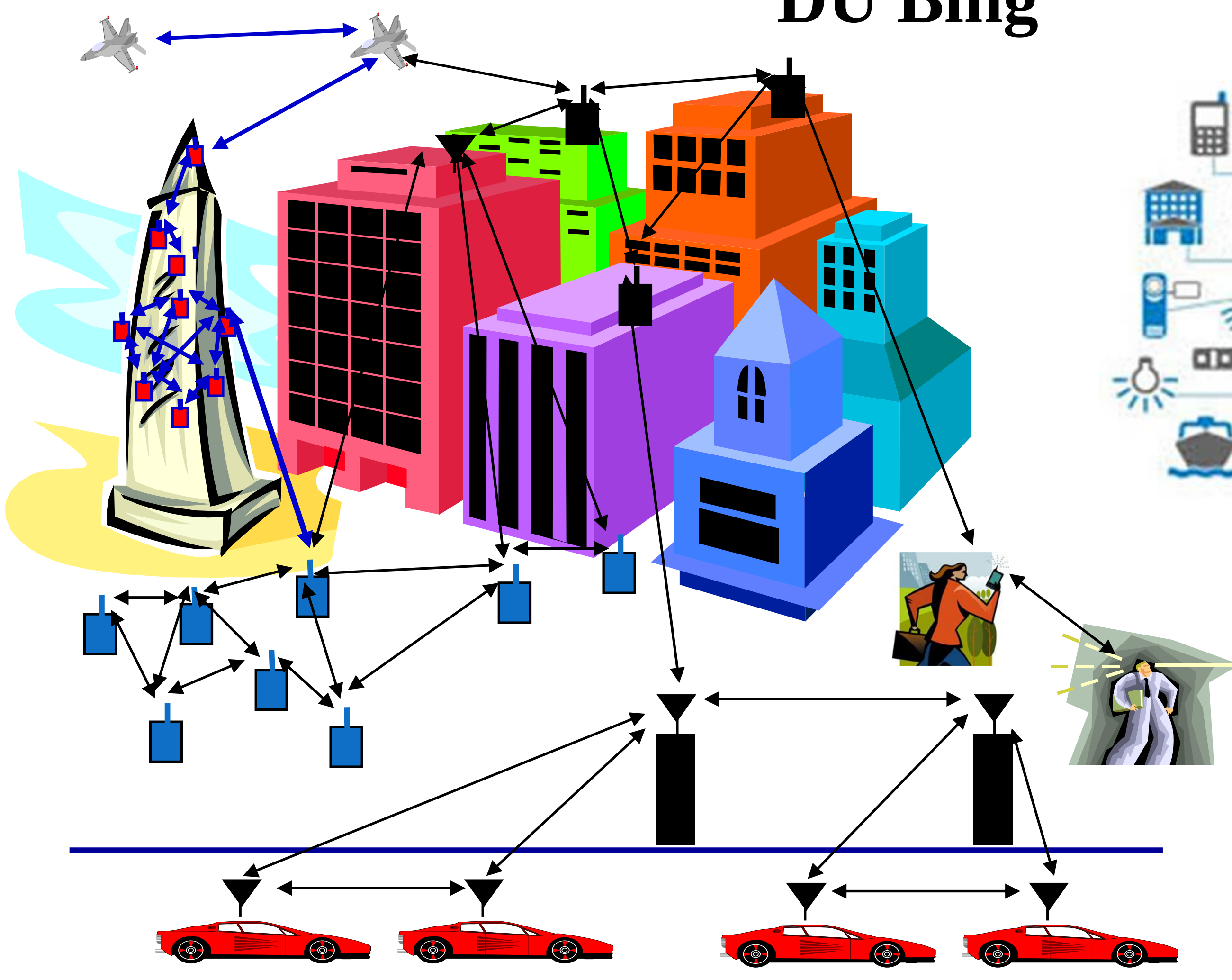
Wireless Communications

School of Computer and Communication Engineering

DU Bing



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

About me

- Beijing University of Aeronautics & Astronautics Bachelor & Ph.D.
  - School of Electronic Information Engineer
- 04/2010 – 06/2014 Tsinghua University Assistant professor & Postdoc
  - Department of Electronic Engineering
- 10/2015 – present University of Science & Technology Beijing Assistant professor
  - School of Computer and Communication Engineering
- 03/2017-04/2018 University of British Columbia UBC Canada Visiting Scholar
- Best Results: Moana (7)

Outline

- Course Basics
- Course Syllabus
- Wireless History
- The Wireless Vision
- Technical Challenges
- Current/Next-Gen Wireless Systems
- Spectrum Regulation and Standards
- Emerging Wireless Systems (Optional Lecture)

Course Information

- Instructor: Du Bing, dubing@ustb.edu.cn
- Office: Yifu Building 903.
- Homework 30% +presentation 40% +Final 30%
- Homework: Sample Problems will be given weekly.
- Closed Books: Most of the problems will be from the slides.
- Final
  - A project report: the project (for students electing to do a project) is a research project related to any topic in wireless
  - Or an open book exam

Course Information
Nuts and Bolts

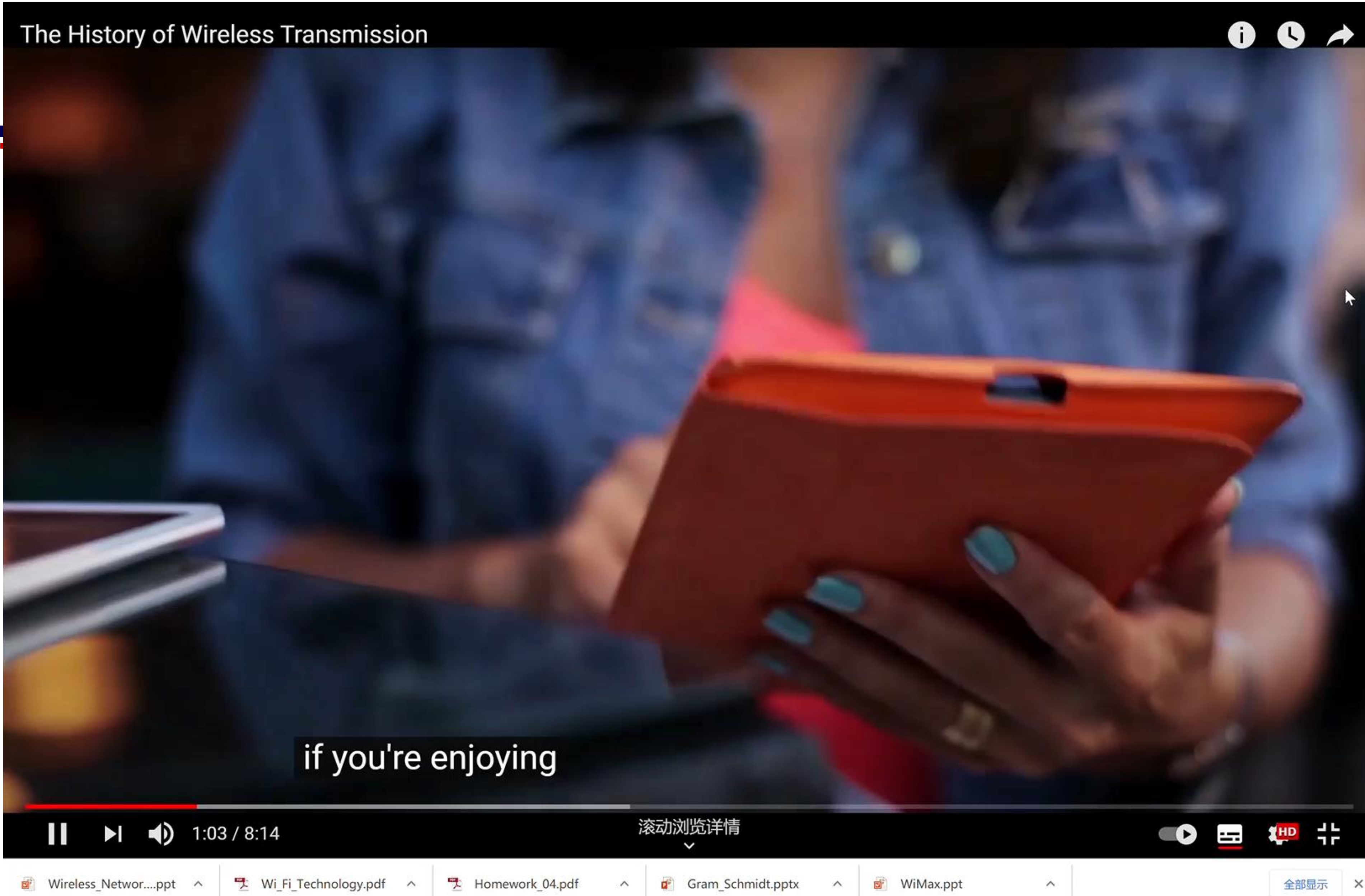
- **Prerequisites: Digital Communications**
- **Textbook: *Wireless Communications***
  - ***Available on piazza***
- **Class Homepage: piazza.com/ustb.edu.cn/spring2021/cs202**
- **Wechat group**

Course Syllabus

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

Tentative Detailed Syllabus

Lecture #	Date	Topic	Required Reading
		Introduction	
1	2/3	Overview of Wireless Communications	Chapter 1
Wireless Channel Models			
2-3	5/3, 9/3	Path Loss and Shadowing Models, Millimeter wave propagation	Chapter 2
4-5	12/3, 16/3	Statistical Fading Models, Narrowband Fading	Section 3.1-3.2.3
6	19/3	Wideband Fading Models	Section 3.3
Impact of Fading and ISI on Wireless Performance			
7	23/3	Capacity of Wireless Channels	Chapter 4
8,9,10	????	Digital Modulation and its Performance	Lec 8: Chapter 5 Lec 9-10: Chapter 6
Flat-Fading Countermeasures			
11	26/3	Diversity	Chapter 7
12-13	30/3-2/4	Adaptive Modulation	Chapter 9.1-9.3
14-15	6/4-9/4	Multiple Input/Output Systems (MIMO)	Chapter 10, Appendix C
ISI Countermeasures			
16-17	13/4,16/4	Multicarrier Systems, OFDM, and other multicarrier waveforms	Chapter 12
18-19	20/4-23/4	Multiuser and Cellular Systems	Topics in Chapters 13-15
Course Summary			
20	23/4	Course summary/final review	


The History of Wireless Transmission
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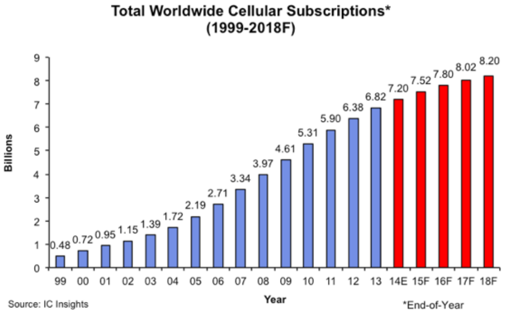
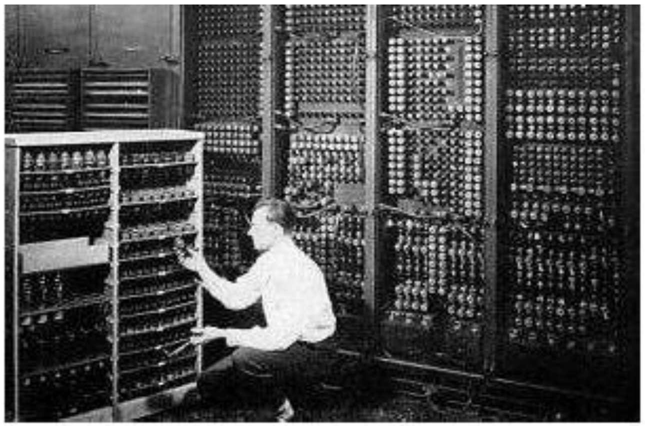
Wireless History

- 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

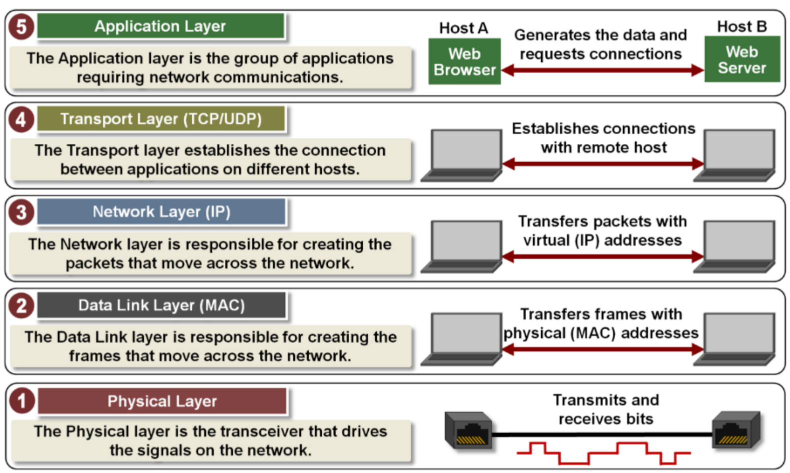


- Wifi also enjoying tremendous success and growth
- Bluetooth pervasive, satellites also widespread

Internet



The world's first electronic digital computer was officially put into operation at the University of Pennsylvania on February 15, 1946, and its name was ENIAC (ENIAC).



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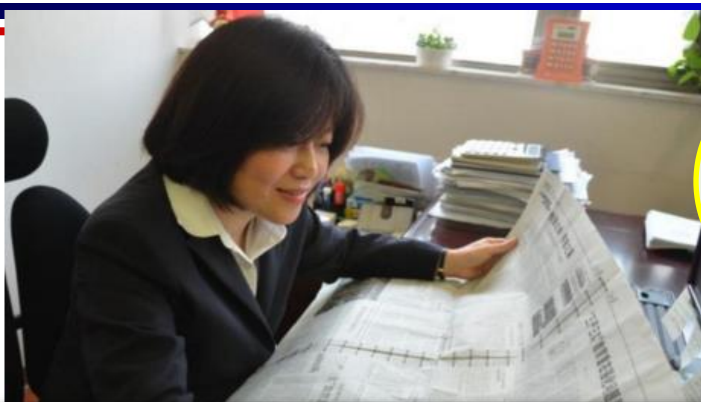
Different network environments, operating systems, and terminal devices emerged as required

The internet has changed our lives



Traditionally ,People get information through newspapers, books, TV, radio, etc.

In online life, people obtain information through search engines, news portals, etc.

Convenient

Search engines make the acquisition of information faster and more accurate;

Massive

Aggregate massive amounts of text, sound, and pictures to form a huge database

Community sharing

Break through the limitations of time and space, and realize information sharing between people.

The internet has changed our lives

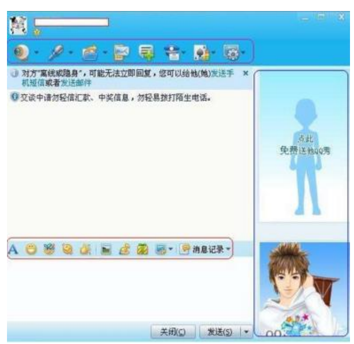
In traditional life, people communicate information through telephones, mobile phones, faxes, letters, etc.

Variety

Various communication methods such as instant messaging, emails, forums, blogs, etc.; through voice, video, text and other forms

Personality

Virtual spaces such as Weibo and Moments allow people to better demonstrate their individuality in communication



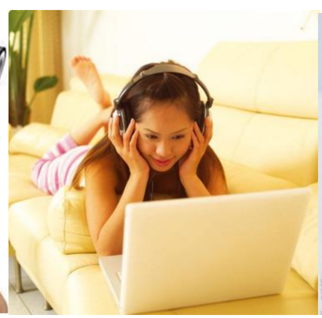
In online life, people communicate through e-mail, text, voice, video, etc.

The internet has changed our lives

In traditional life, people enjoy leisure and entertainment through TV, movies, outdoor sports, etc.

Rich life

Provide a full range of entertainment applications such as online games, movies, music, etc.



Interactive

It is easy to realize the participation and interaction of topics or time; collaborative sharing in the entertainment experience, reflecting participation;

In online life, people enjoy leisure and entertainment through rich channels such as online games, videos, and music

The internet has changed our lives

In traditional life, people pay by cash or bills

Economic

For sellers, saving store costs makes their operating costs cheaper; for buyers, they can conclude transactions at lower prices

Efficient

Improve transaction efficiency through IM, video, electronic banking and other means;

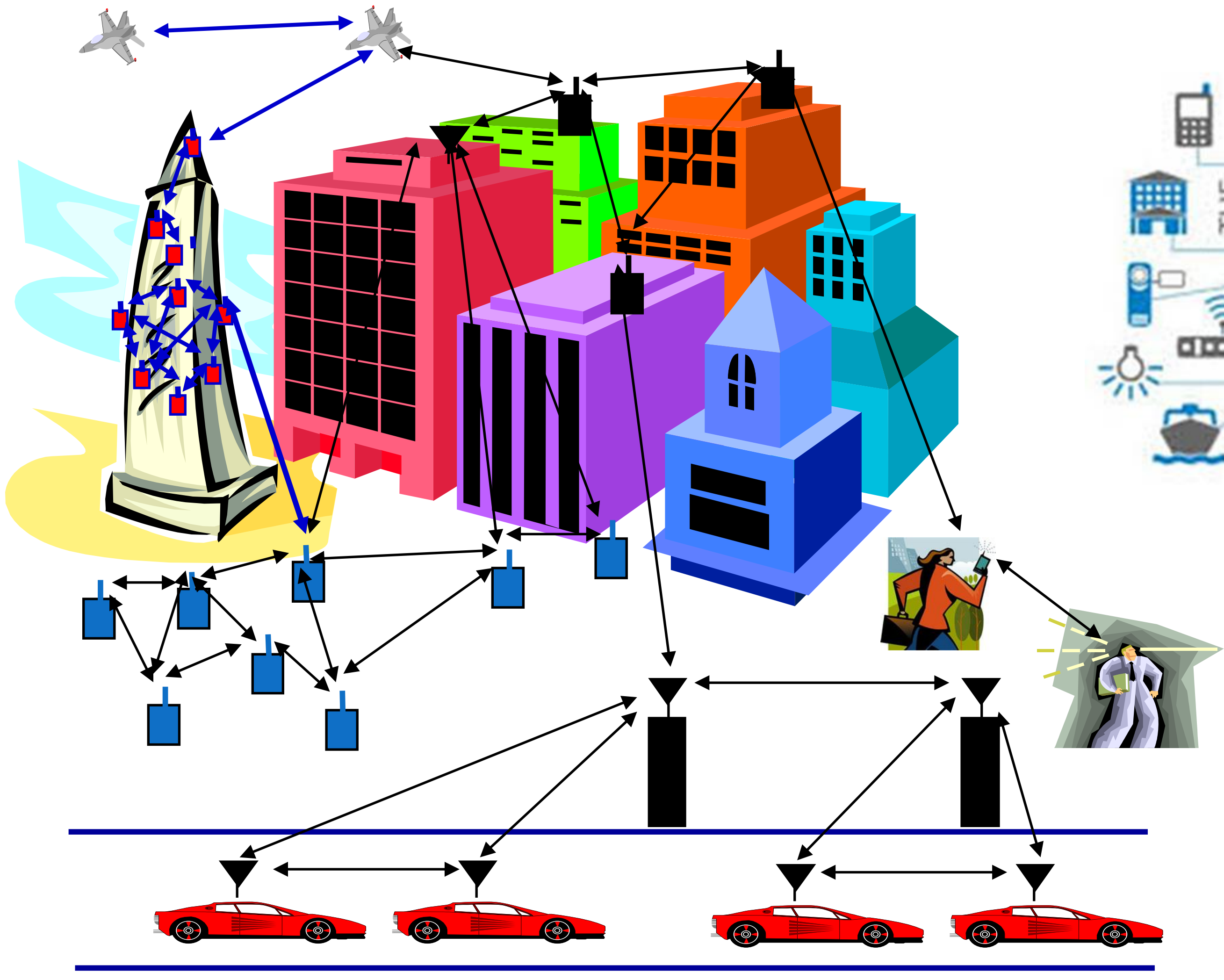
More options

Break through the limitations of space and realize remote transactions

In online life, people realize transactions through e-commerce platforms and electronic payment systems

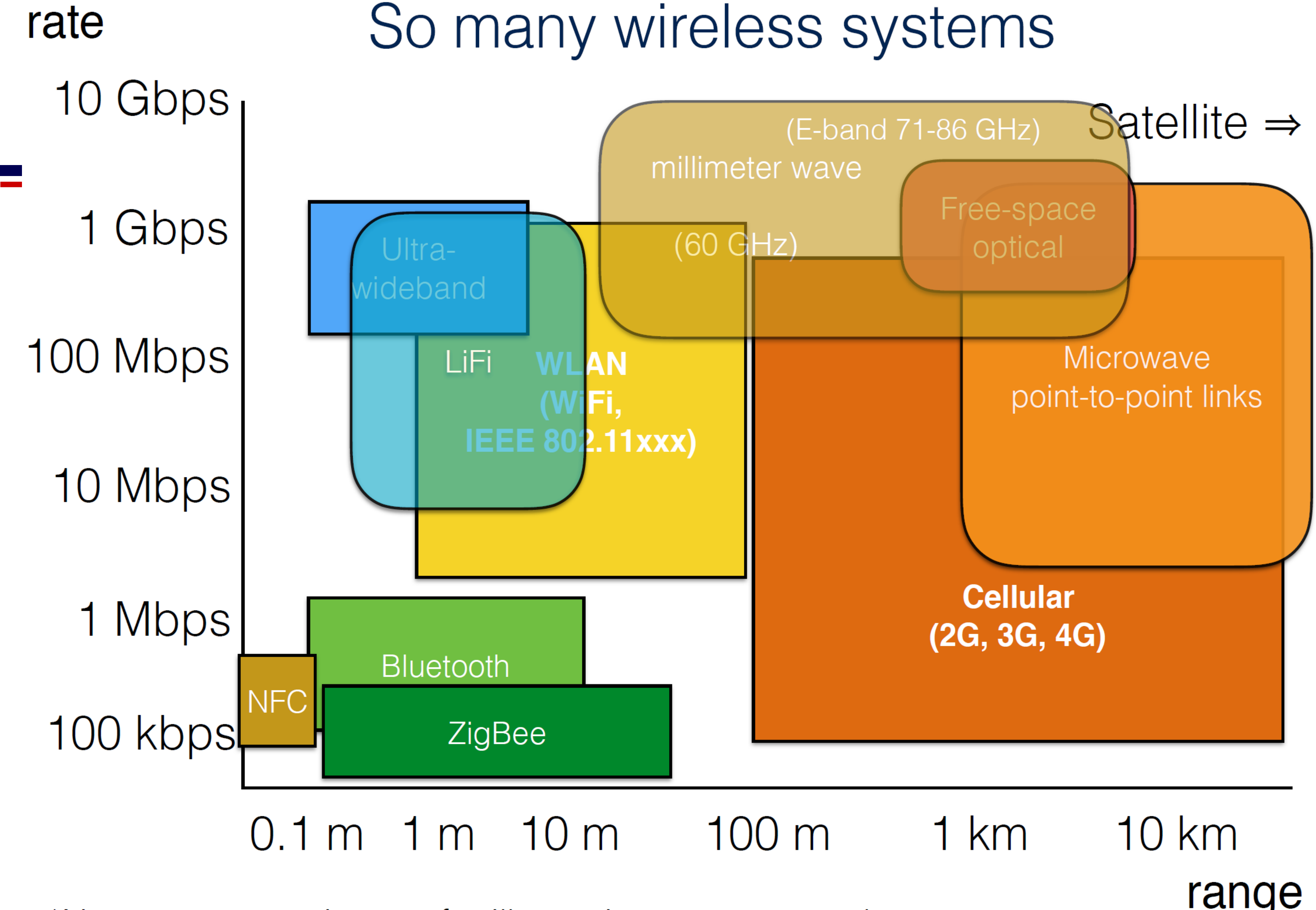
Future Wireless Networks

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 …

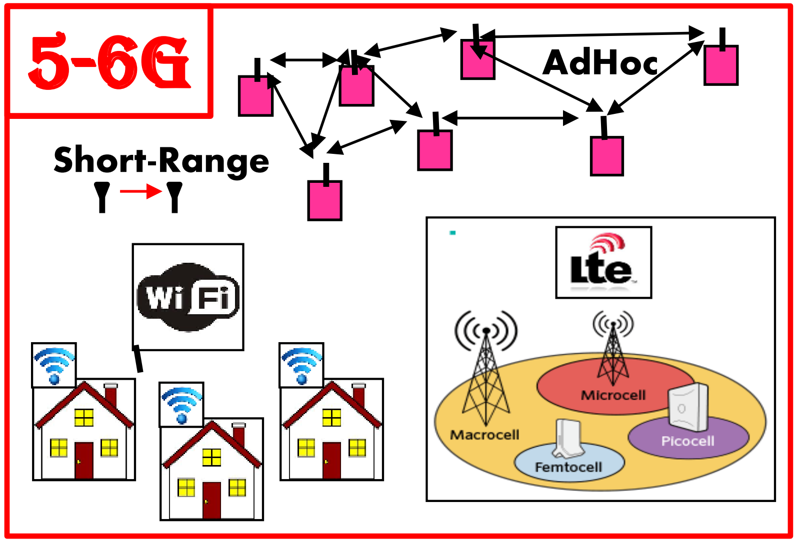
So many wireless systems



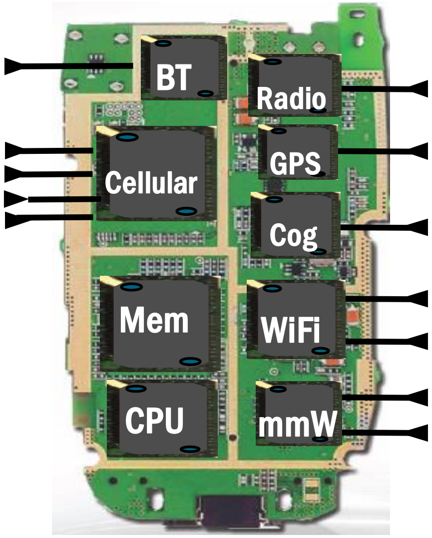
*Note: coarse estimates for illustration purposes only

Challenges

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

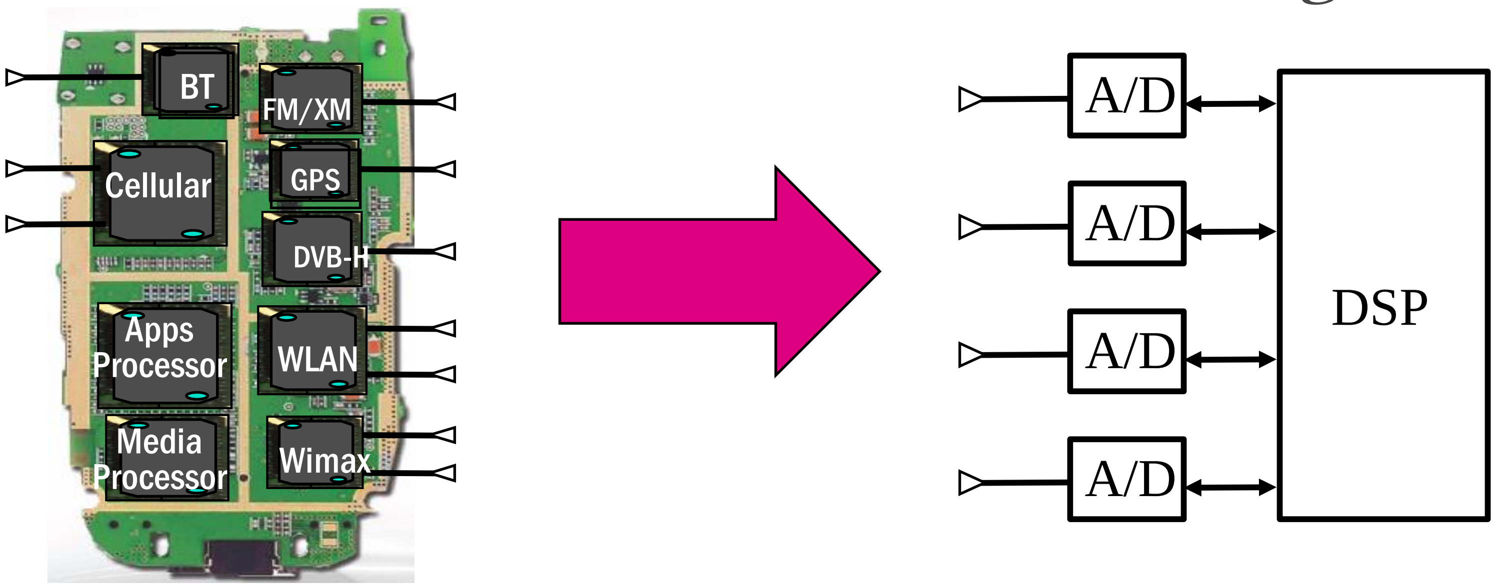


- Device/SoC Challenges
  - Performance
  - Complexity
  - Size, Power, Cost, Energy
  - High frequencies/mmWave
  - Multiple Antennas
  - Multiradio Integration
  - Coexistance



Software-Defined (SD) Radio:

Is this the solution to the device challenges?

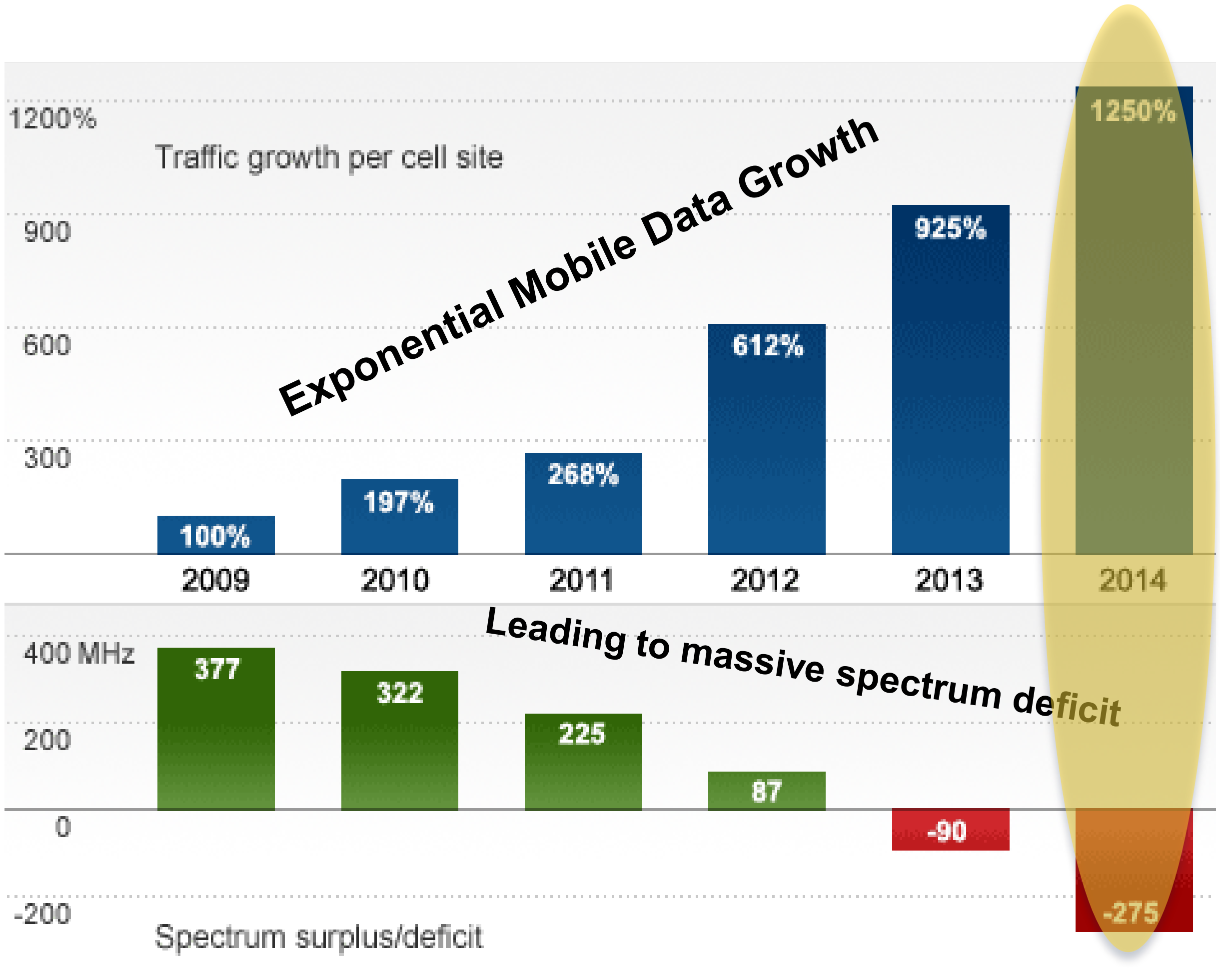


- **Wideband antennas and A/Ds span BW of desired signals**
- **DSP programmed to process desired signal: no specialized HW**

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

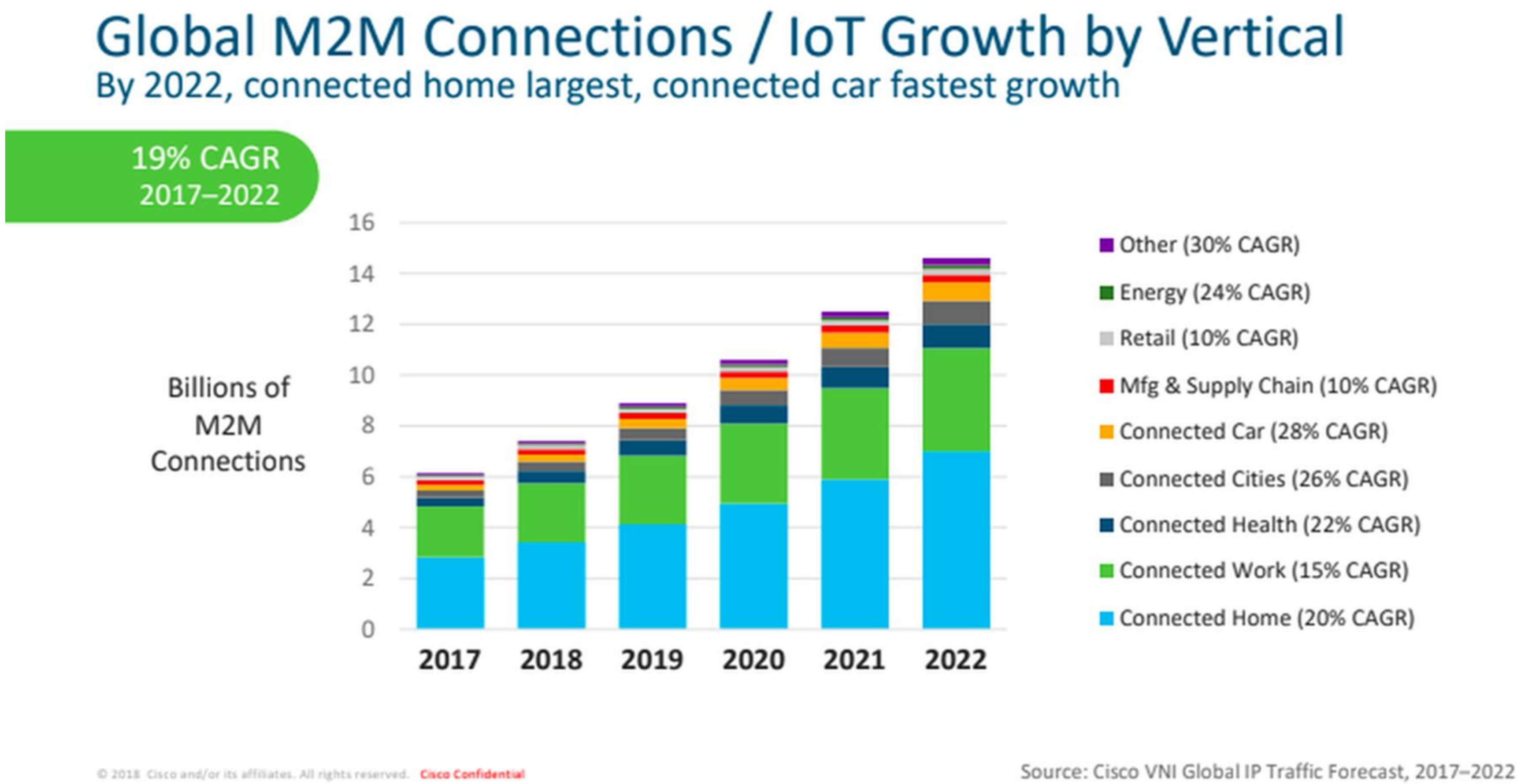
SubNyquist sampling may help with the A/D and DSP requirements

"Sorry, the airwaves are full*"

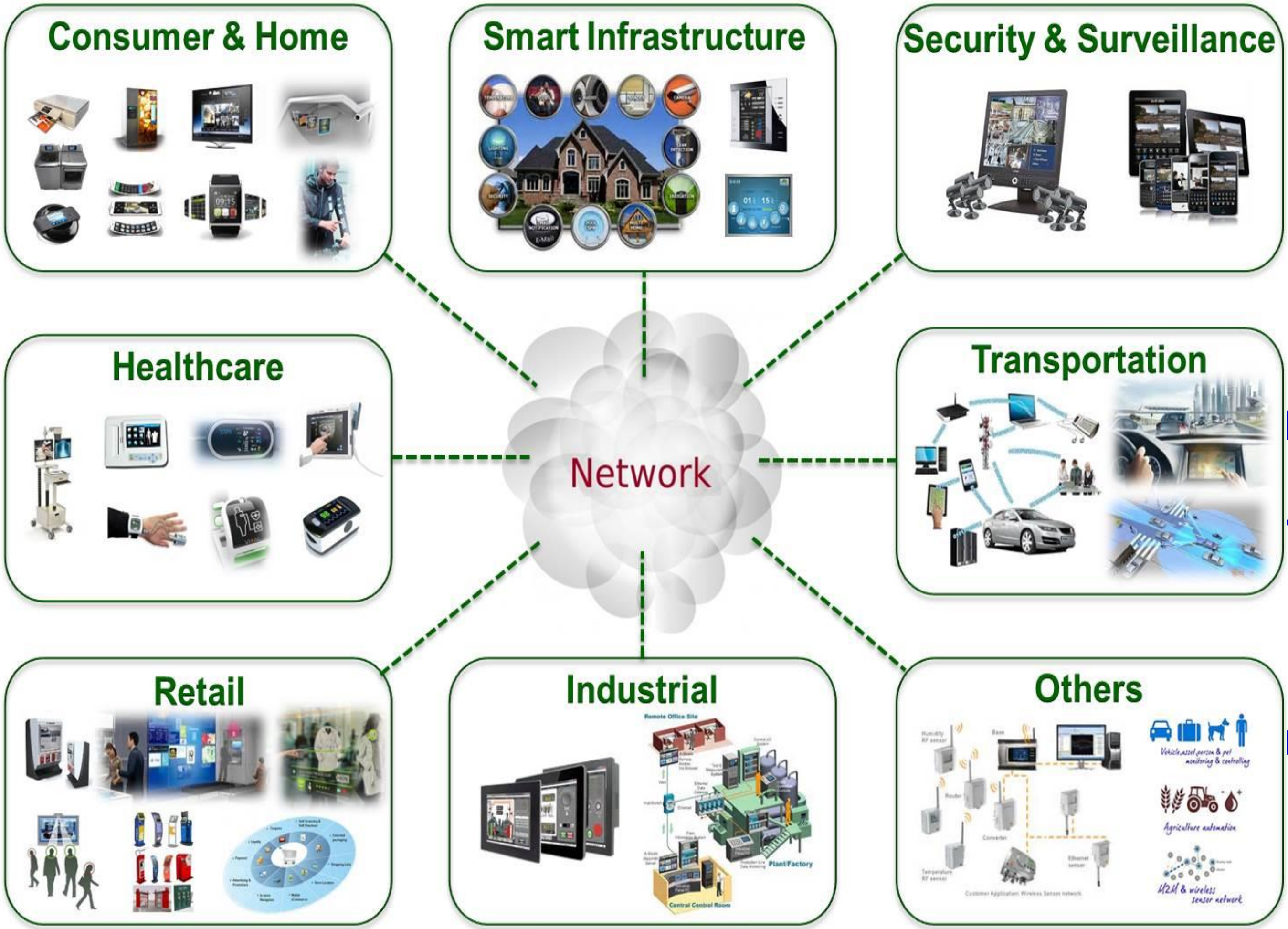


Source: FCC

On the Horizon, the Internet of Things



What is the Internet of Things:



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Different requirements than smartphones: low rates/energy consumption

Are we at the Shannon limit of the Physical Layer?

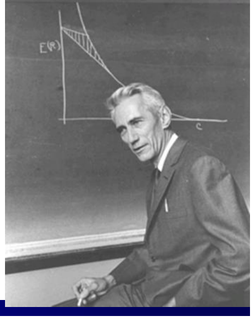
We are at the Shannon Limit

- "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*
- "Effectively unlimited" capacity possible via *personal* cells (pcells). *S. Perlman, Artemis.*

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

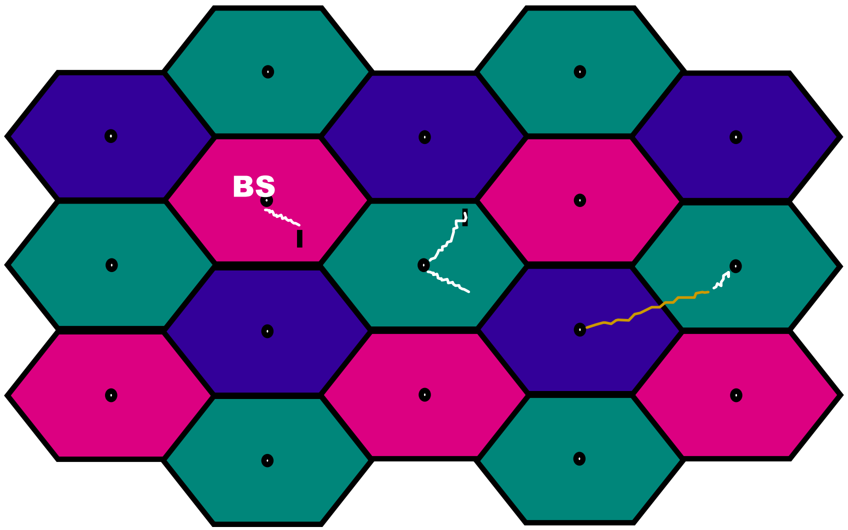
Much room
For innovation

Spectral Reuse

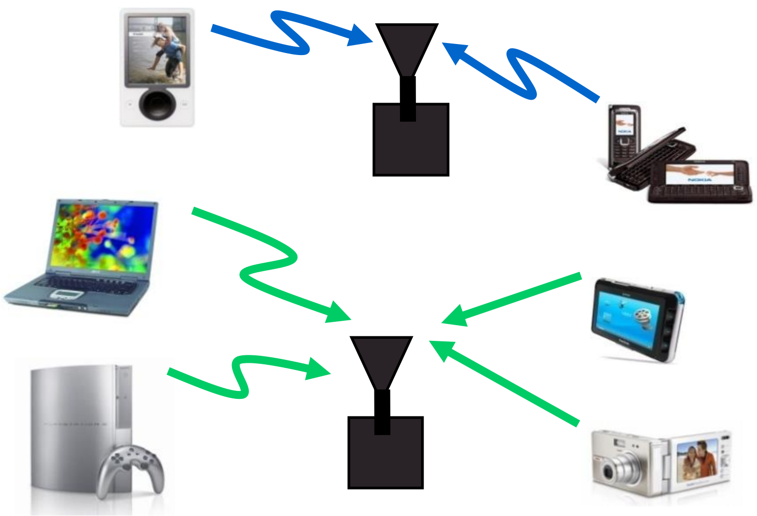
Due to its scarcity, spectrum is *reused*

In licensed bands

and unlicensed bands



Cellular

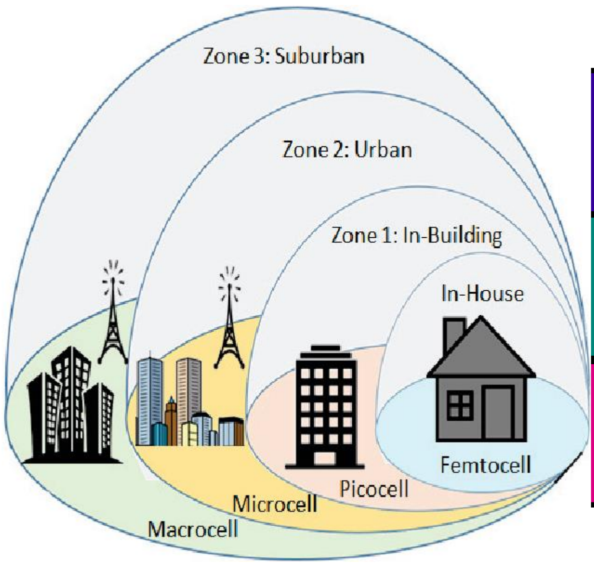


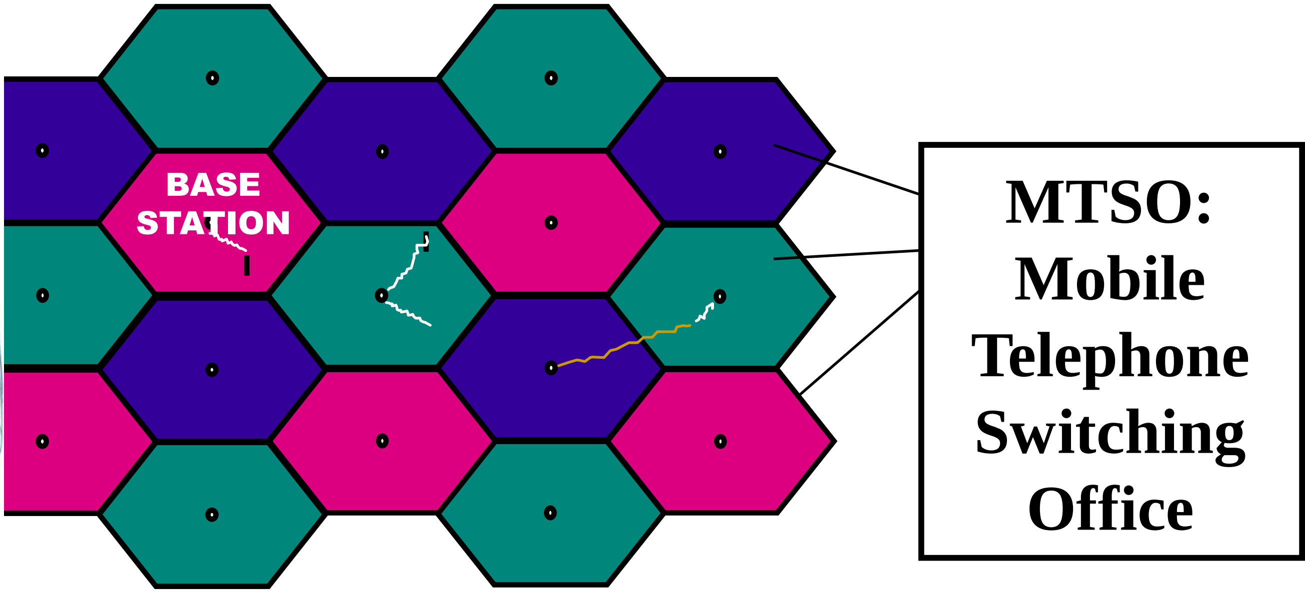
Wifi, BT, UWB,…

Reuse introduces interference

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/MTSOs coordinate handoff and control functions
- Shrinking cell size increases capacity, as well as complexity, handoff, …

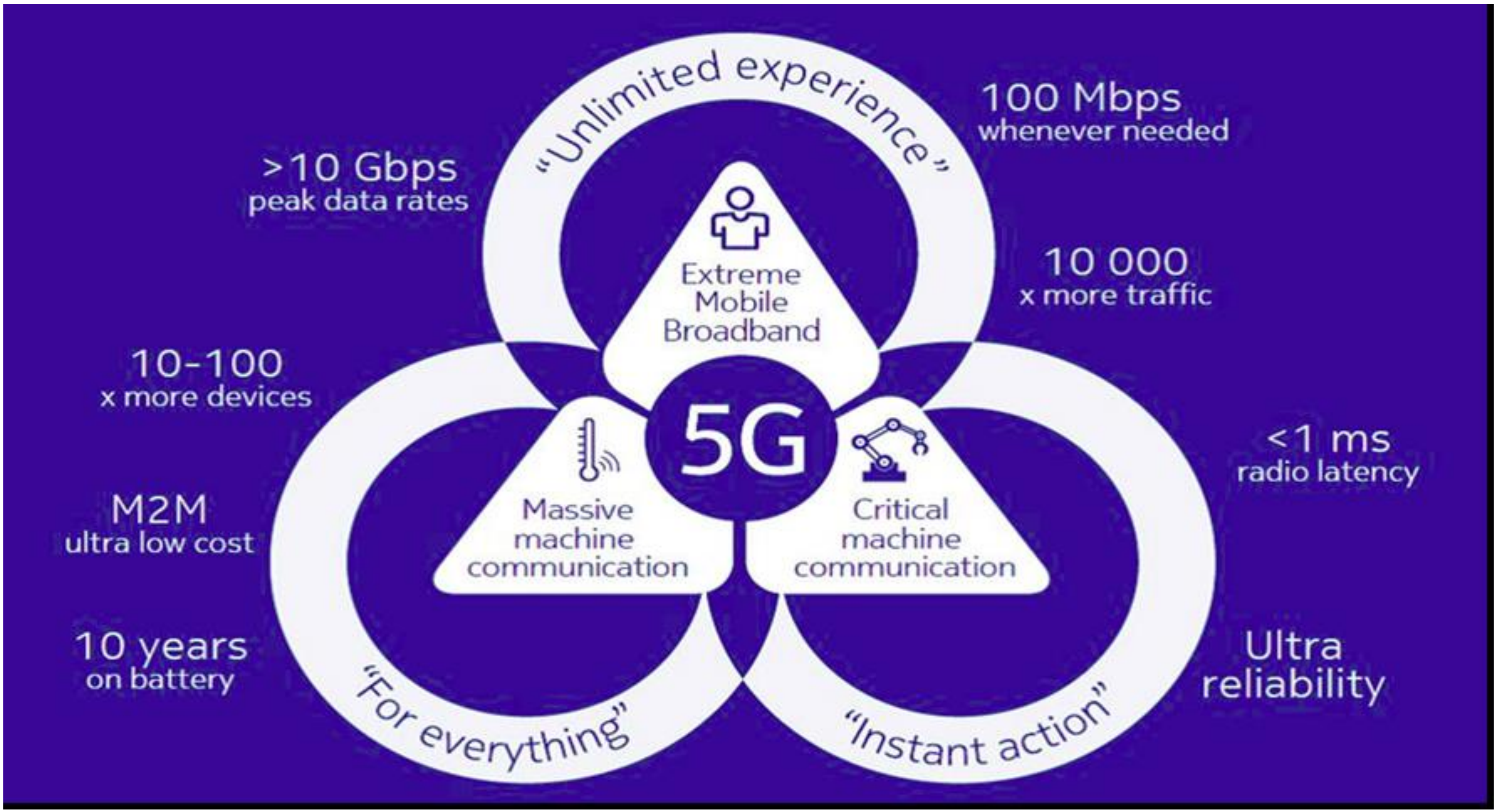




4G/LTE Cellular

- 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



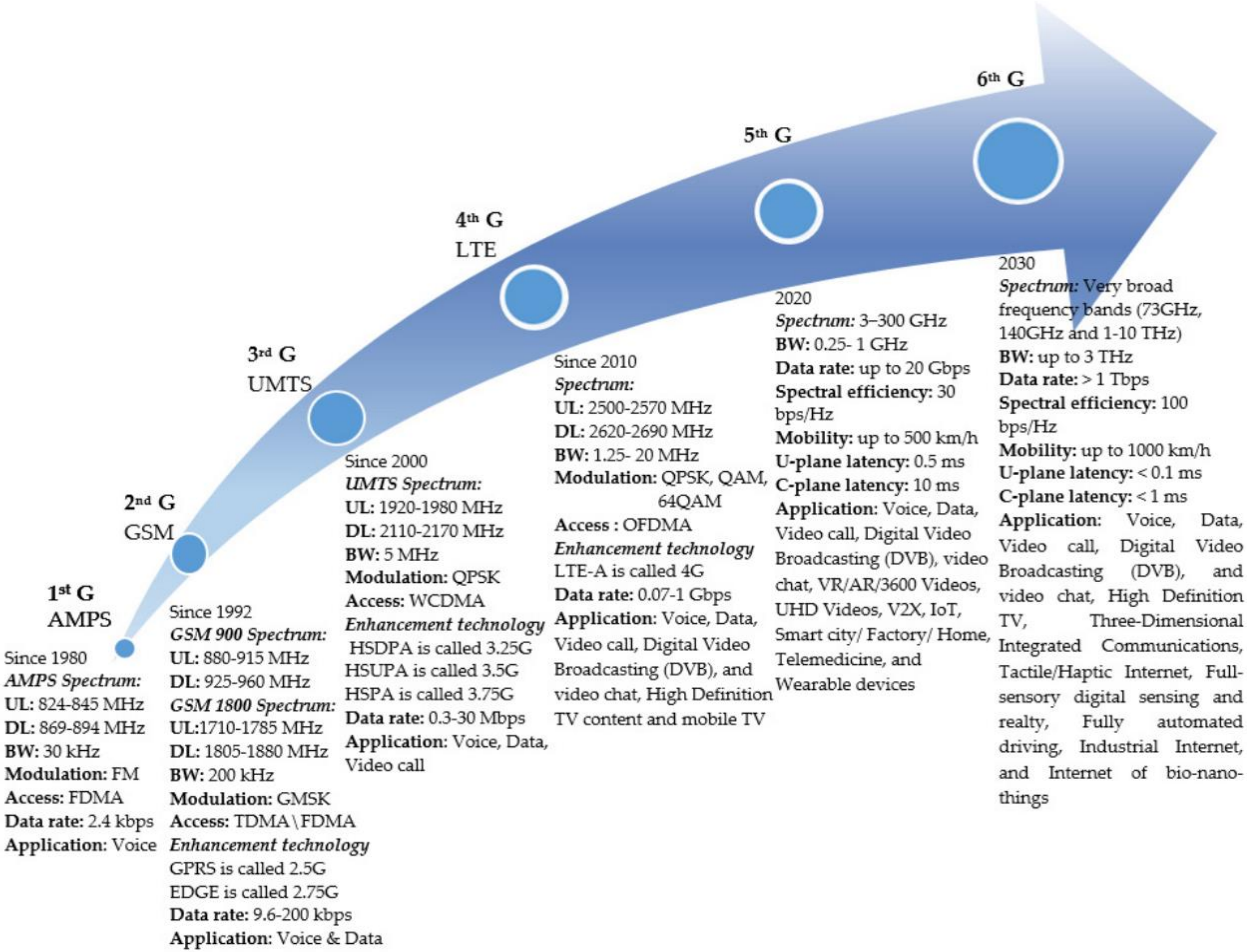
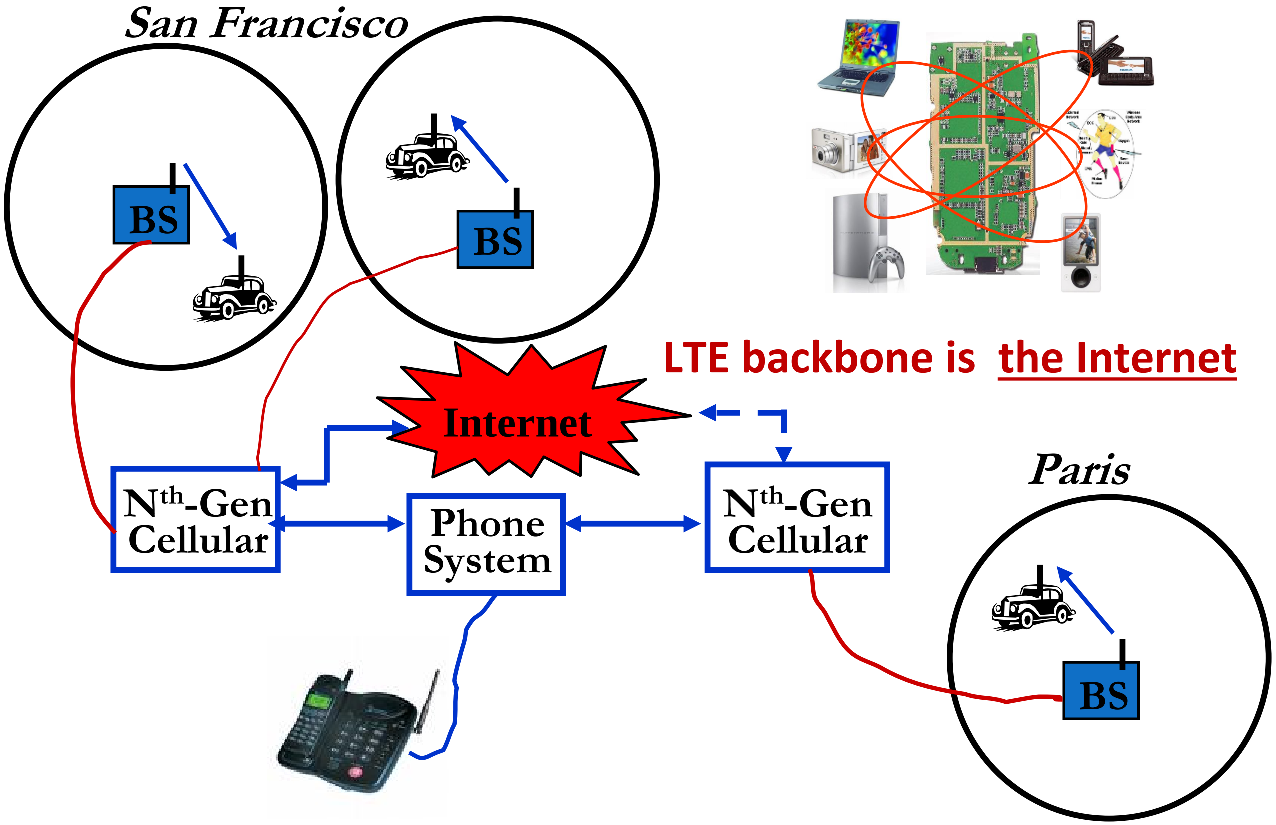


Figure 1. Major milestones for different generations of communications (1–6G).

Future Cellular Phones

Burden for this performance is on the backbone network



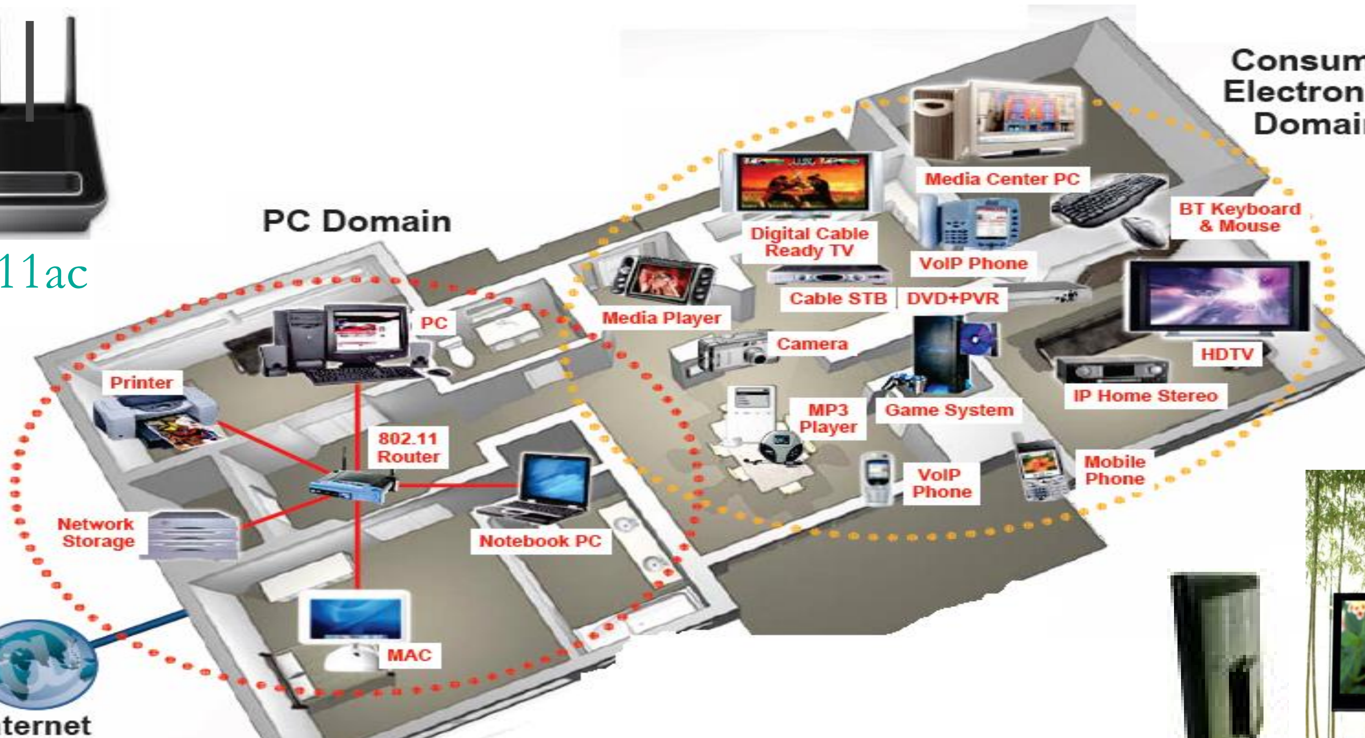
Much better performance and reliability than today

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

Wifi Networks

Multimedia Everywhere, Without Wires

802.11ac



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

Wireless HDTV and Gaming

Wireless LAN Standards

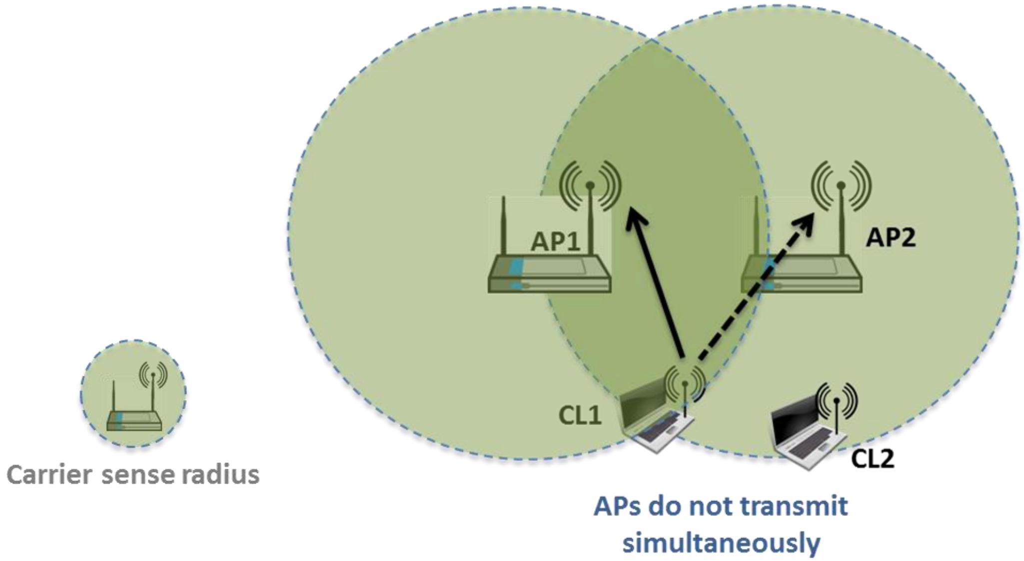
- **802.11b (Old – 1990s)**
  - Standard for 2.4GHz ISM band (80 MHz)
  - Direct sequence spread spectrum (DSSS)
  - Speeds of 11 Mbps, approx. 500 ft range
- **802.11a/g (Middle Age– mid-late 1990s)**
  - Standard for 5GHz band (300 MHz)/also 2.4GHz
  - OFDM in 20 MHz with adaptive rate/codes
  - Speeds 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?

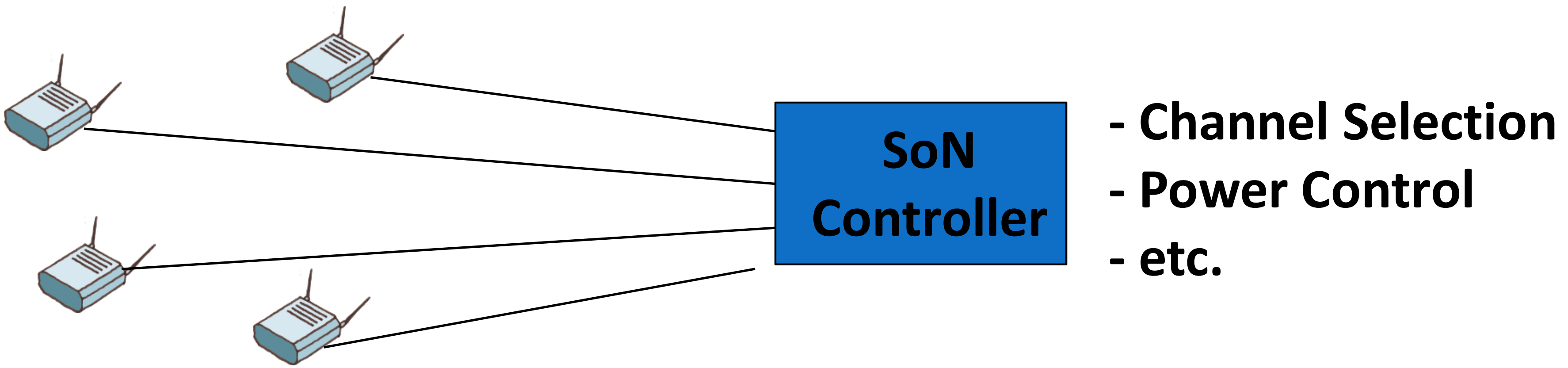
Carrier Sense Multiple Access: if another WiFi signal detected, random backoff

Collision Detection: if collision detected, resend



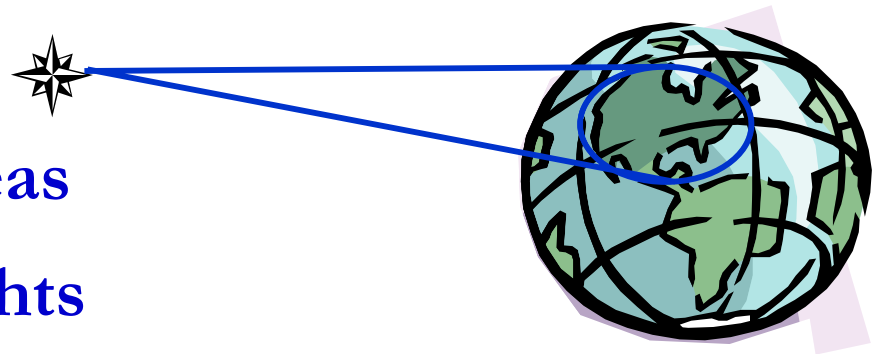
- The WiFi standard lacks good mechanisms to mitigate interference, especially in dense AP deployments
  - Multiple access protocol (CSMA/CD) from 1970s
  - Static channel assignment, power levels, and sensing thresholds
  - In such deployments WiFi systems exhibit poor spectrum reuse and significant 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



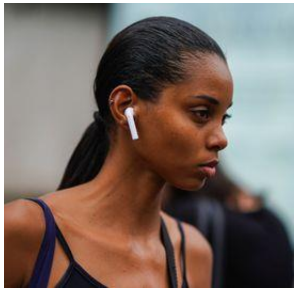
- SoN-for-WiFi: dynamic self-organization network software to manage of WiFi APs.
- Allows for capacity/coverage/interference mitigation tradeoffs.
- Also provides network analytics and planning.

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

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

FCC-related COVID-19 pandemic information is on our **coronavirus web page**.

FCC Federal Communications Commission

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Related Materials >

Standards

- Interacting
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Technology	Frequency	Data Rate	Range	Power Usage	Cost
2G/3G	Cellular Bands	10 Mbps	Several Miles	High	High
Bluetooth/BLE	2.4Ghz	1, 2, 3 Mbps	~300 feet	Low	Low
802.15.4	subGhz, 2.4GHz	40, 250 kbps	> 100 square miles	Low	Low
LoRa	subGhz	< 50 kbps	1-3 miles	Low	Medium
LTE Cat 0/1	Cellular Bands	1-10 Mbps	Several Miles	Medium	High
NB-IoT	Cellular Bands	0.1-1 Mbps	Several Miles	Medium	High
SigFox	subGhz	< 1 kbps	Several Miles	Low	Medium
Weightless	subGhz	0.1-24 Mbps	Several Miles	Low	Low
Wi-Fi	subGhz, 2.4Ghz, 5Ghz	0.1-54 Mbps	< 300 feet	Medium	Low
WirelessHART	2.4Ghz	250 kbps	~300 feet	Medium	Medium
ZigBee	2.4Ghz	250 kbps	~300 feet	Low	Medium
Z-Wave	subGhz	40 kbps	~100 feet	Low	Medium

Advanced Topics Lecture: See Backup Slides

Emerging Systems

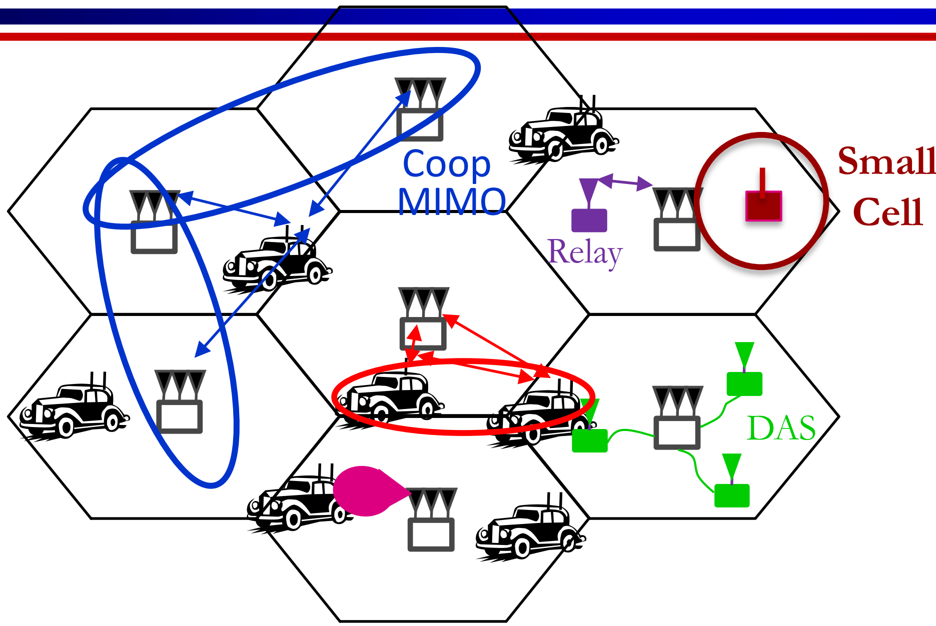
- New cellular system architectures
- mmWave/massive MIMO communications
- Software-defined network architectures
- Ad hoc/mesh wireless networks
- Cognitive radio networks
- Wireless sensor networks
- Energy-constrained radios
- Distributed control networks
- Chemical Communications
- Applications of Communications in Health, Bio-medicine, and Neuroscience

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

Backup Slides:
Emerging Systems

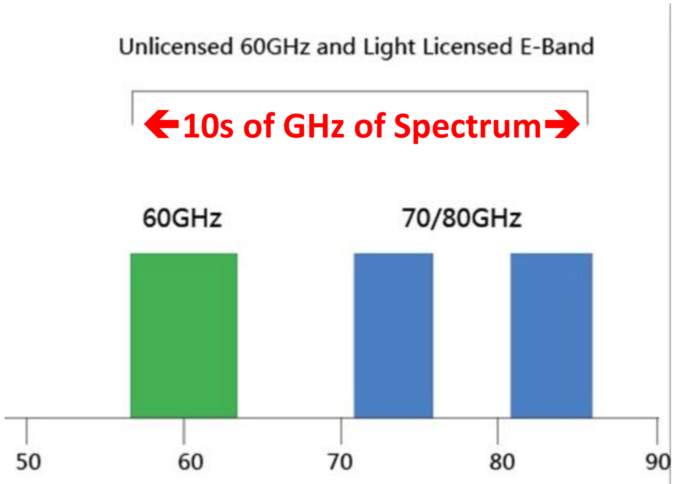
Rethinking "Cells" in Cellular

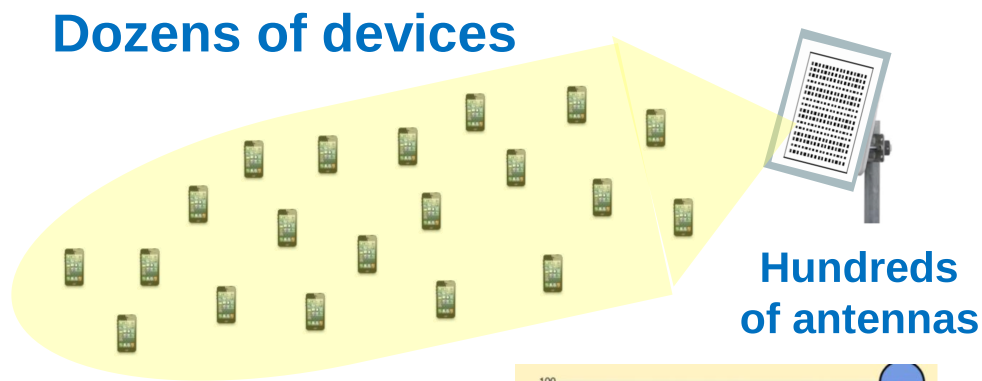


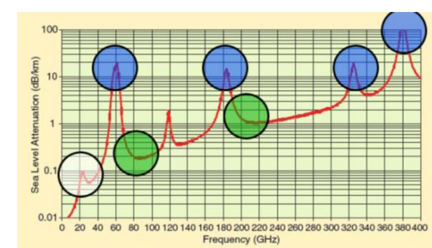
How should cellular systems be designed for
- *Capacity*
- *Coverage*
- *Energy efficiency*
- *Low latency*

- **Traditional cellular design "interference-limited"**
  - **MIMO/multiuser detection can remove interference**
  - **Cooperating BSs form a MIMO array: what is a cell?**
  - **Relays change cell shape and boundaries**
  - **Distributed antennas move BS towards cell boundary**
  - **Small cells create a cell within a cell**
  - **Mobile cooperation via relays, virtual MIMO, network coding.**

mmWave Massive MIMO

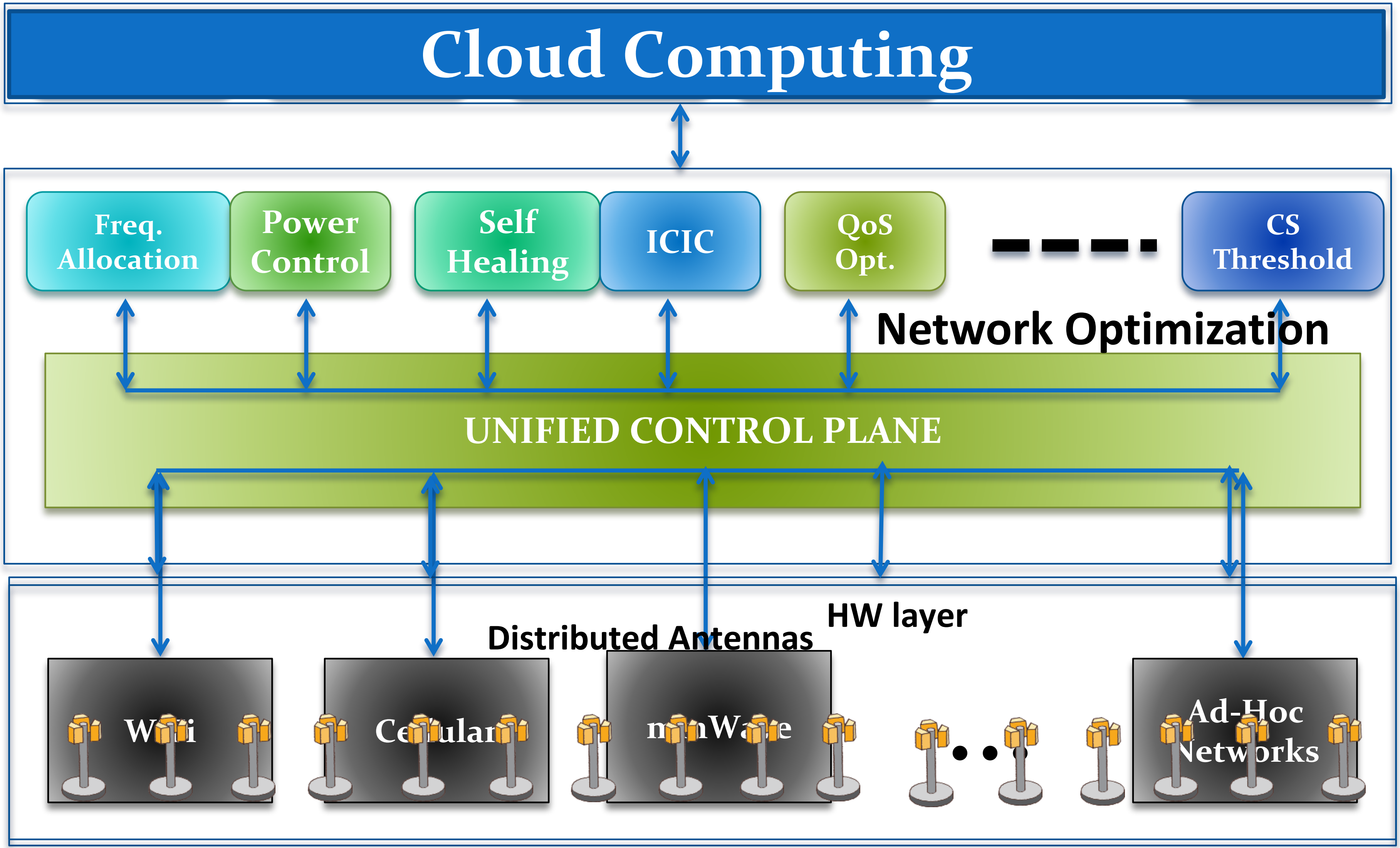




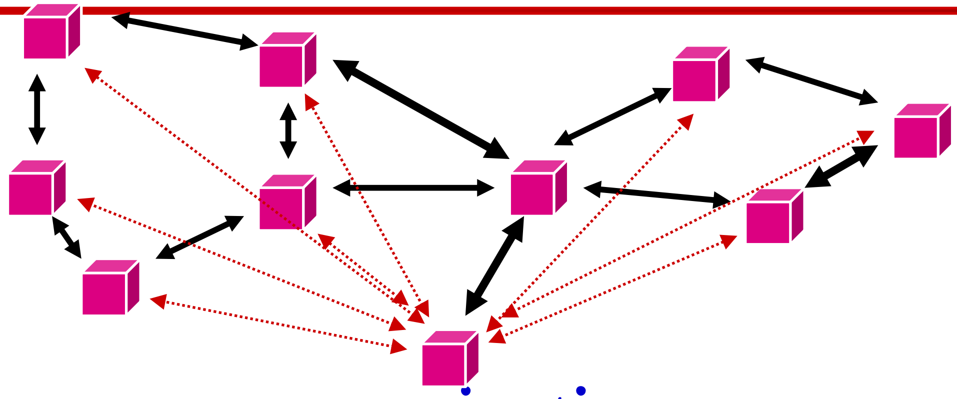


- mmWaves have large non-monotonic path loss
  - Channel model poorly understood
- For asymptotically large arrays with channel state information, no attenuation, fading, interference or noise
- mmWave antennas are small: perfect for massive MIMO
- Bottlenecks: channel estimation and system complexity
- Non-coherent design holds significant promise

Software-Defined Network Architectures

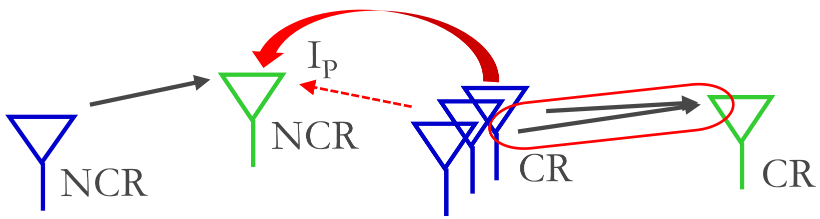


Ad-Hoc Networks

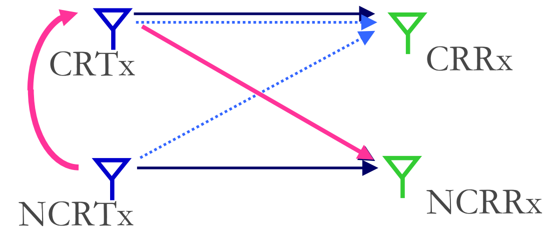


- Peer-to-peer communications
  - No backbone infrastructure or centralized control
- Routing can be multihop.
- Topology is dynamic.
- Fully connected with different link SINRs
- Open questions
  - Fundamental capacity region
  - Resource allocation (power, rate, spectrum, etc.)
  - Routing

Cognitive Radios



MIMO Cognitive Underlay

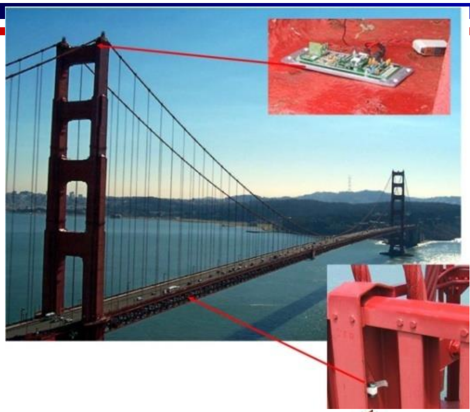


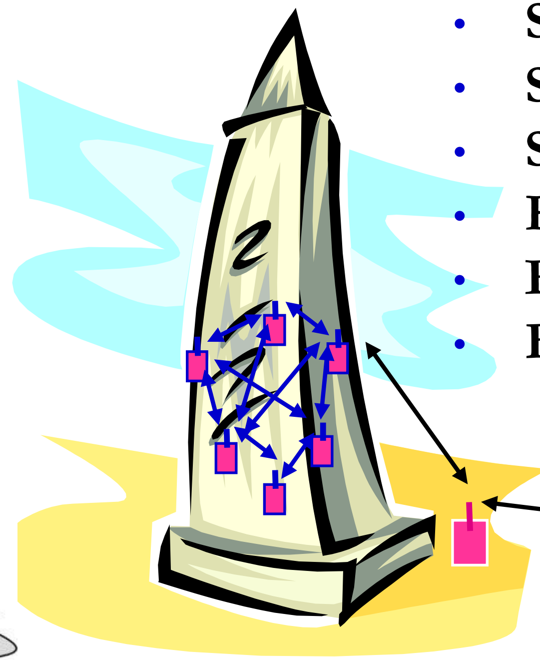
Cognitive Overlay

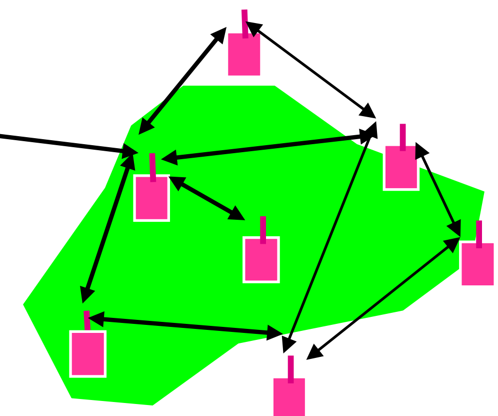
- **Cognitive radios support new users in existing crowded spectrum <u>without degrading licensed users</u>**
  - **Utilize advanced communication and DSP techniques**
  - **Coupled with novel spectrum allocation policies**

- **Multiple paradigms**
  - **(MIMO) Underlay (interference below a threshold)**
  - **Interweave finds/uses unused time/freq/space slots**
  - **Overlay (overhears/relays primary message while cancelling interference it causes to cognitive receiver)**

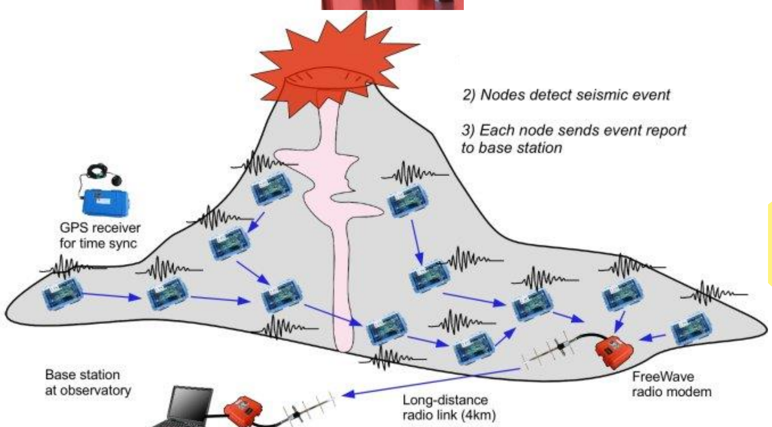
Wireless Sensor Networks
Data Collection and Distributed Control







- Smart homes/buildings
- Smart structures
- Search and rescue
- Homeland security
- Event detection
- Battlefield surveillance



- Energy (transmit and processing) is the driving constraint
- Data flows to centralized location (joint compression)
- Low per-node rates but tens to thousands of nodes
- Intelligence is in the network rather than in the devices

Energy-Constrained Radios

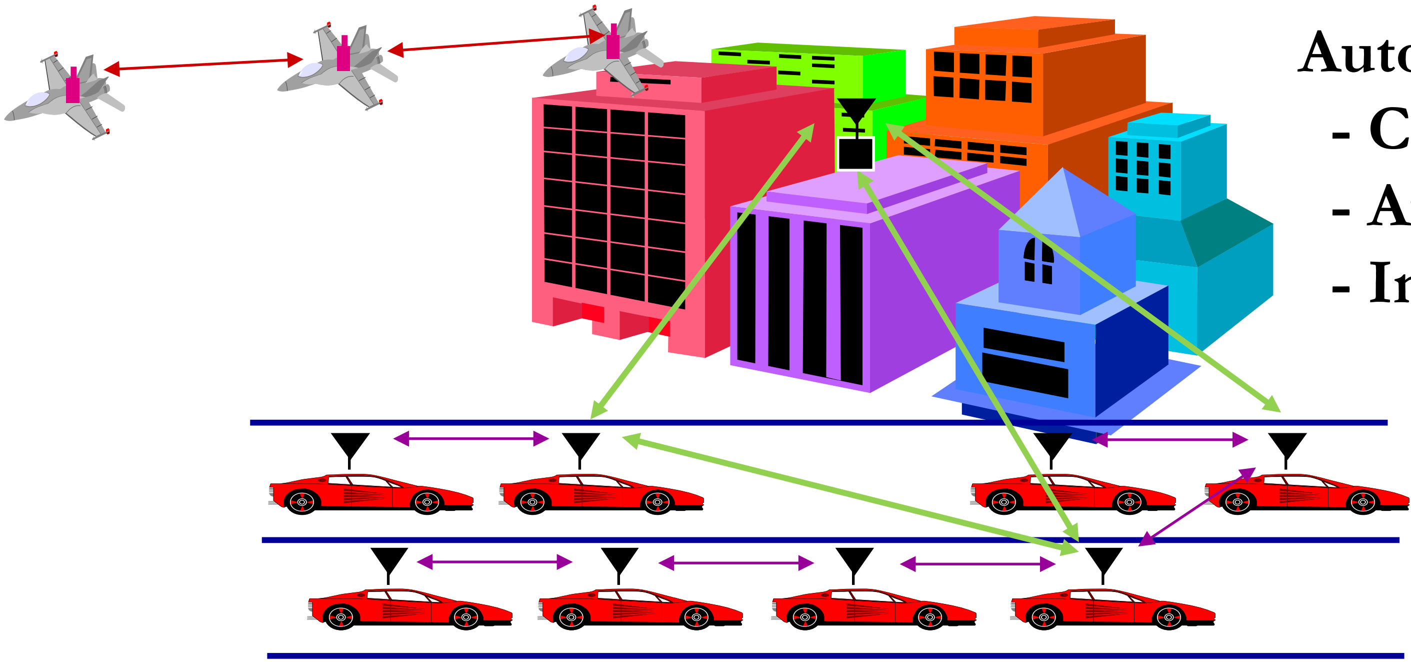
- Transmit energy minimized by sending bits slowly
  - Leads to increased circuit energy consumption

- Short-range networks must consider both transmit and processing/circuit energy.
  - Sophisticated encoding/decoding not always energy-efficient.
  - MIMO techniques not necessarily energy-efficient
  - Long transmission times not necessarily optimal
  - Multihop routing not necessarily optimal
  - Sub-Nyquist sampling can decrease energy and is sometimes optimal!

Where should energy come from?

- Batteries and traditional charging mechanisms
  - Well-understood devices and systems
- Wireless-power transfer
  - Poorly understood, especially at large distances and with high efficiency
- Communication with Energy Harvesting Radios
  - Intermittent and random energy arrivals
  - Communication becomes energy-dependent
  - Can combine information and energy transmission
  - New principles for radio and network design needed.

Distributed Control over Wireless

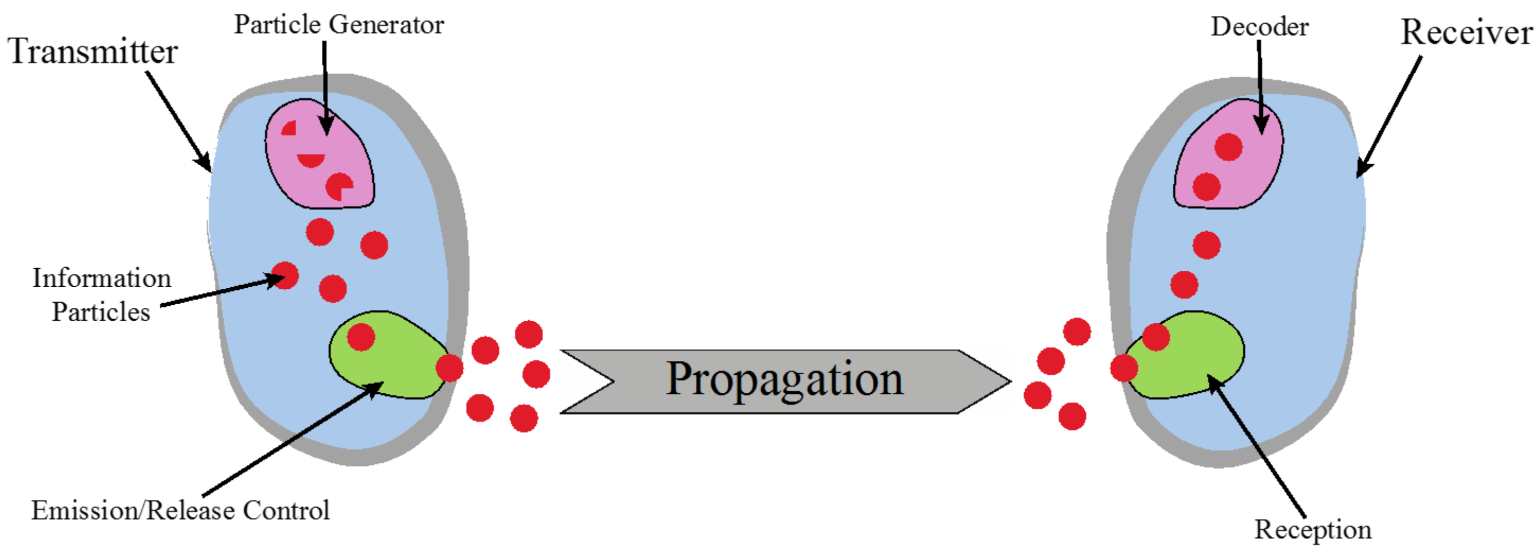


Automated Vehicles
- Cars
- Airplanes/UAVs
- Insect flyers

Interdisciplinary design approach

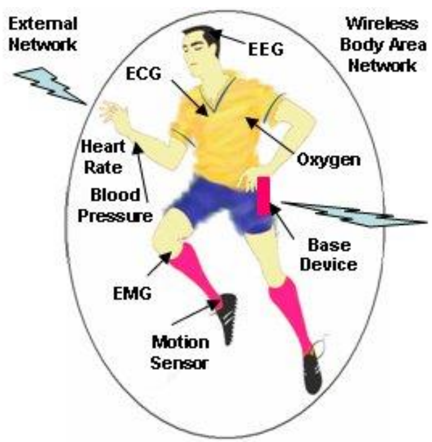
- Control requires fast, accurate, and reliable feedback.
- Wireless networks introduce delay and loss
- Need reliable networks and robust controllers
- Mostly open problems : *Many design challenges*

Chemical Communications

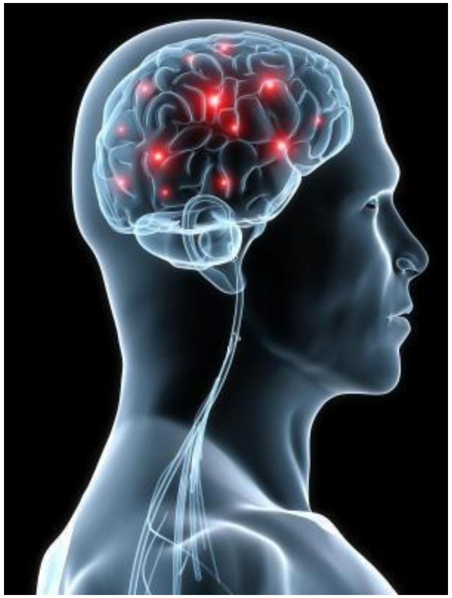


- Can be developed for both macro (>cm) and micro (<mm) scale communications
- Greenfield area of research:
  - Need new modulation schemes, channel impairment mitigation, multiple acces, etc.

Applications in Health, Biomedicine and Neuroscience



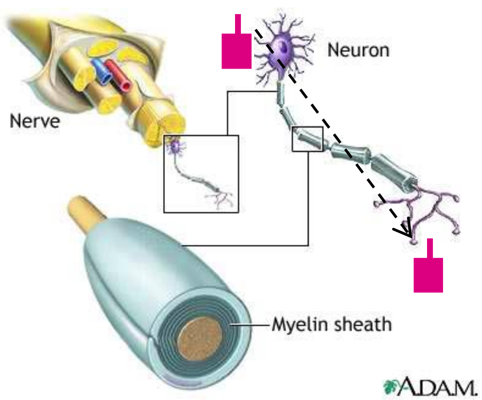
Body-Area Networks



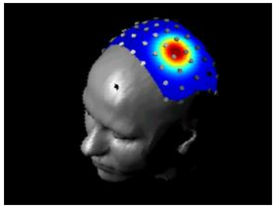
Neuroscience

-Nerve network (re)configuration
-EEG/ECoG signal processing
- Signal processing/control for deep brain stimulation
- SP/Comm applied to bioscience

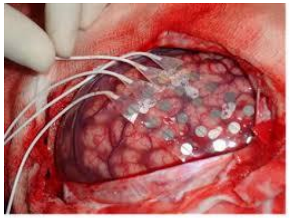
Recovery from Nerve Damage



EEG



ECoG



ECoG Epileptic Seizure Localization