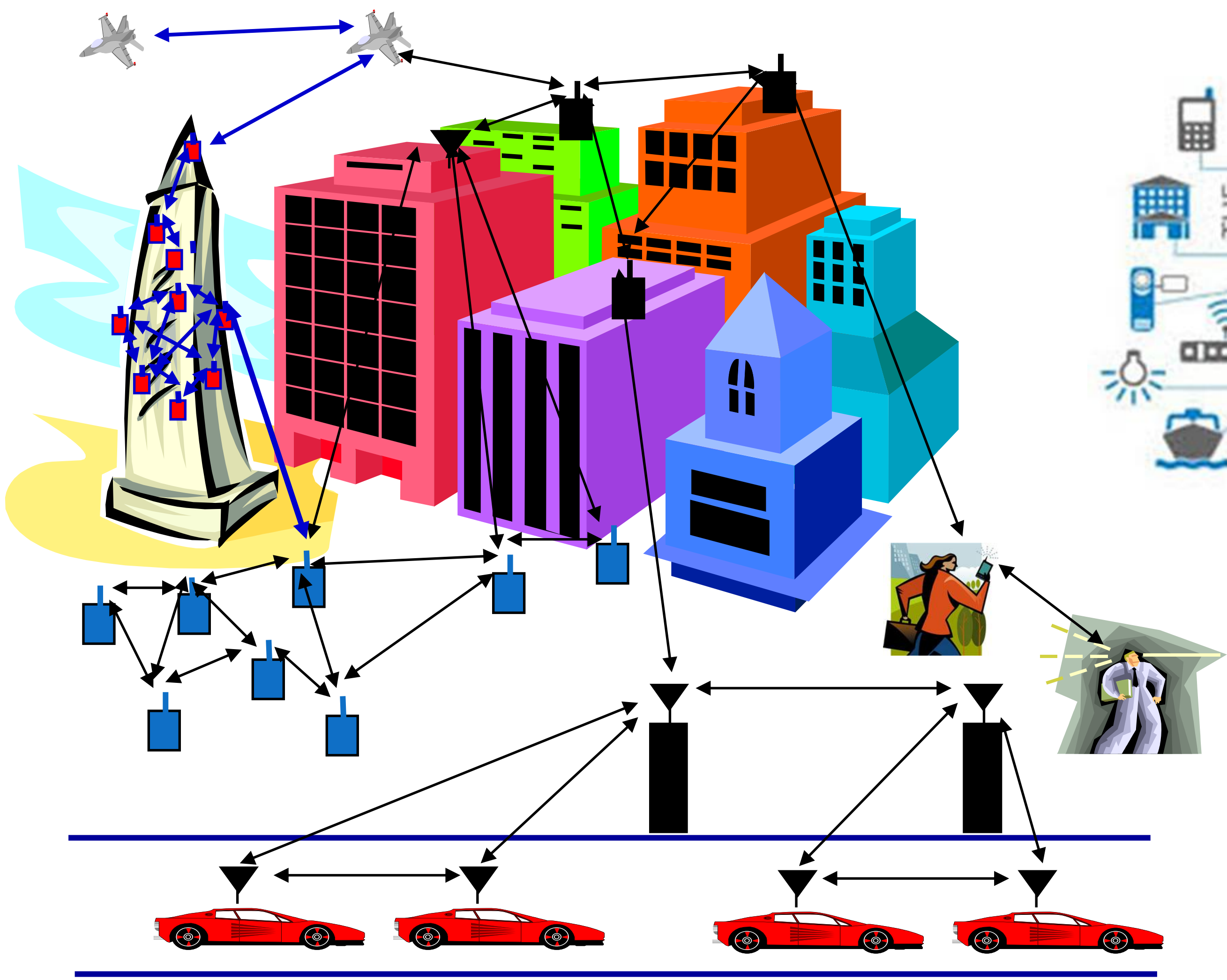
EE 359: Wireless Communications

Professor Andrea Goldsmith



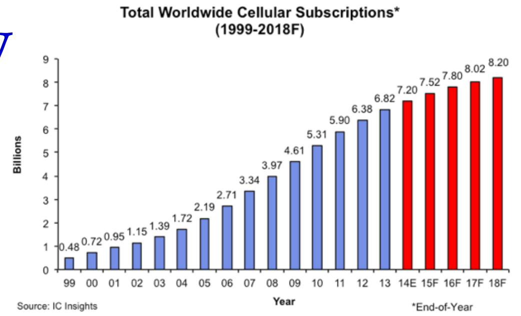
- Next-Gen Cellular/WiFi
- Smart Homes/Spaces
- Autonomous Cars
- Smart Cities
- Body-Area Networks
- Internet of Things
- All this and more …

Course Syllabus

- 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 Modulation and OFDM
- Multiuser Systems
- Cellular Systems

Wireless History

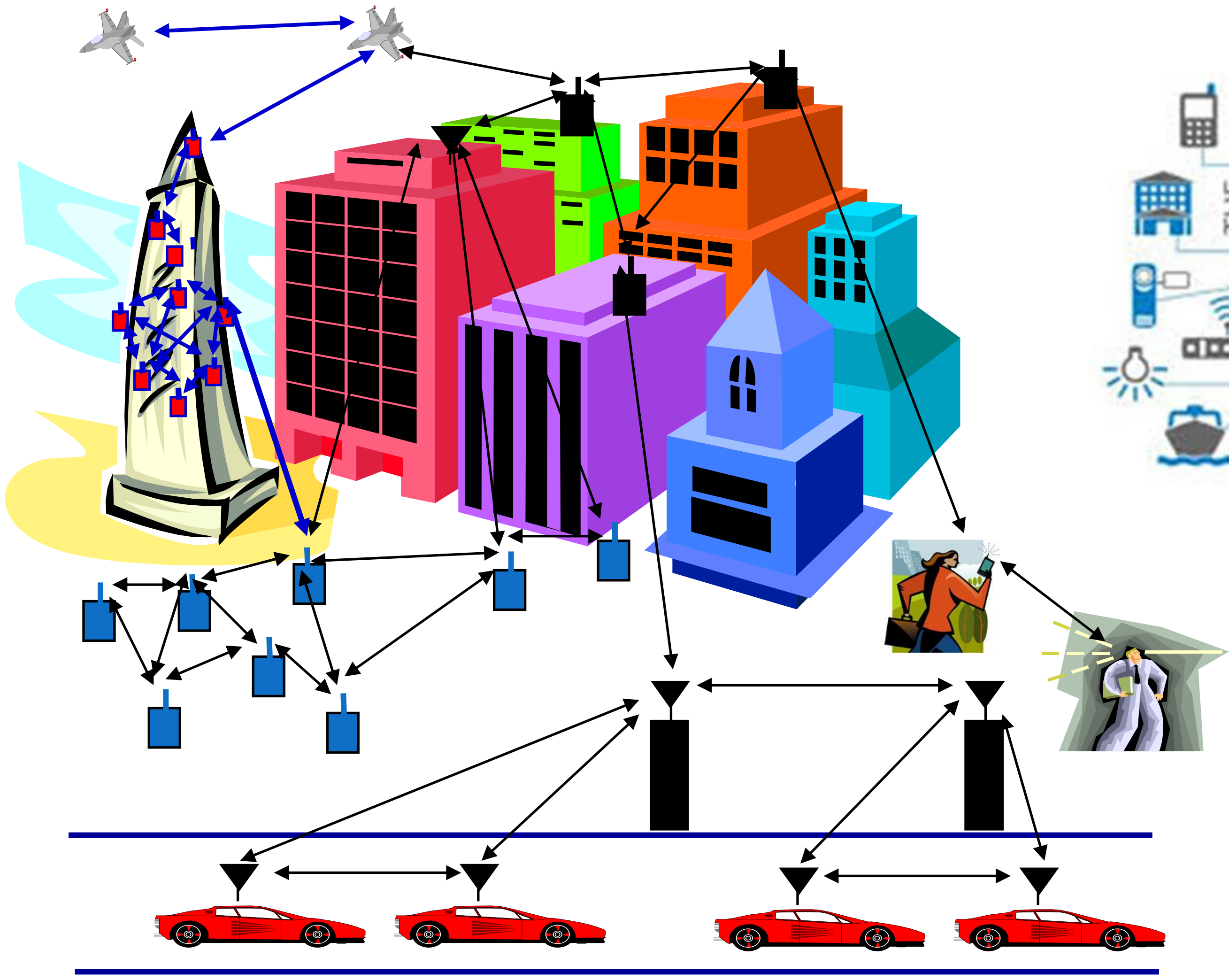
- Ancient Systems: Smoke Signals, Carrier Pigeons, …
- Radio invented in the 1880s by Marconi
- Many sophisticated military radio systems were developed during and after WW2
- Exponential growth in cellular use since 1988: approx. 8 billion worldwide users today
  - Ignited the wireless revolution
  - 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

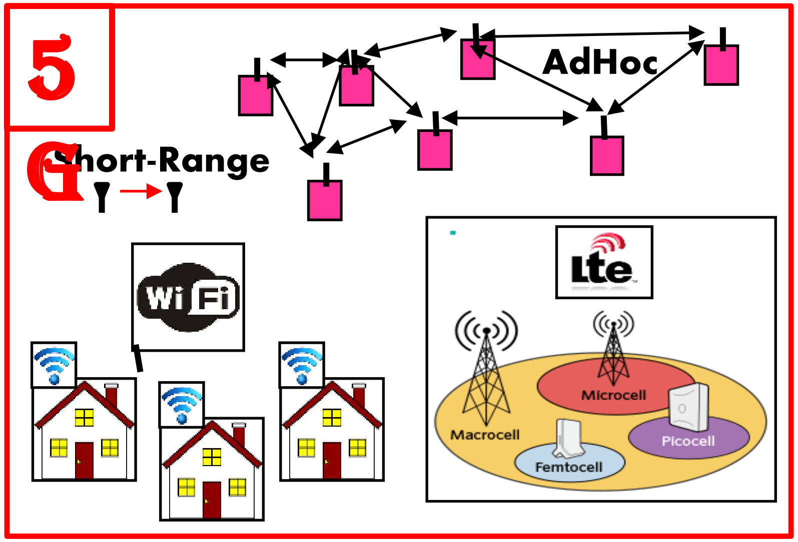
Ubiquitous Communication Among People and Devices



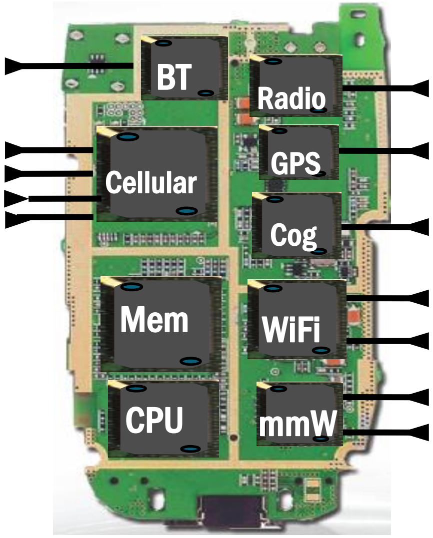
Next-Gen Cellular/WiFi
Smart Homes/Spaces
Autonomous Cars
Smart Cities
Body-Area Networks
Internet of Things
All this and more …

Challenges

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

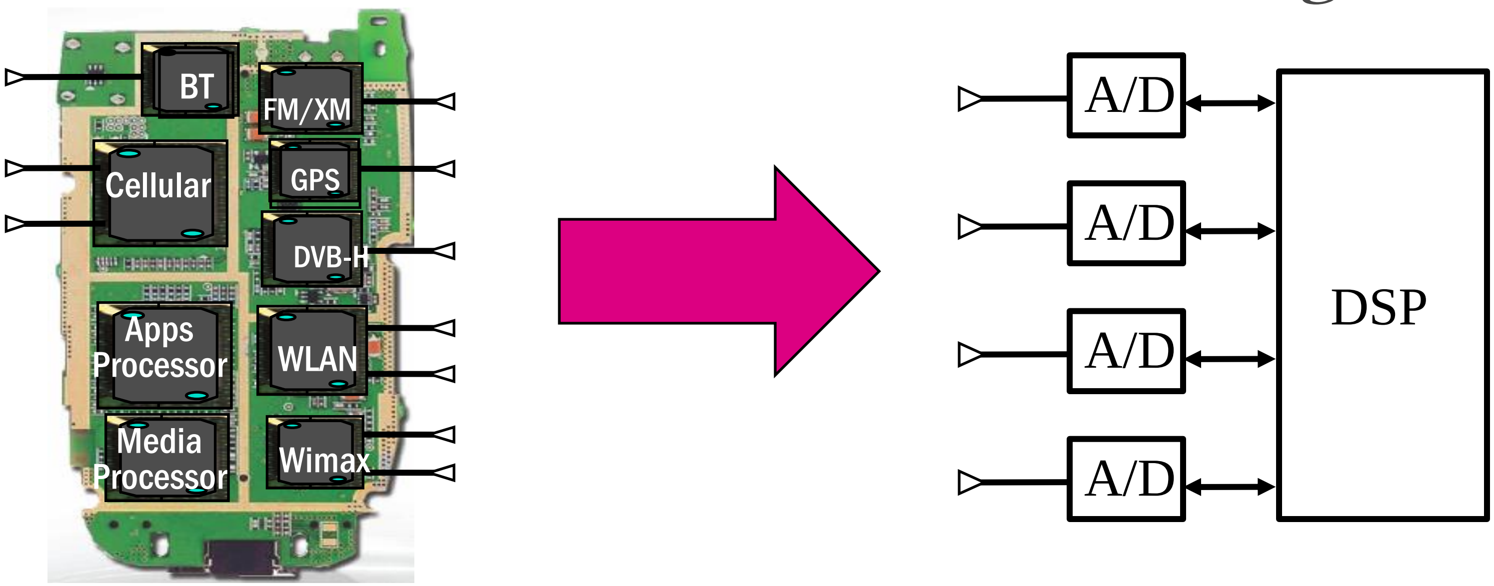


- Device/SoC Challenges
  - Performance
  - Complexity
  - Size, Power, Cost
  - High frequencies/mmWave
  - Multiple Antennas
  - Multiradio Integration
  - Coexistance



Software-Defined (SD) Radio:

Is this the solution to the device challenges?

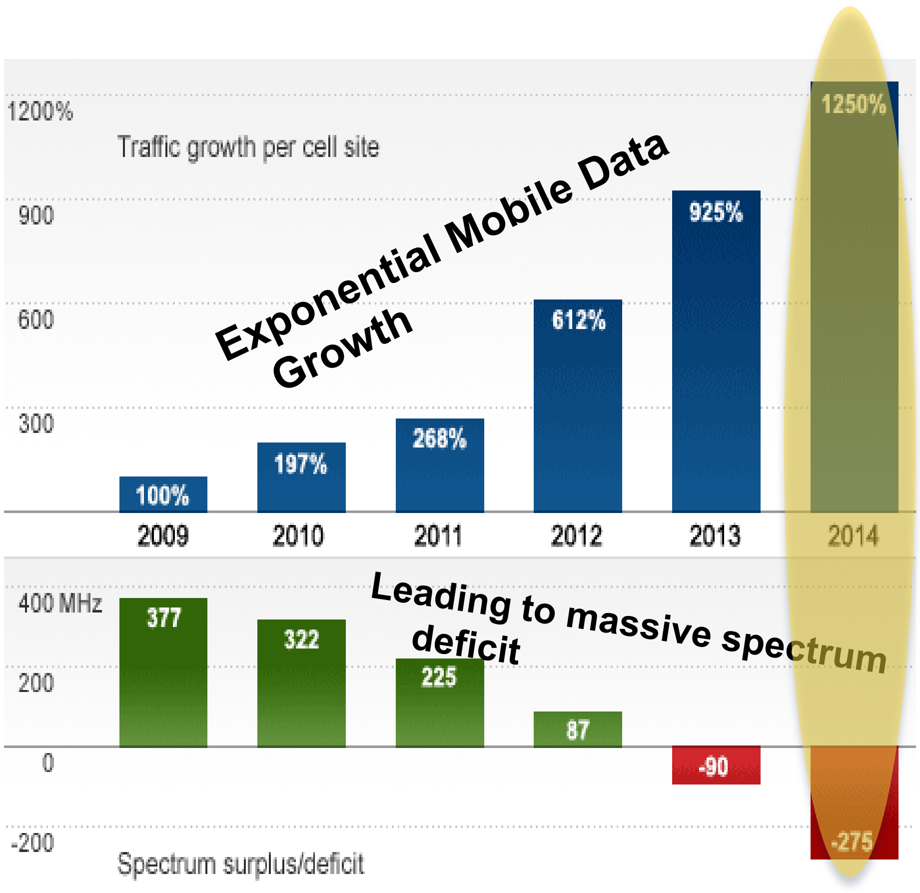


- **Wideband antennas and A/Ds span BW of desired signals**
- **DSP programmed to process desired signal: no specialized HW**

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

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

“Sorry America, your airwaves are full*”



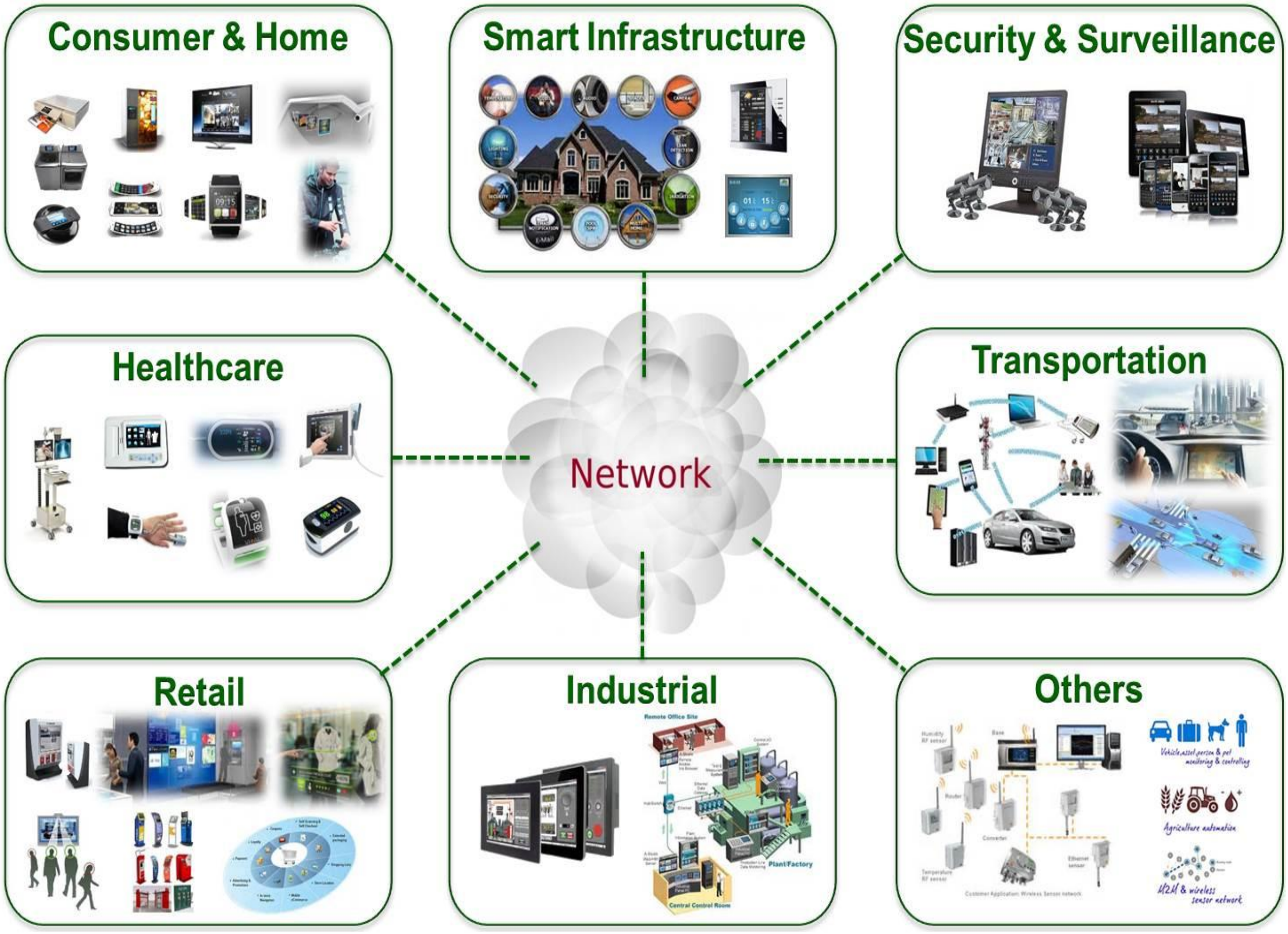
Source: FCC

On the Horizon: “The Internet of Things”

50 billion devices by 2020

***CNN MoneyTech – Feb. 2012**

What is the Internet of Things:



What is the Internet of Things:

- Enabling every electronic device to be connected to each other and the Internet
- Includes smartphones, consumer electronics, cars, lights, clothes, sensors, medical devices,…
- Value in IoT is data processing in the cloud

Different requirements than smartphones: low rates/energy consumption

Are we at the Shannon limit of the Physical Layer?

$$C = B \log_2(1 + SNR)$$

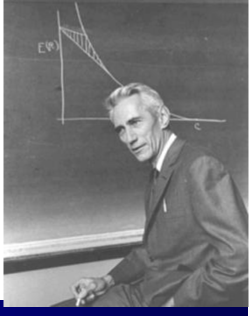
We are at the Shannon Limit

- "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

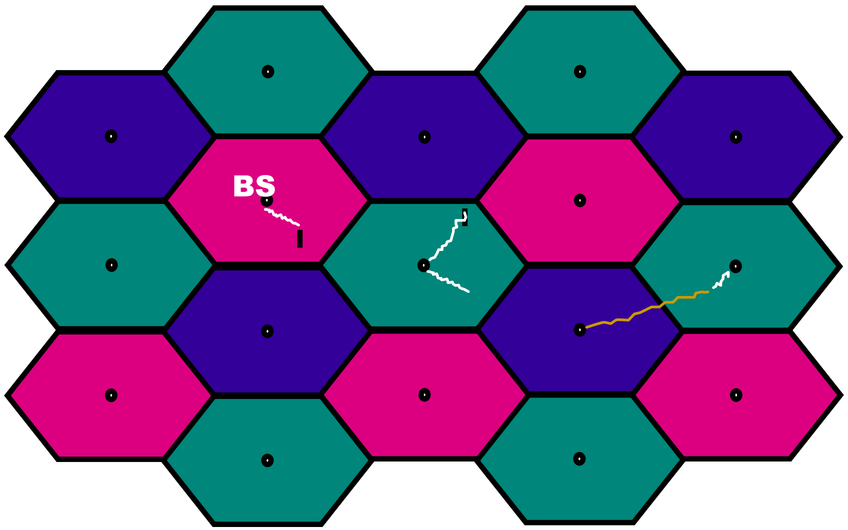
- Current:
  - 4G Cellular Systems (LTE-Advanced)
  - 4G Wireless LANs/WiFi (802.11ac)
  - mmWave massive MIMO systems
  - Satellite Systems
  - Bluetooth
  - Zigbee
  - WiGig
- Emerging
  - 5G Cellular and WiFi Systems
  - Ad/hoc and Cognitive Radio Networks
  - Energy-Harvesting Systems
  - Chemical/Molecular

Much room
For innovation

Spectral Reuse

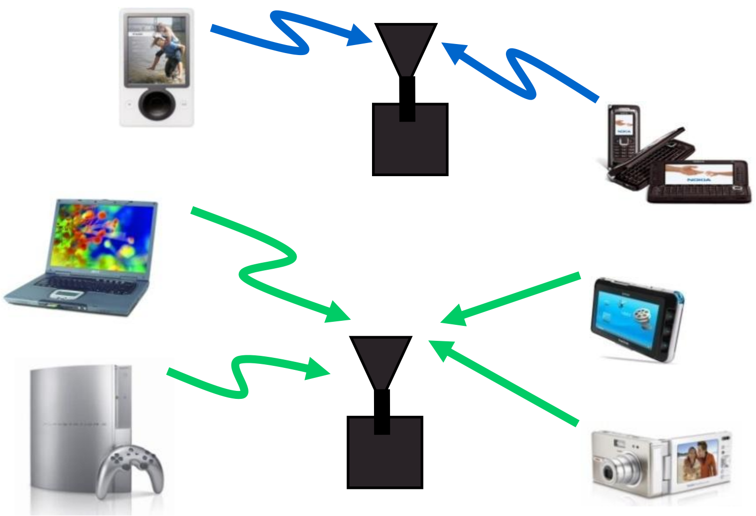
Due to its scarcity, spectrum is *reused*

In licensed bands



Cellular

and unlicensed bands

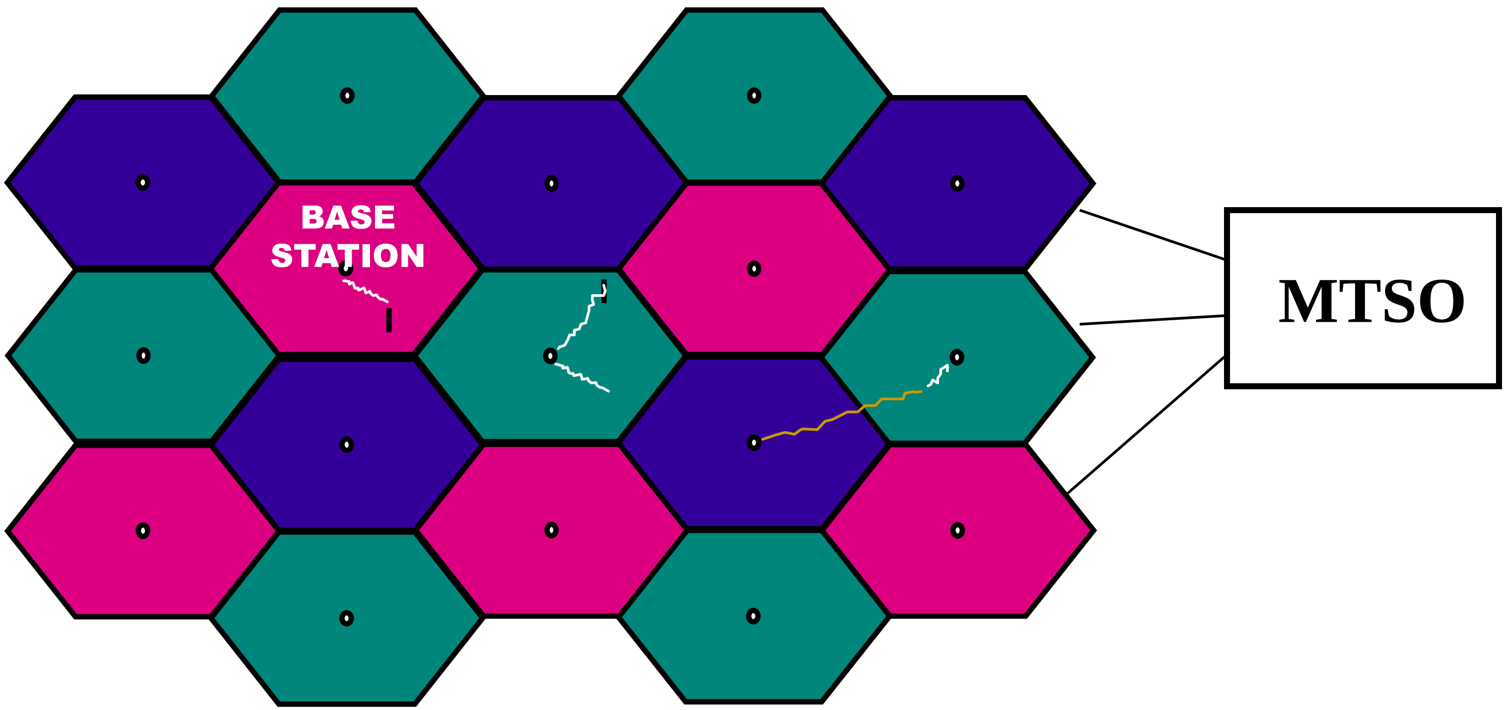


WiFi, BT, UWB,…

Reuse introduces interference

Cellular Systems: Reuse channels to maximize capacity

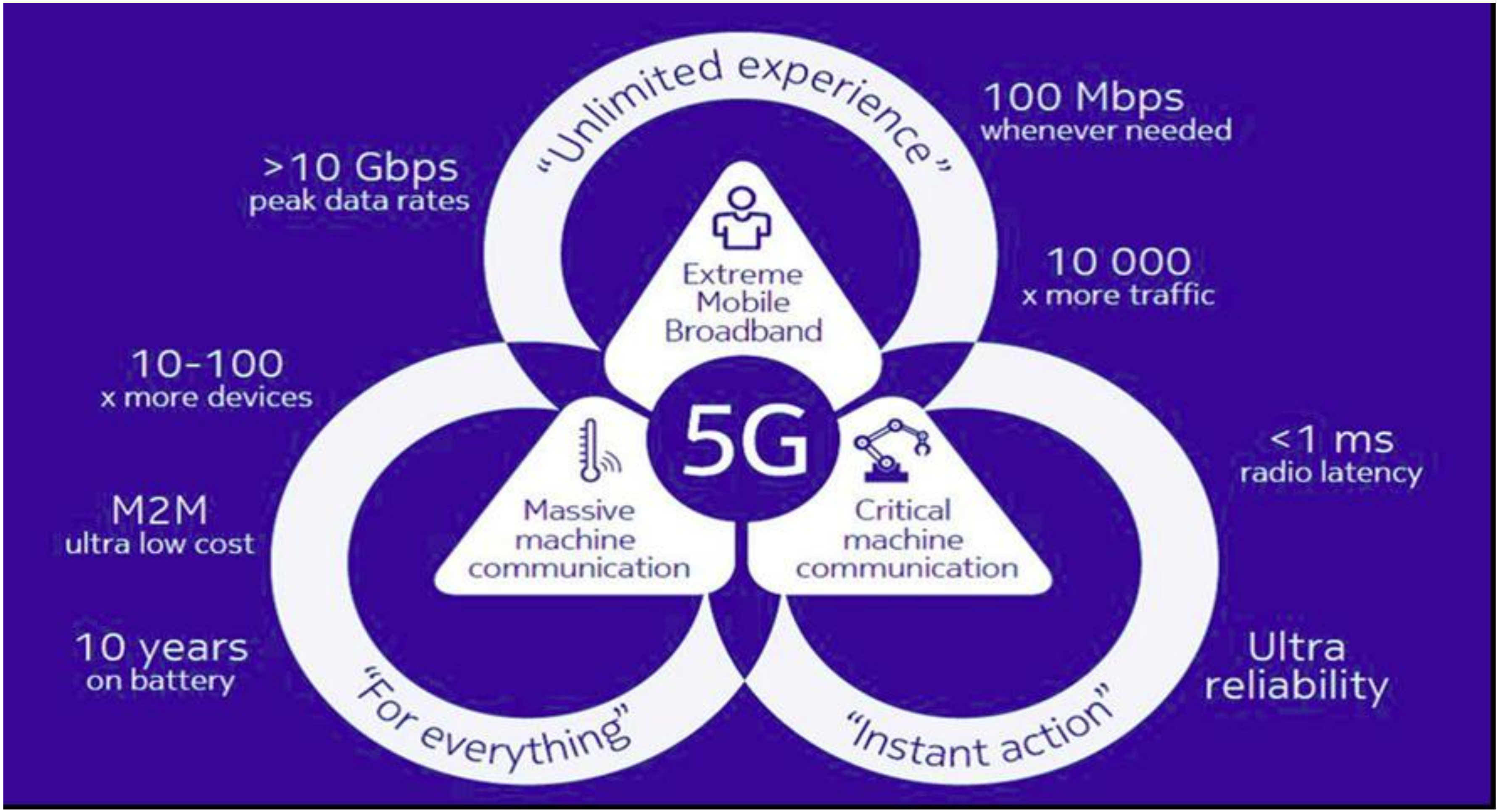
- Geographic region divided into cells
- Freq./timeslots/codes/space reused in different cells (reuse 1 common).
- Interference between cells using same channel: interference mitigation key
- Base stations/MTSOs coordinate handoff and control functions
- Shrinking cell size increases capacity, as well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



4G/LTE Cellular

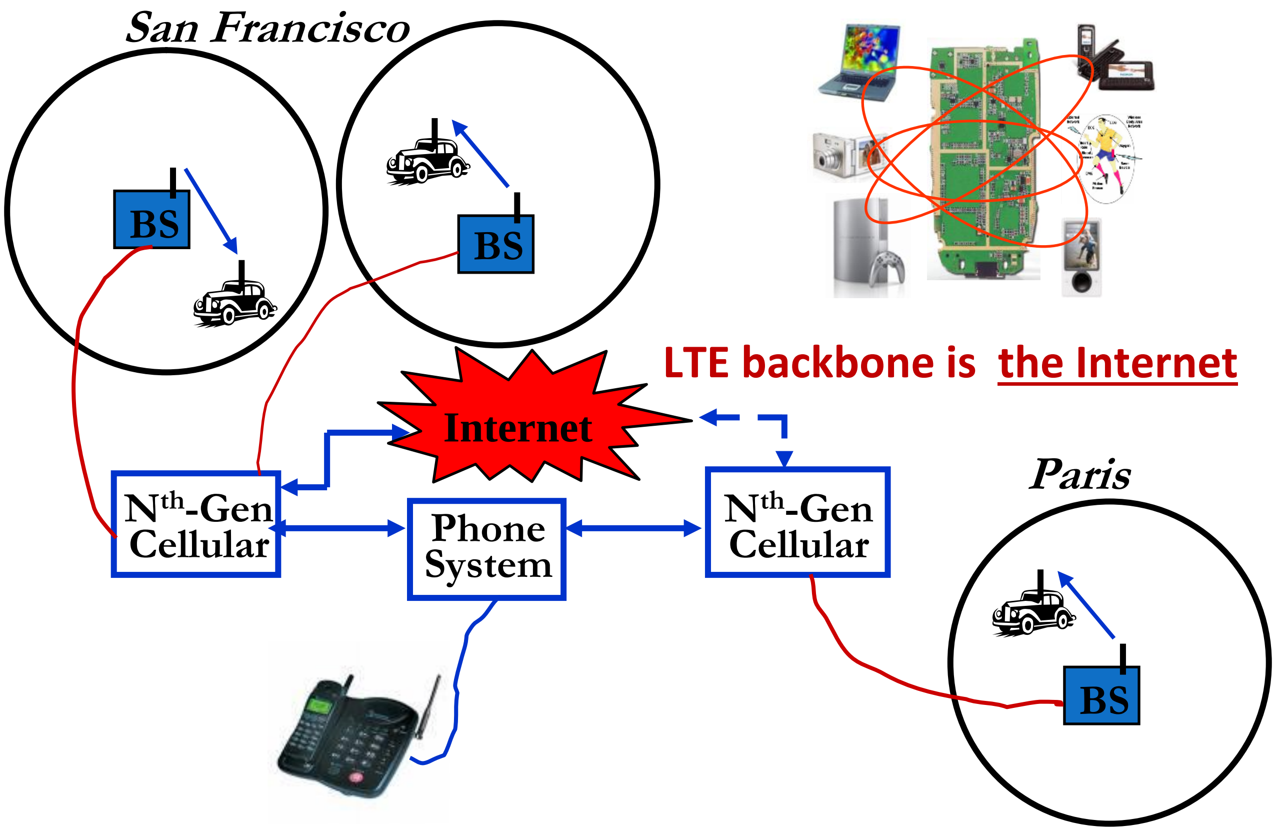
- Much higher data rates than 3G (50-100 Mbps)
  - 3G systems has 384 Kbps peak rates
- Greater spectral efficiency (bits/s/Hz)
  - More bandwidth, adaptive OFDM-MIMO, reduced interference
- Flexible use of up to 100 MHz of spectrum
  - 10-20 MHz spectrum allocation common
- Low packet latency (<5ms).
- Reduced cost-per-bit (not clear to customers)
- All IP network

5G Upgrades from 4G



Future Cellular Phones

Burden for this performance is on the backbone network



Much better performance and reliability than today

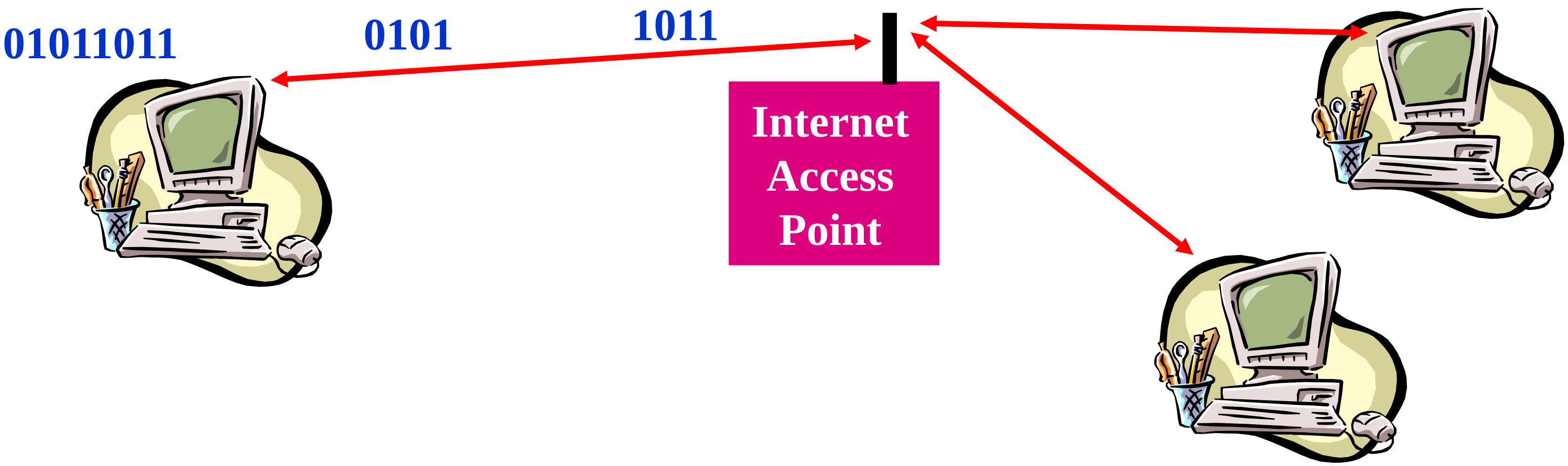
- Gbps rates, low latency, 99% coverage, energy efficiency

WiFi Networks
Multimedia Everywhere, Without Wires

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

Wireless HDTV and Gaming

Wireless Local Area Networks (WLANs)



- WLANs connect "local" computers (100 m range)
- Breaks data into packets
- Channel access shared (random access + backoff)
- Backbone Internet provides best-effort service
  - Poor performance in some apps (e.g. video)

Wireless LAN Standards

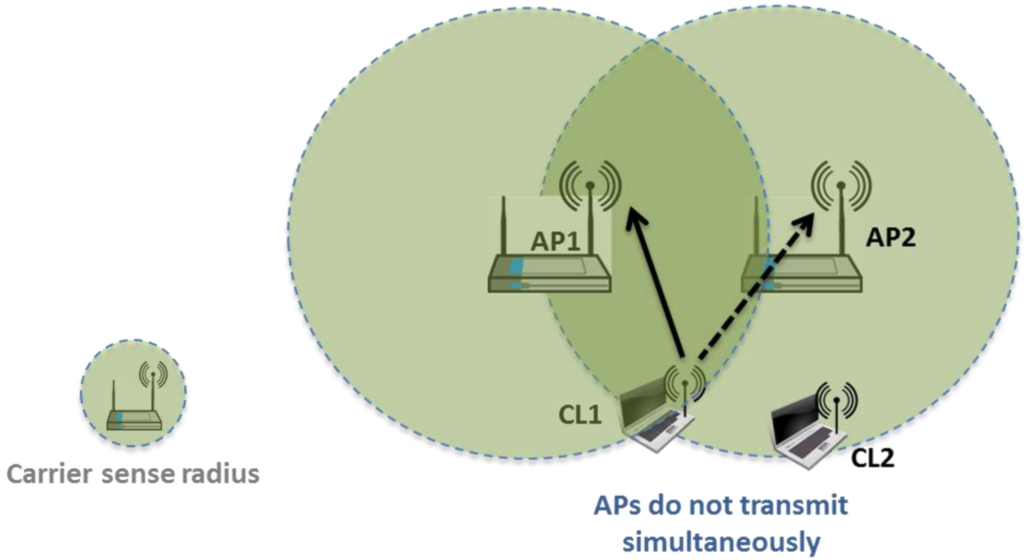
- 802.11b (Old – 1990s)
  - Standard for 2.4GHz ISM band (80 MHz)
  - Direct sequence spread spectrum (DSSS)
  - Speeds of 11 Mbps, approx. 150 m range
- 802.11a/g (Middle Age– mid-late 1990s)
  - Standard for 5GHz band (300 MHz)/also 2.4GHz
  - OFDM in 20 MHz with adaptive rate/codes
  - Speeds of 54 Mbps, approx. 30-60 m range
- 802.11n/ac/ax (current/next 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. 60 m range
  - Other advances in packetization, antenna use, multiuser MIMO

Many WLAN cards have (a/b/g/n)

Why does WiFi performance suck?

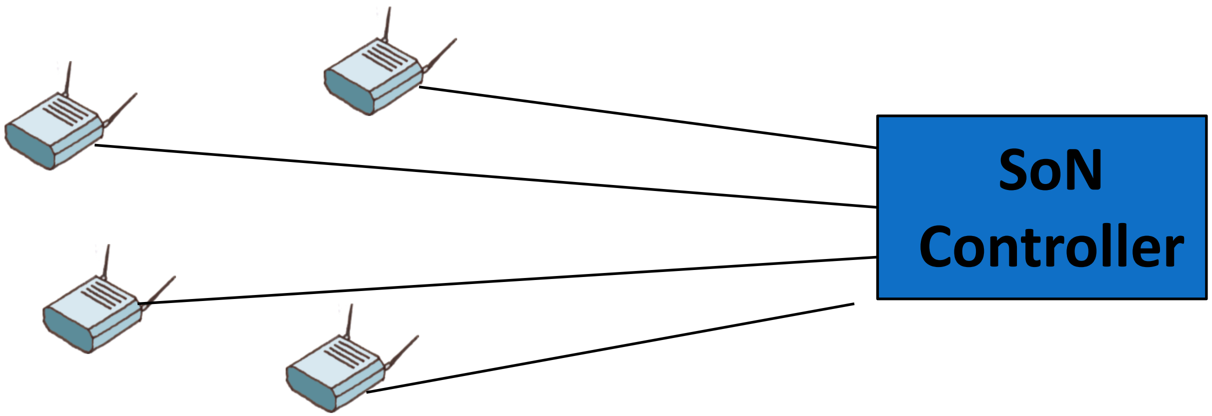
Carrier Sense Multiple Access: if another WiFi signal detected, random backoff

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 carrier 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**

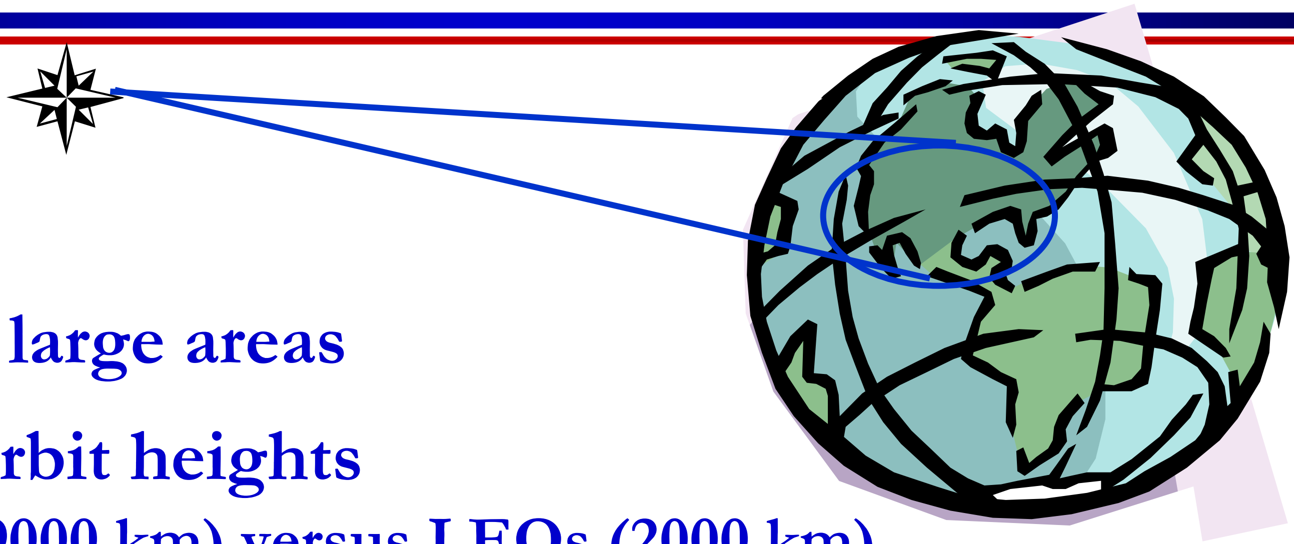
Self-Organizing Networks for WiFi



- 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
  - GEOs (39000 km) versus LEOs (2000 km)
- Optimized for one-way transmission
  - Radio (XM, Sirius) and movie (SatTV, DVB/S) broadcasts
  - Most two-way systems went bankrupt
- 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 (10 m, extendable to 100 m)
- 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: 20 Kbps, 40 Kbps, 250 Kbps
- Range: 10-100 m 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)**
- **FCC 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

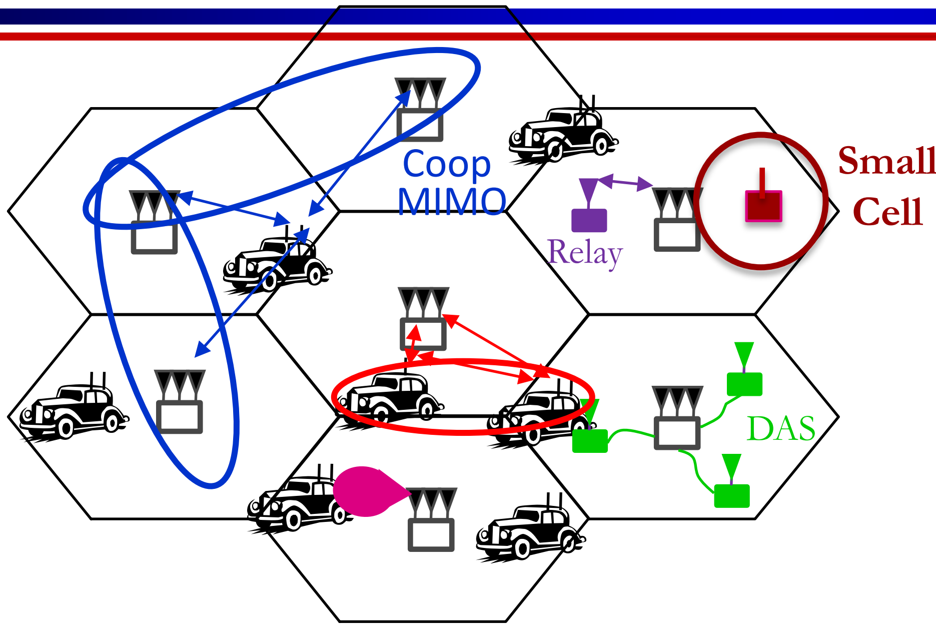
- Interacting systems require standardization
- Companies want their systems adopted as standard
  - Alternatively try for de-facto standards
- Standards determined by TIA/CTIA in US
  - IEEE standards often adopted
  - Process fraught with inefficiencies and conflicts
- Worldwide standards determined by ITU-T
  - In Europe, ETSI is equivalent of IEEE

Standards for current systems are summarized in Appendix D.

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

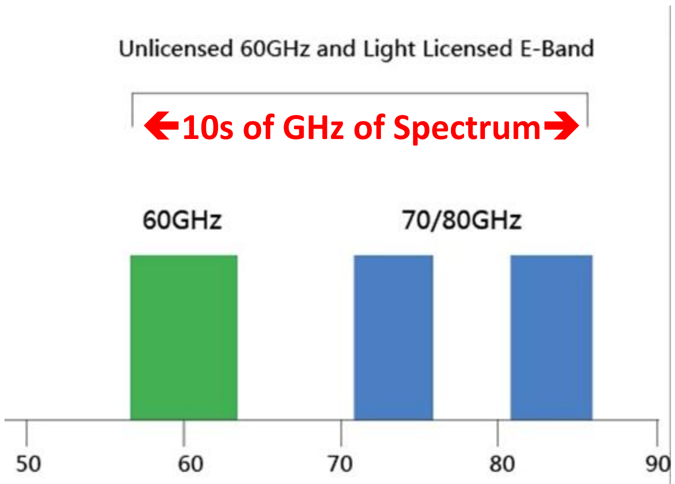
Rethinking "Cells" in Cellular

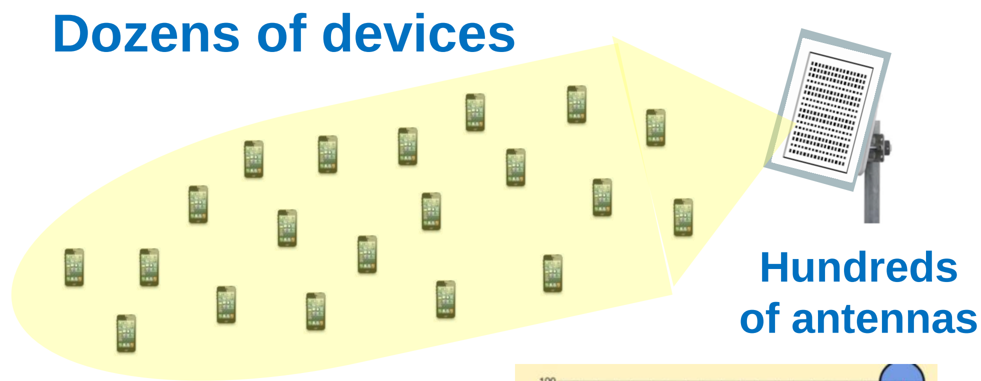


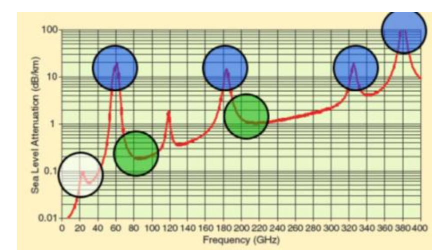
How should cellular systems be designed for
- *Capacity*
- *Coverage*
- *Energy efficiency*
- *Low latency*

- **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

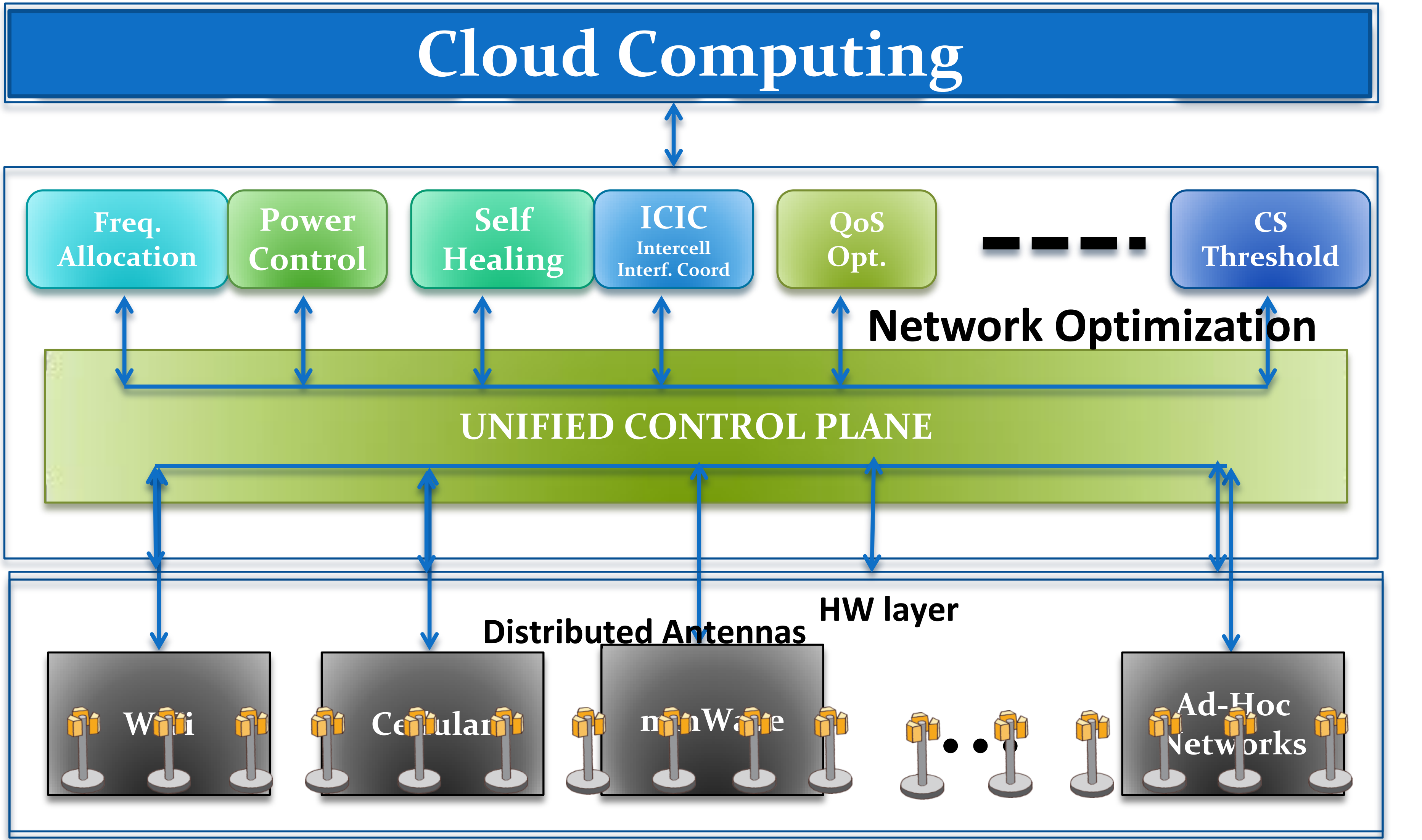




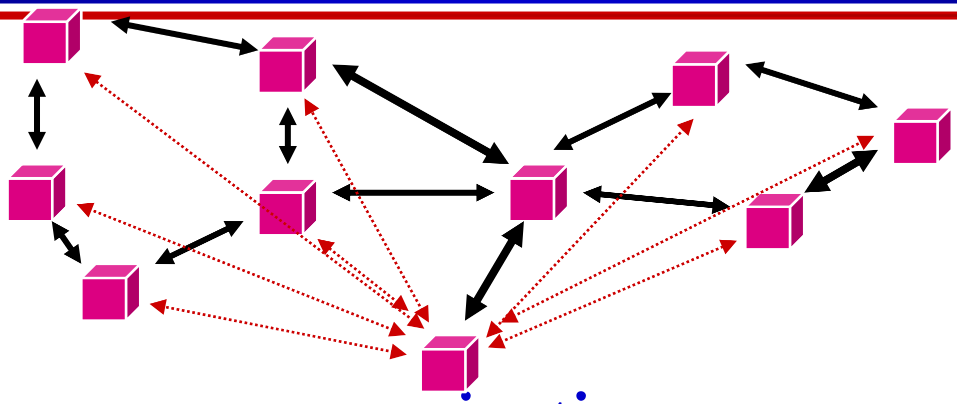


- mmWaves have large non-monotonic path loss
  - Channel model poorly understood
- For asymptotically large arrays with channel state information, no attenuation, fading, interference or noise
- mmWave antennas are small: perfect for massive MIMO
- Bottlenecks: channel estimation and system complexity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

Software-Defined Network Architectures

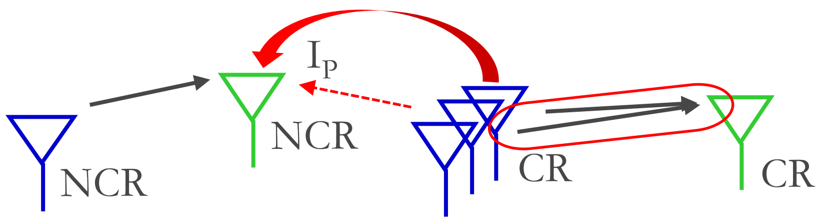


Ad-Hoc Networks

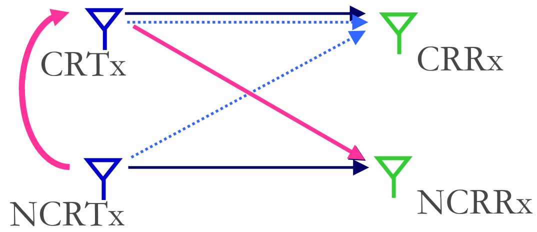


- Peer-to-peer communications
  - No backbone infrastructure or centralized control
- Routing can be multihop.
- Topology is dynamic.
- Fully connected with different link SINRs
- Open questions
  - Fundamental capacity region
  - Resource allocation (power, rate, spectrum, etc.)
  - Routing

Cognitive Radios



MIMO Cognitive Underlay

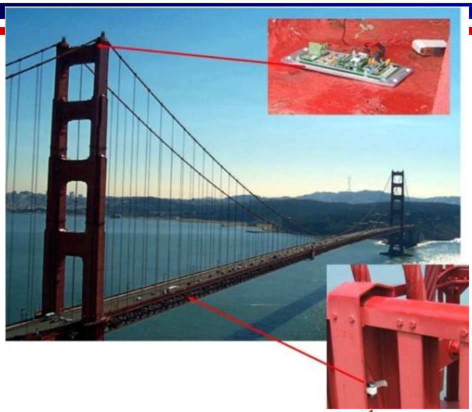


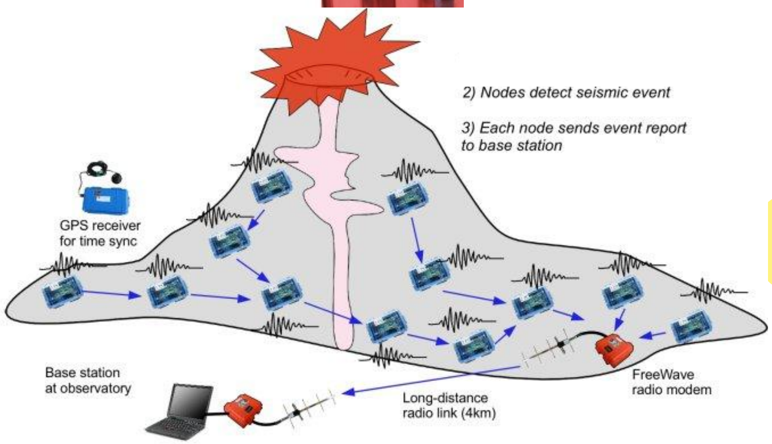
Cognitive Overlay

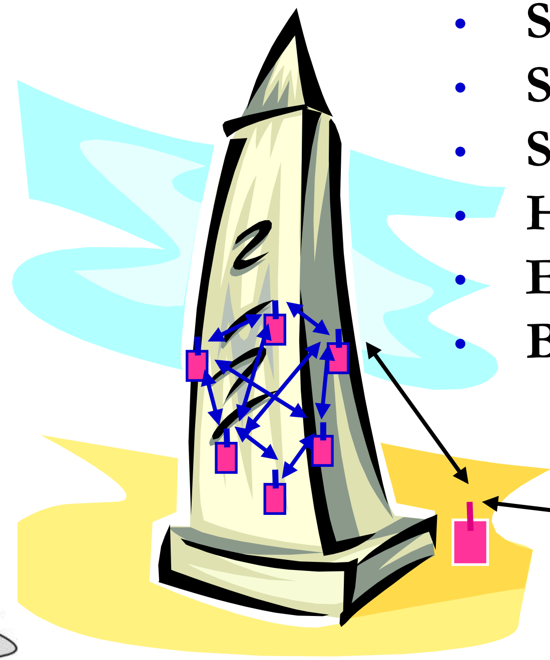
- **Cognitive radios support new users in existing crowded spectrum <u>without degrading licensed users</u>**
  - **Utilize advanced communication and DSP techniques**
  - **Coupled with novel spectrum allocation policies**

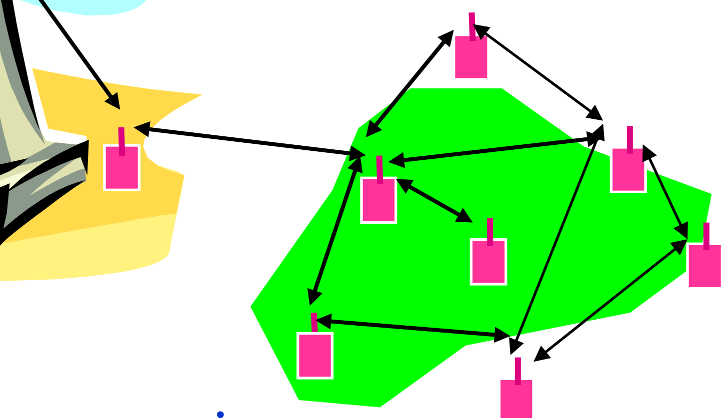
- **Multiple paradigms**
  - **(MIMO) Underlay (interference below a threshold)**
  - **Interweave finds/uses unused time/freq/space slots**
  - **Overlay (overhears/relays primary message while cancelling interference it causes to cognitive receiver)**

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

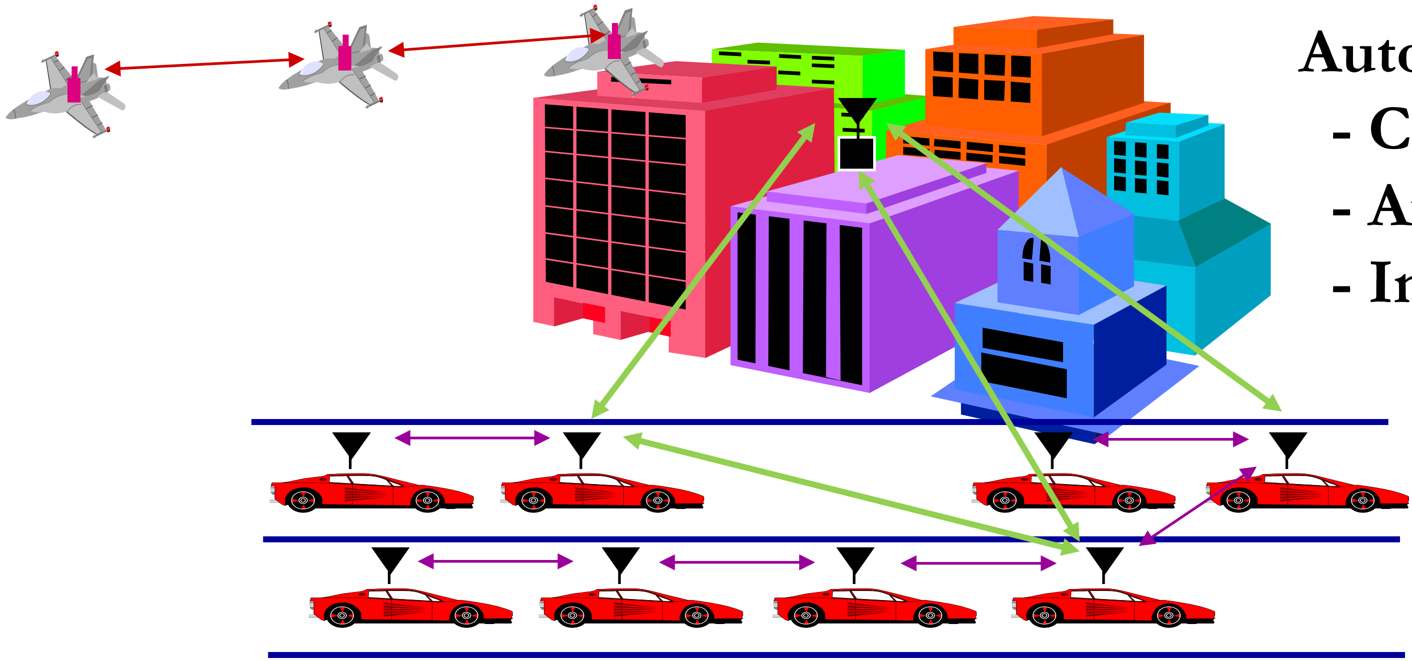
- Transmit energy minimized by sending bits slowly
  - Leads to increased circuit energy consumption

- 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

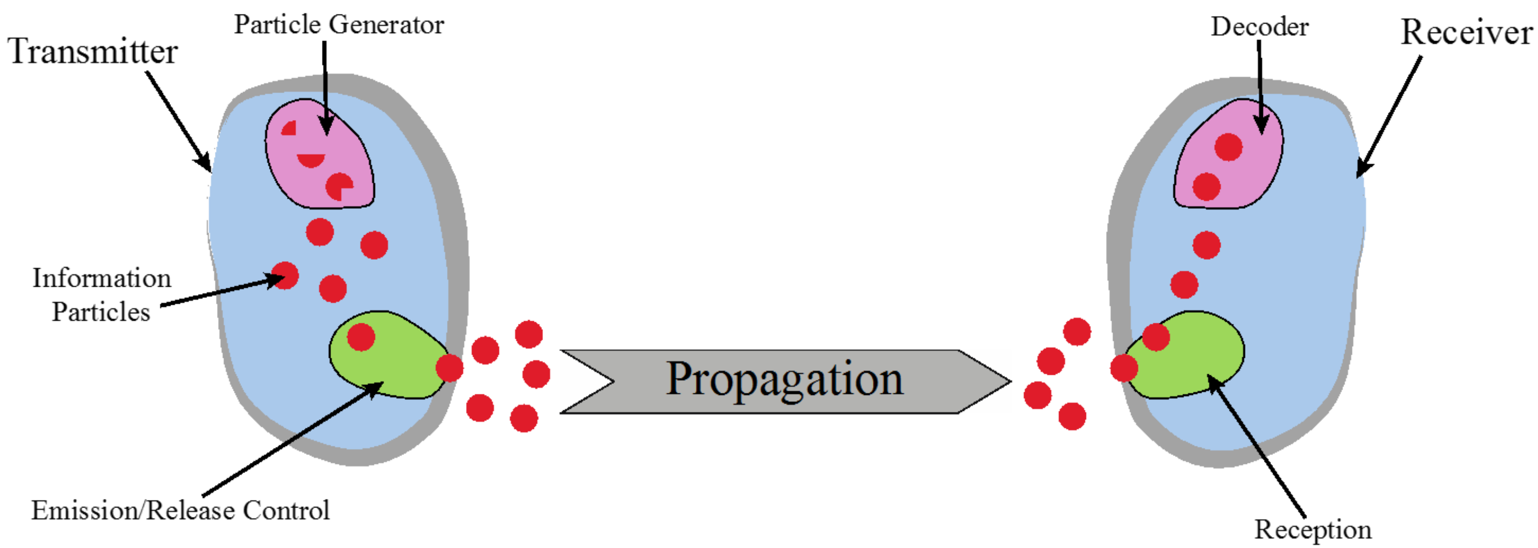


Automated Vehicles
- Cars
- Airplanes/UAVs
- Insect flyers

Interdisciplinary design approach

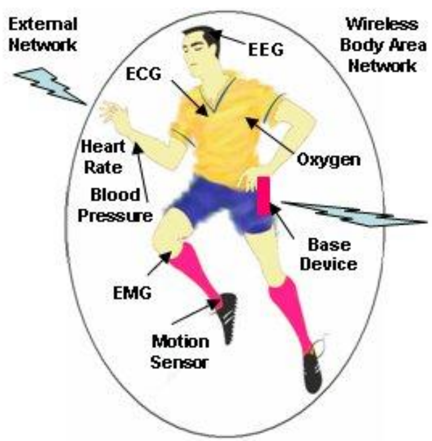
- Control requires fast, accurate, and reliable feedback.
- Wireless networks introduce delay and loss
- Need reliable networks and robust controllers
- Mostly open problems : *Many design challenges*

Chemical Communications

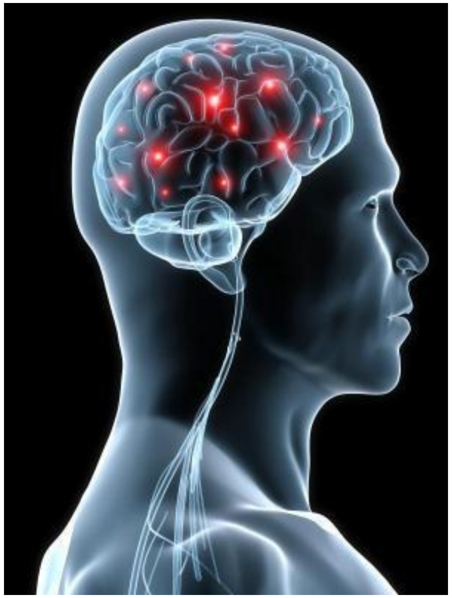


- Can be developed for both macro (>cm) and micro (<mm) scale communications
- Greenfield area of research:
  - Need new modulation schemes, channel impairment mitigation, multiple access, etc.

Applications in Health, Biomedicine and Neuroscience



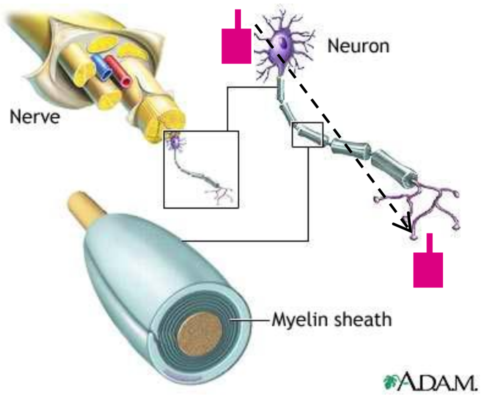
Body-Area Networks



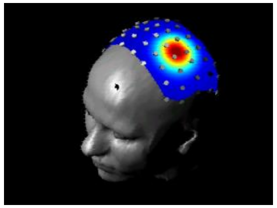
Neuroscience

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

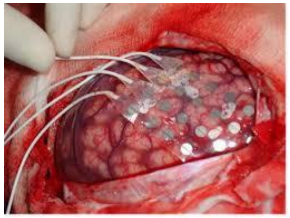
Recovery from Nerve Damage



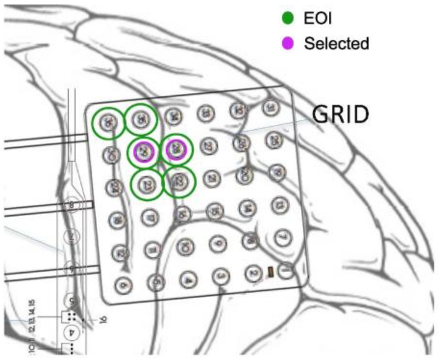
EEG



ECoG



ECoG Epileptic Seizure Localization



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