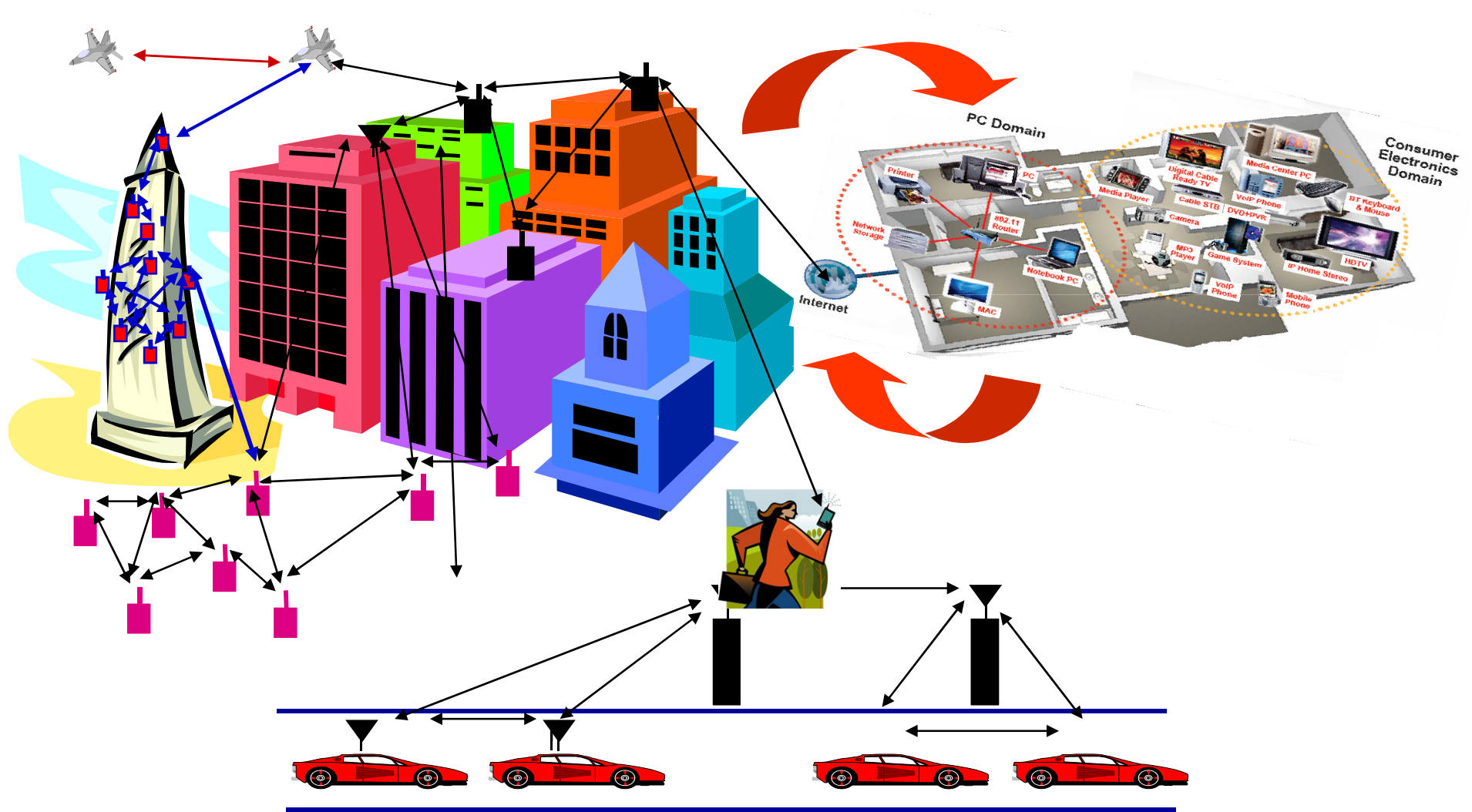


Wireless Communications



Outline

- **Course Basics**
- **Course Syllabus**
- **The Wireless Vision**
- **Technical Challenges**
- **Current Wireless Systems**
- **Emerging Wireless Systems**
- **Spectrum Regulation**
- **Standards**

Course Syllabus

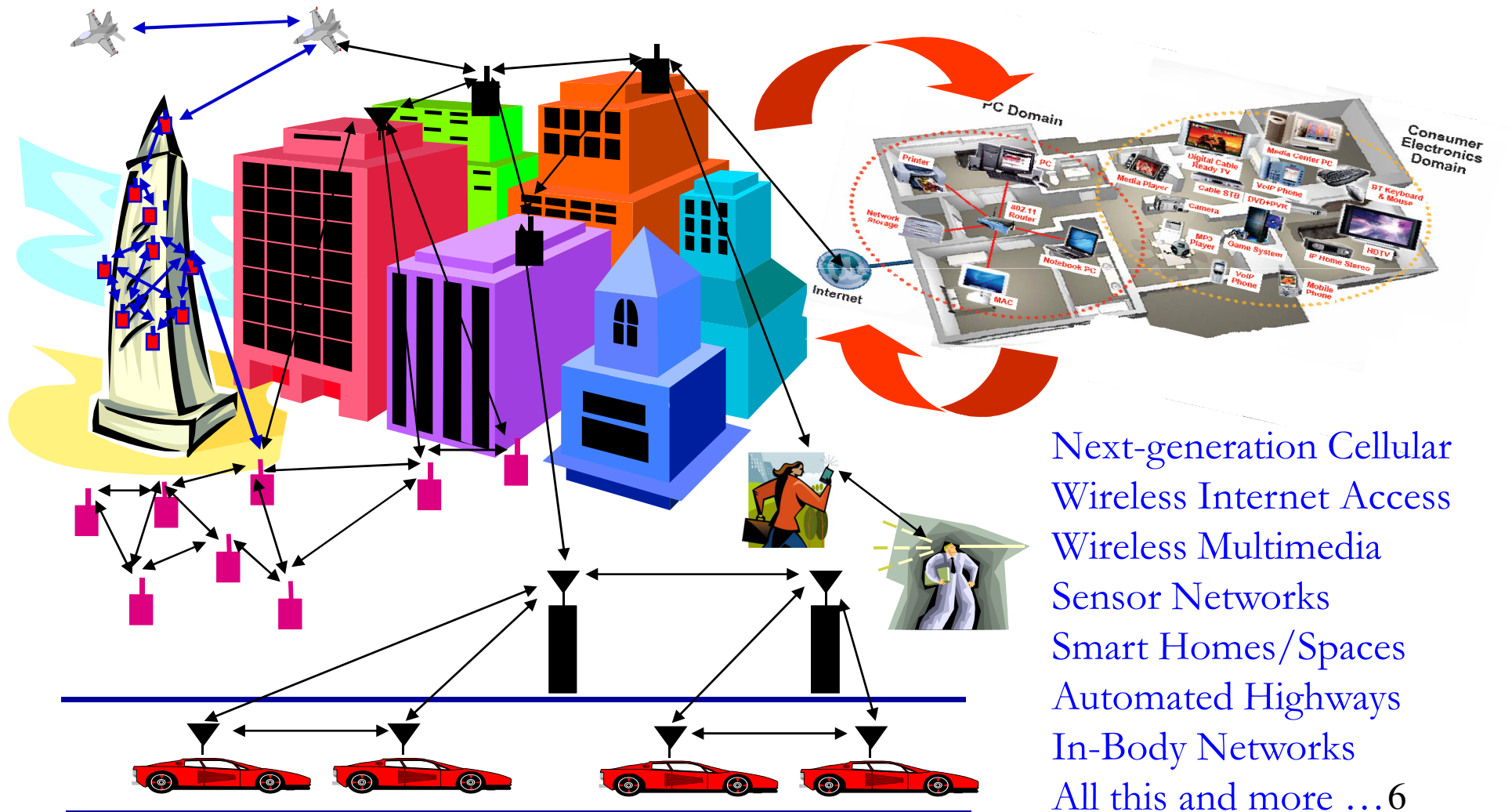
- Overview of Wireless Communications
- Path Loss, Shadowing, and Fading Models
- Capacity of Wireless Channels
- Digital Modulation and its Performance
- Adaptive Modulation
- Diversity
- MIMO Systems
- Multicarrier Modulation
- Spread Spectrum
- Multiuser Communications & Wireless Networks 4

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
- Cellular has enjoyed exponential growth since 1988, with almost 3 billion users worldwide today
 - Ignited the wireless revolution
 - Voice, data, and multimedia becoming ubiquitous
 - Use in third world countries growing rapidly
- Wifi also enjoying tremendous success and growth
 - Wide area networks (e.g. Wimax) and short-range systems other than Bluetooth (e.g. UWB) less successful

Future Wireless Networks

Ubiquitous Communication Among People and Devices



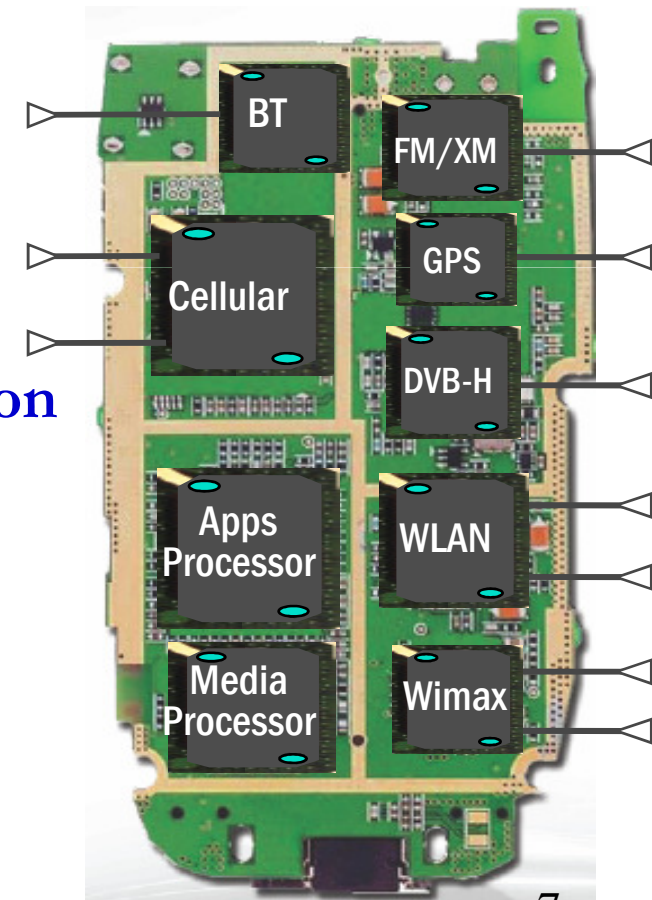
Challenges

- **Network Challenges**

- Scarce spectrum
- Demanding/diverse applications
- Reliability
- Ubiquitous coverage
- Seamless indoor/outdoor operation

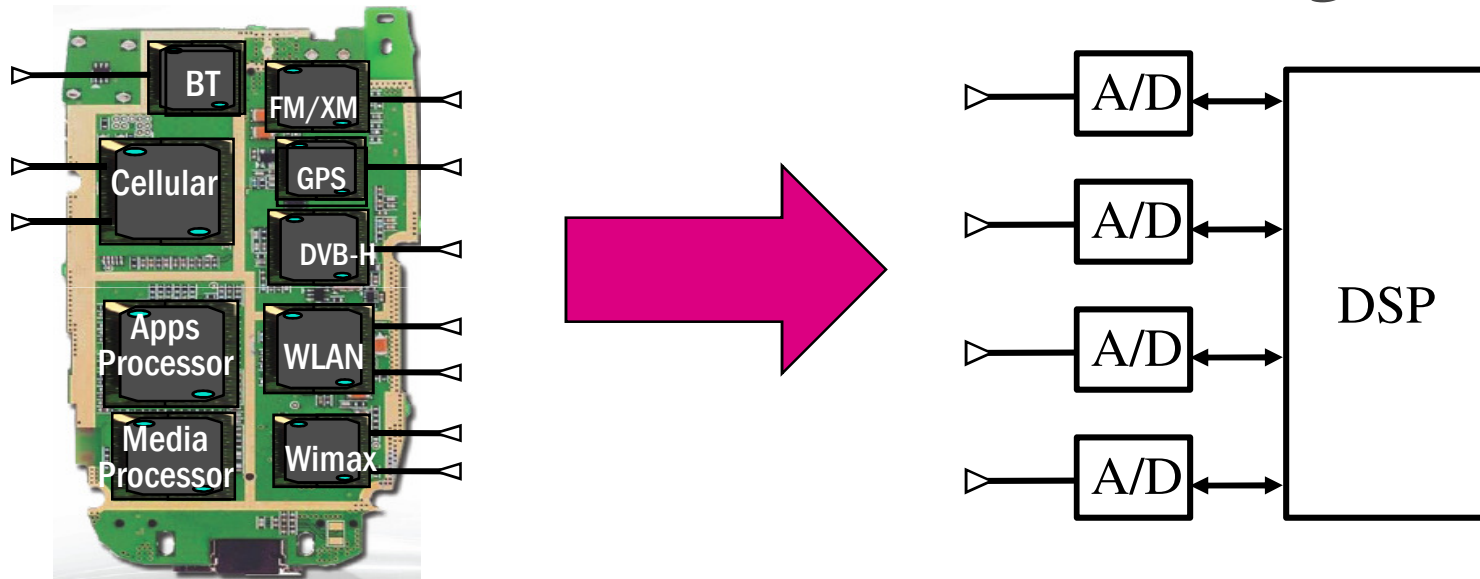
- **Device Challenges**

- Size, Power, Cost
- Multiple Antennas in Silicon
- Multiradio Integration
- Coexistence



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

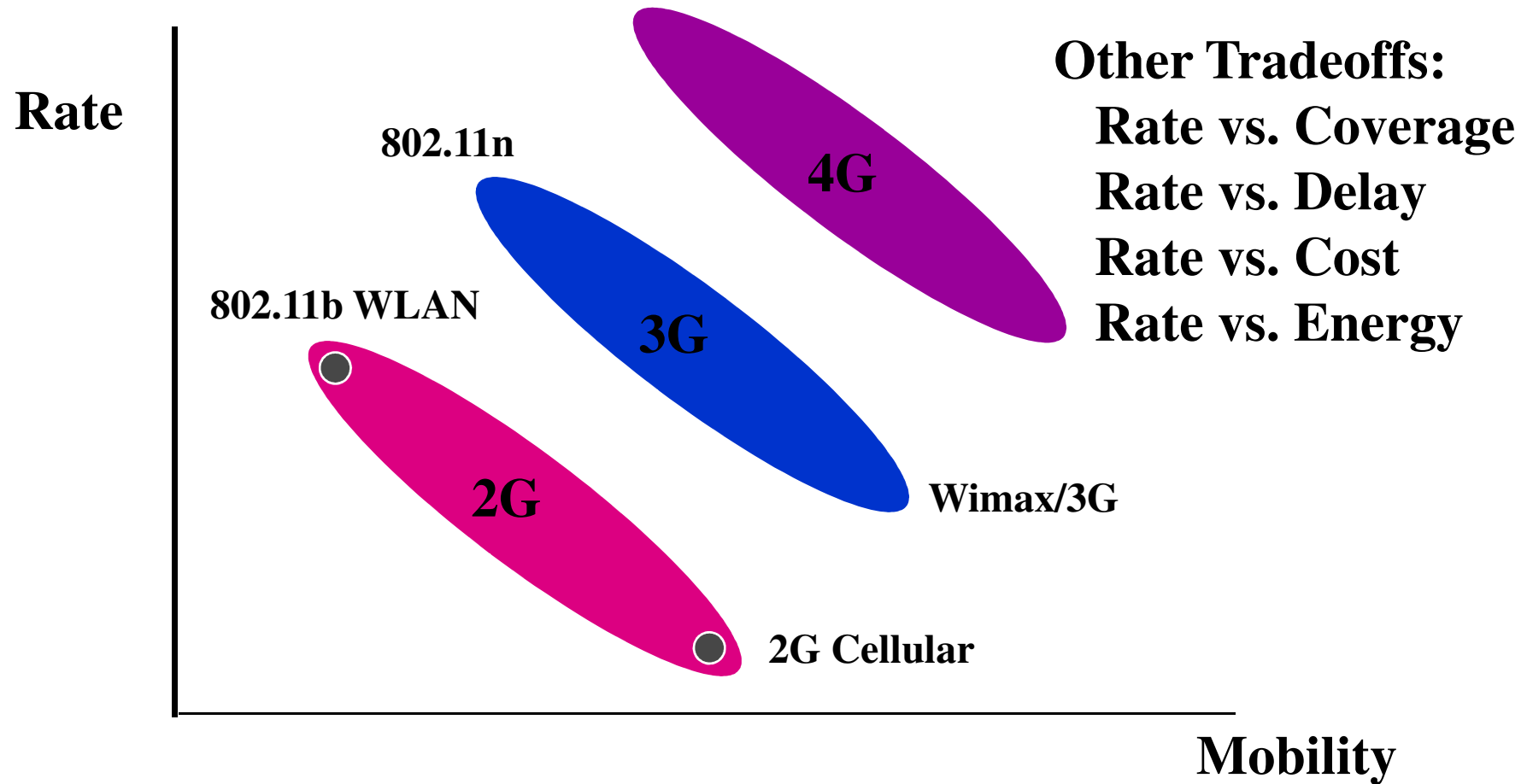
Today, this is not cost, size, or power efficient

Compressed sensing may be a solution for sparse signals ⁸

Evolution of Current Systems

- **Wireless systems today**
 - **3G Cellular:** ~200-300 Kbps.
 - **WLANs:** ~450 Mbps (and growing).
- **Next Generation is in the works**
 - **4G Cellular:** OFDM/MIMO
 - **4G WLANs:** Wide open, 3G just being finalized
- **Technology Enhancements**
 - **Hardware:** Better batteries. Better circuits/processors.
 - **Link:** More bandwidth, more antennas, better modulation and coding, adaptivity, cognition.
 - **Network:** better resource allocation, cooperation, relaying, femtocells.
 - **Application:** Soft and adaptive QoS.

Future Generations



Fundamental Design Breakthroughs Needed

Multimedia Requirements

	Voice	Data	Video
Delay	<100ms	-	<100ms
Packet Loss	<1%	0	<1%
BER	10^{-3}	10^{-6}	10^{-6}
Data Rate	8-32 Kbps	10-1000 Mbps	10-1000 Mbps
Traffic	Continuous	Bursty	Continuous

One-size-fits-all protocols and design do not work well

Wired networks use this approach, with poor results

Quality-of-Service (QoS)

- QoS refers to the requirements associated with a given application, typically rate and delay requirements.
- It is hard to make a one-size-fits all network that supports requirements of different applications.
- Wired networks often use this approach with poor results, and they have much higher data rates and better reliability than wireless.
- QoS for all applications requires a cross-layer design approach.

Crosslayer Design

- Application
- Network
- Access
- Link
- Hardware



Delay Constraints
Rate Constraints
Energy Constraints

Adapt across design layers
Reduce uncertainty through scheduling
Provide robustness via diversity

Current Wireless Systems

- Cellular Systems
- Wireless LANs
- Wimax
- Satellite Systems
- Paging Systems
- Bluetooth
- Zigbee radios

Cellular Phones

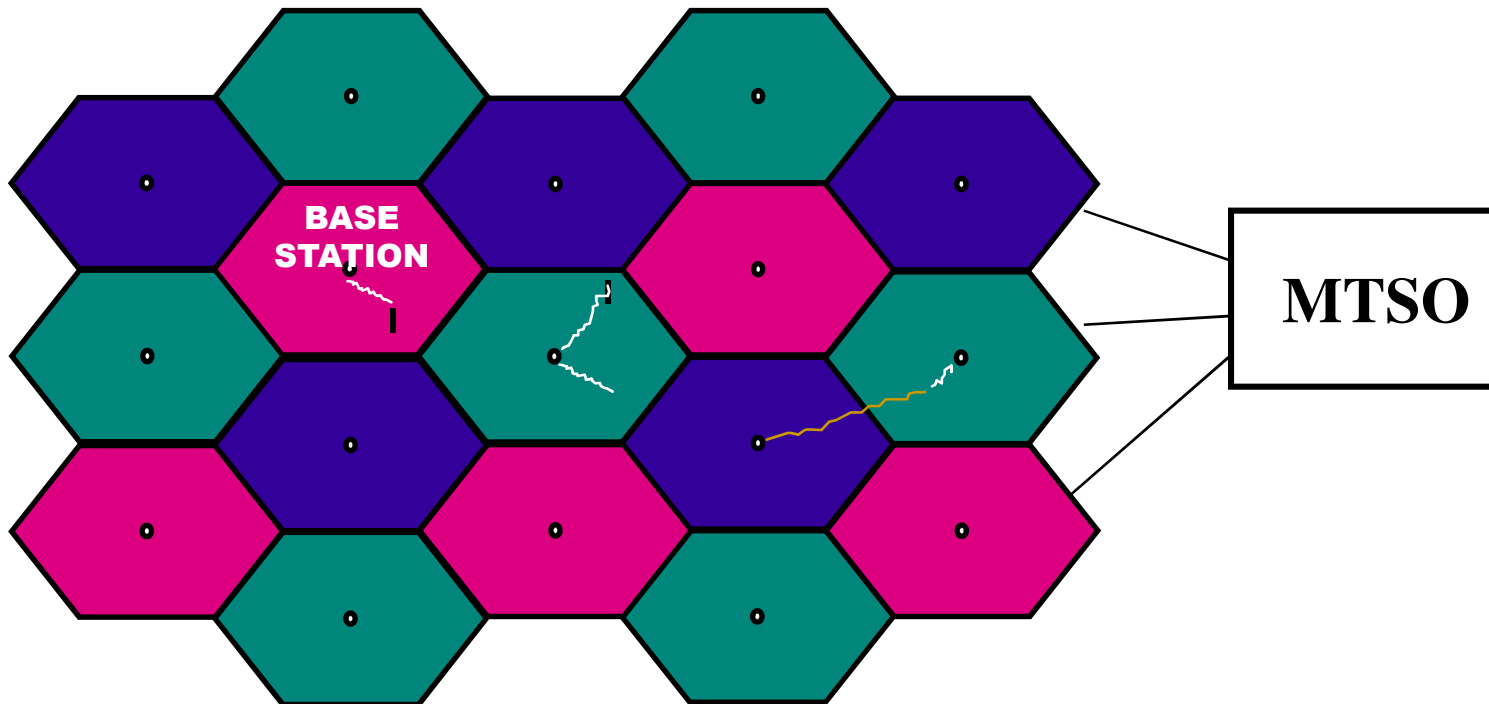
Everything Wireless in One Device



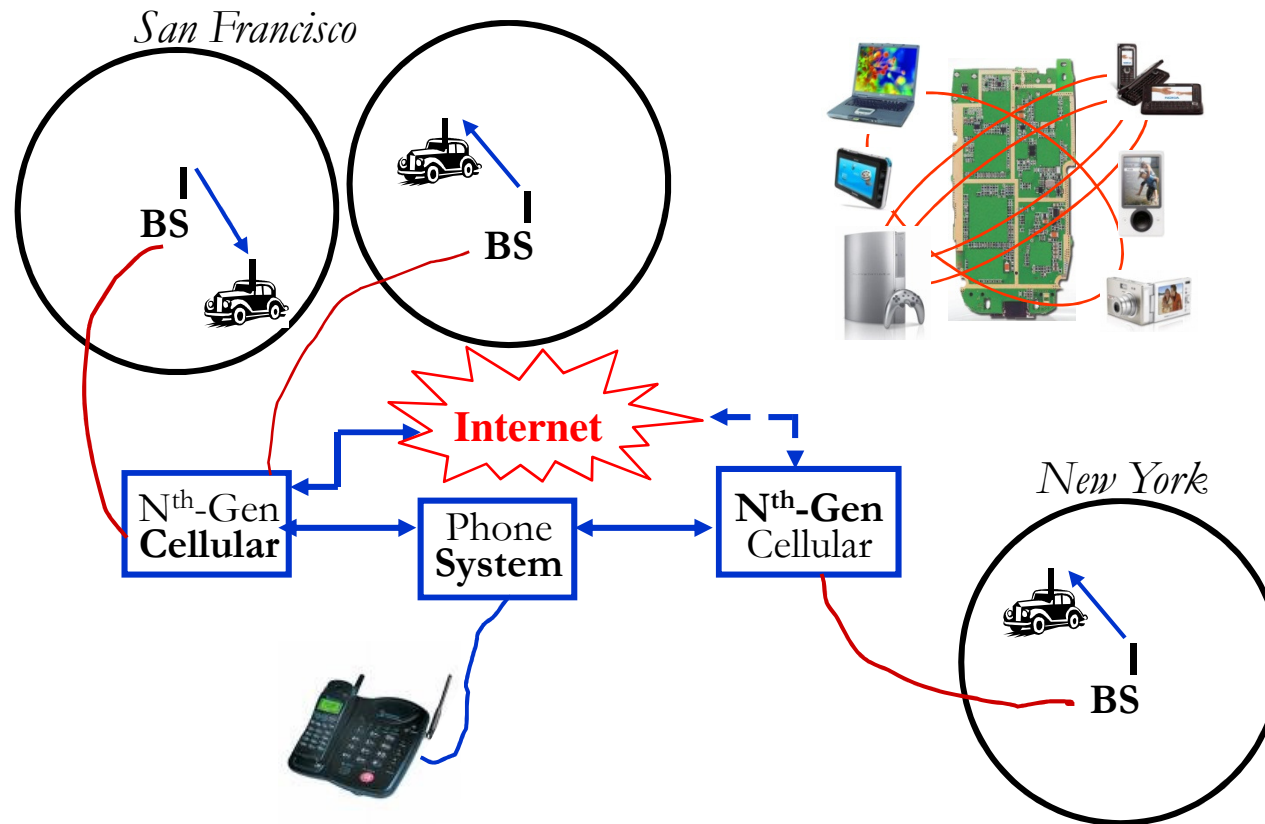
Cellular Systems:

Reuse channels to maximize capacity

- Geographic region divided into cells
- Frequency/timeslots/codes/ reused at spatially-separated locations.
- Co-channel interference between same color cells.
- Base stations/MTSOs coordinate handoff and control functions
- Shrinking cell size increases capacity, as well as networking burden



Cellular Networks



Future networks want better performance and reliability
- *Gbps rates, low latency, 99% coverage indoors and out*₁₇

3G Cellular Design: Voice and Data

- Data is bursty, whereas voice is continuous
 - Typically require different access and routing strategies
- 3G “widens the data pipe”:
 - 384 Kbps (802.11n has 100s of Mbps).
 - Standard based on wideband CDMA
 - Packet-based switching for both voice and data
 - 3G cellular popular in Asia and Europe
- Evolution of existing systems in US (2.5G++)
 - GSM+EDGE, IS-95(CDMA)+HDR
 - 100 Kbps may be enough
 - Dual phone (2/3G+Wifi) use growing (iPhone, Google)
- What is beyond 3G?

4G/LTE/IMT Advanced

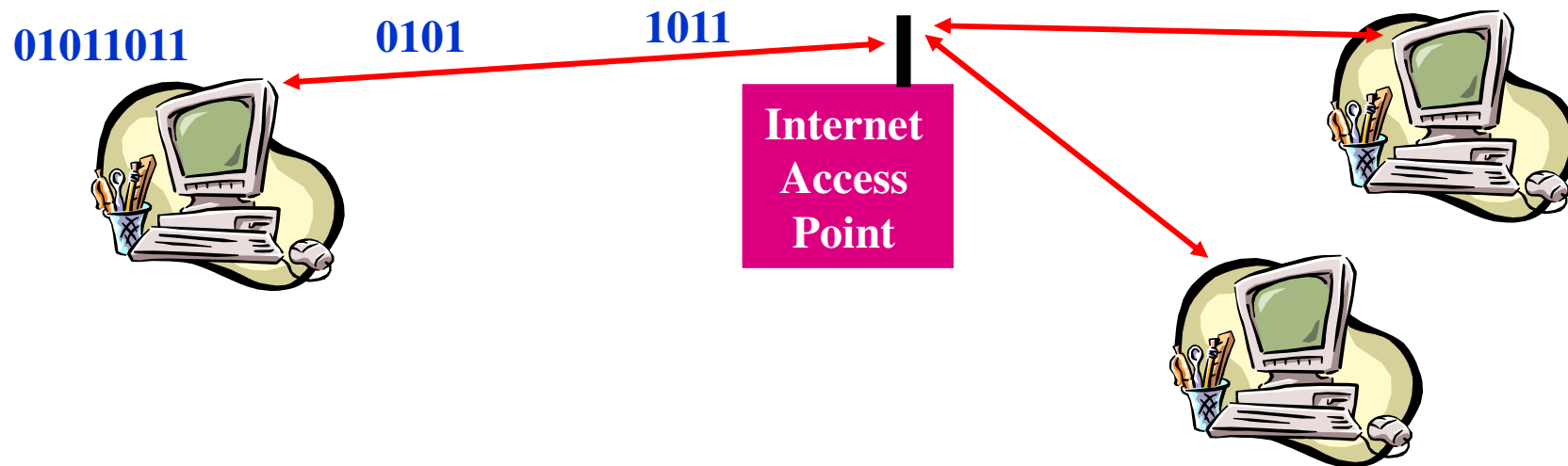
- Much higher peak data rates (50-100 Mbps)
- Greater spectral efficiency (bits/s/Hz)
- Flexible use of up to 100 MHz of spectrum
- Low packet latency (<5ms).
- Increased system capacity
- Reduced cost-per-bit
- Support for multimedia

Wifi Networks

Multimedia Everywhere, *Without Wires*




Wireless Local Area Networks (WLANs)



- WLANs connect “local” computers (100m range)
- Breaks data into packets
- Channel access is shared (random access)
- 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. 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 (young pup)**  **802.11ac/ad**
 - Standard in 2.4 GHz and 5 GHz band
 - Adaptive OFDM /MIMO in 20/40 MHz (2-4 antennas)
 - Speeds up to 600Mbps, approx. 200 ft range
 - Other advances in packetization, antenna use, etc.

Many
WLAN
cards
have
all 3
(a/b/g)

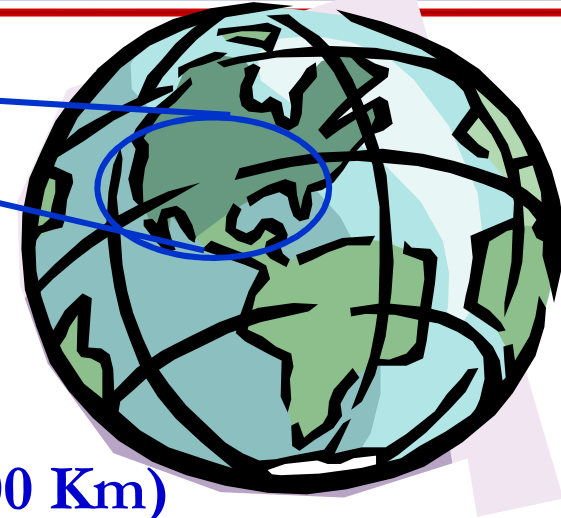
Wimax (802.16)

- **Wide area wireless network standard**
 - System architecture similar to cellular
 - Called “3.xG” (e.g. Sprint EVO), evolving into 4G
- **OFDM/MIMO is core link technology**
- **Operates in 2.5 and 3.5 GHz bands**
 - Different for different countries, 5.8 also used.
 - Bandwidth is 3.5-10 MHz
- **Fixed (802.16d) vs. Mobile (802.16e) Wimax**
 - Fixed: 75 Mbps max, up to 50 mile cell radius
 - Mobile: 15 Mbps max, up to 1-2 mile cell radius

WiGig and Wireless HD

- New standards operating in 60 GHz band
- Data rates of 7-25 Gbps
- Bandwidth of around 10 GHz (unregulated)
- Range of around 10m (can be extended)
- Uses/extends 802.11 MAC Layer
- Applications include PC peripherals and displays for HDTVs, monitors & projectors

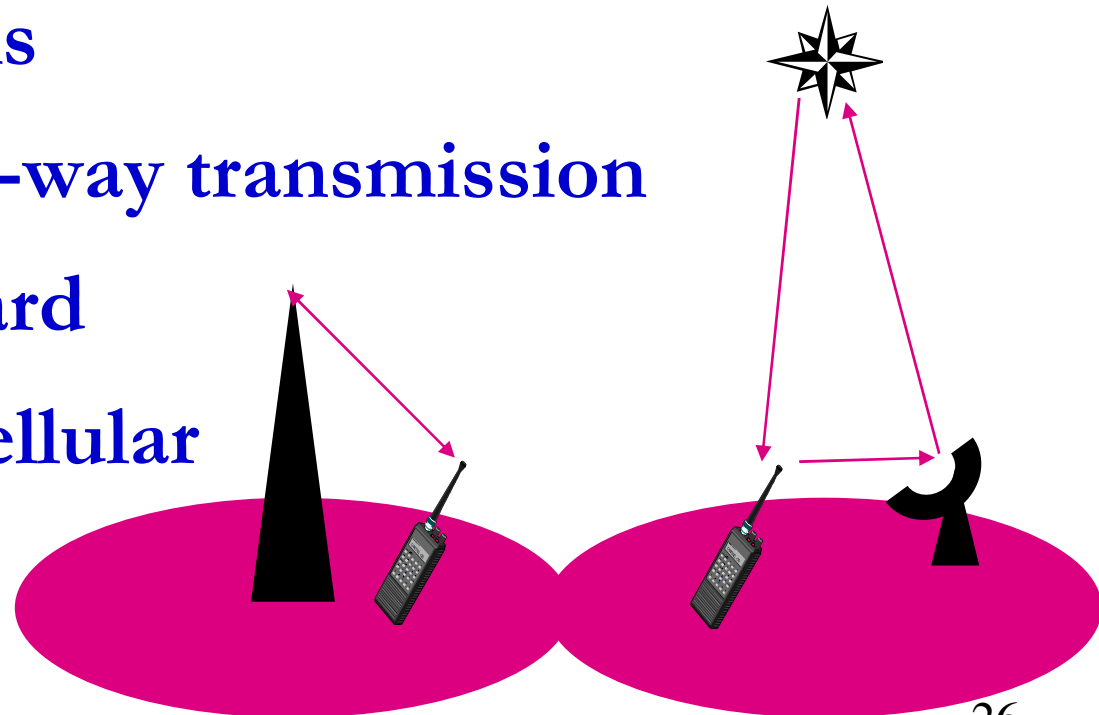
Satellite Systems



- 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 struggling or bankrupt
- Global Positioning System (GPS) use growing
 - Satellite signals used to pinpoint location
 - Popular in cell phones, PDAs, and navigation devices

Paging Systems

- Broad coverage for short messaging
- Message broadcast from all base stations
- Simple terminals
- Optimized for 1-way transmission
- Answer-back hard
- Overtaken by cellular



Bluetooth

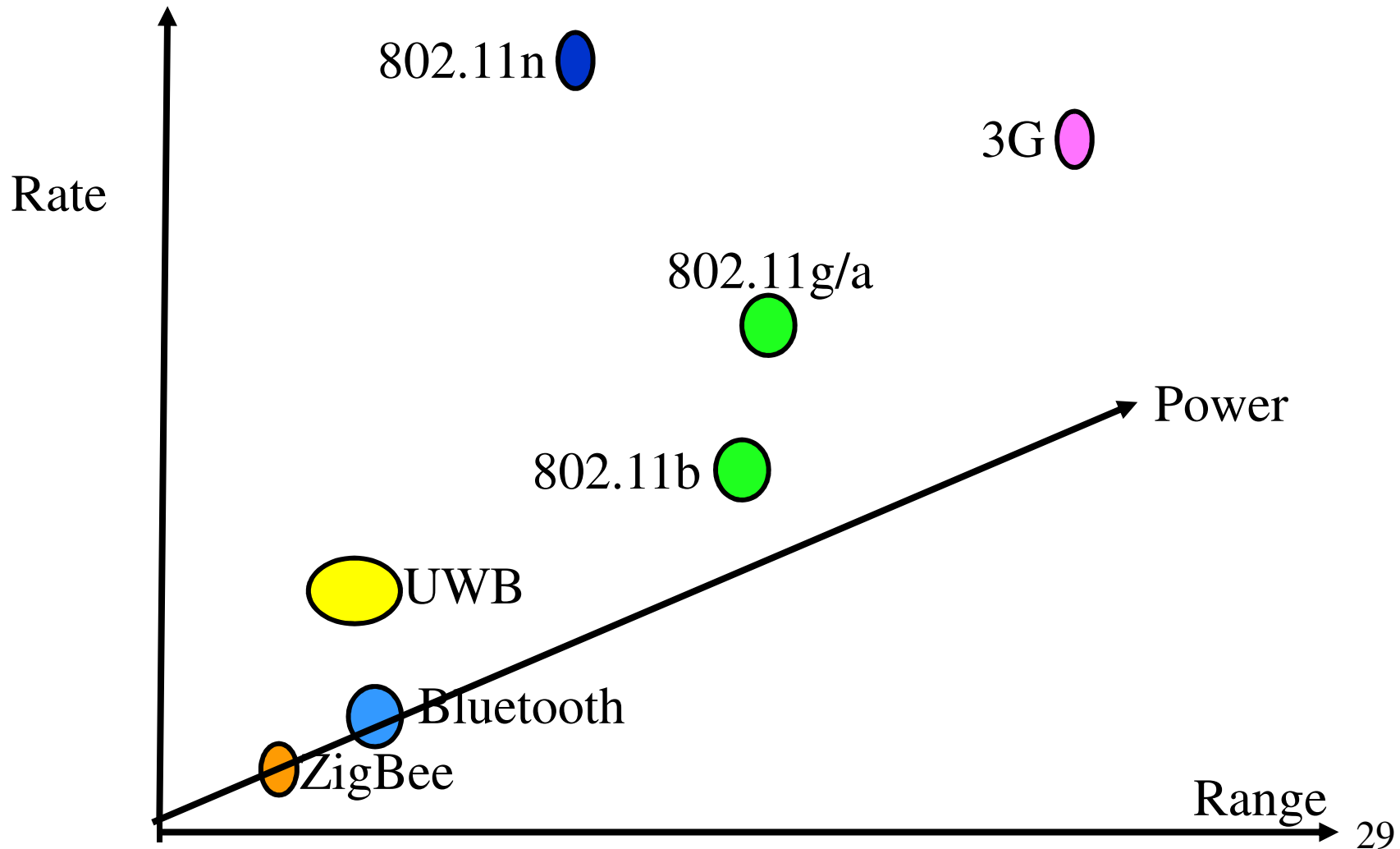
- Cable replacement RF technology (low cost)
- Short range (10m, extendable to 100m)
- 2.4 GHz band (crowded)
- 1 Data (700 Kbps) and 3 voice channels, up to 3 Mbps
- Widely supported by telecommunications, PC, and consumer electronics companies
- Few applications beyond cable replacement

IEEE 802.15.4/ZigBee Radios


- Low-Rate WPAN
- Data rates of 20, 40, 250 Kbps
- Support for large mesh networking or star clusters
- Support for low latency devices
- CSMA-CA channel access
- Very low power consumption
- Frequency of operation in ISM bands

Focus is primarily on low power sensor networks

Tradeoffs



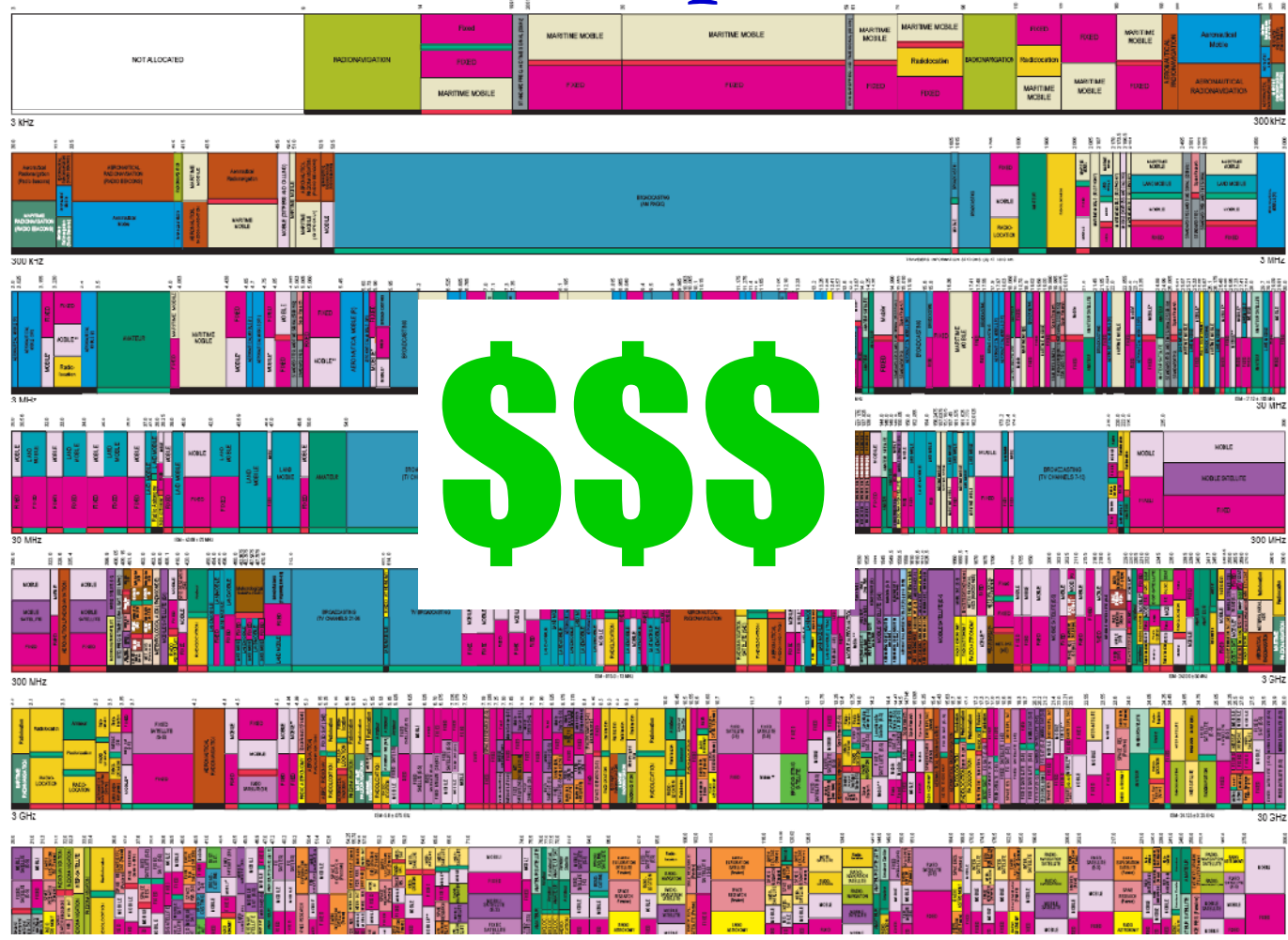
Scarce Wireless Spectrum

 **UNITED STATES FREQUENCY ALLOCATIONS**
THE RADIO SPECTRUM

RADIO SERVICES CO OR I FOUND

-  AEROMOBILE MOBILE
-  AEROMOBILE MOBILE SATELLITE
-  AEROMOBILE FIXED/NAVIGATION
-  AEROMOBILE MARITIME
-  AEROMOBILE MARITIME SATELLITE
-  AEROMOBILE BROADCASTING
-  AEROMOBILE BROADCASTING SATELLITE
-  AEROMOBILE EARTH EXPLORATION
-  AEROMOBILE FIXED
-  AEROMOBILE FIXED SATELLITE
-  AEROMOBILE MOBILE SATELLITE
-  AEROMOBILE MARITIME SATELLITE
-  AEROMOBILE MARITIME MOBILE
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-  AEROMOBILE MARITIME MOBILE SATELLITE

- ACTIVITY CODE
-  GOVERNMENT EXCLUDE
 -  NON-GOVERNMENT EXCLUDE
 -  GOVERNMENT FROM GOVERNMENT CHANNEL
- ALLOCATION USAGE DESIGNATION



and Expensive

Spectrum Regulation

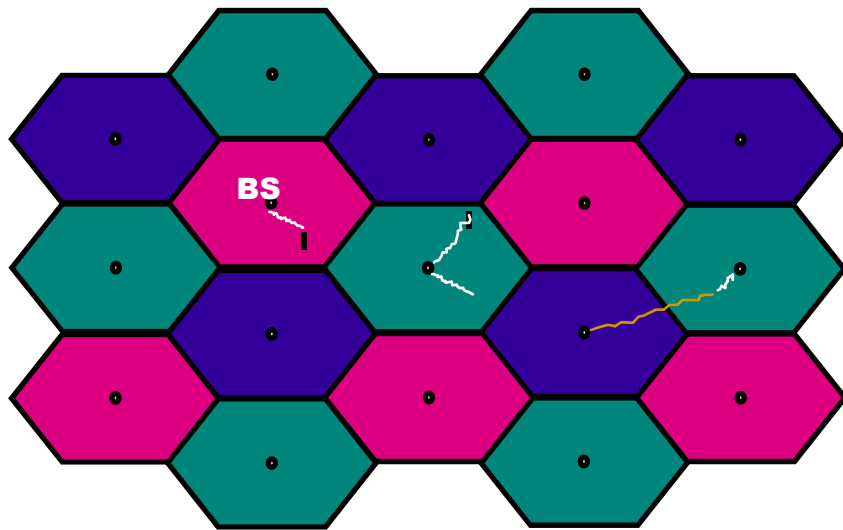
- Spectrum a scarce public resource, hence allocated
- Spectral allocation in US controlled by FCC (commercial) or OSM (defense)
- FCC auctions spectral blocks for set applications.
- Some spectrum set aside for universal use
- Worldwide spectrum controlled by ITU-R
- Regulation is a necessary evil.

Innovations in regulation being considered worldwide, including underlays, overlays, and cognitive radios¹

Spectral Reuse

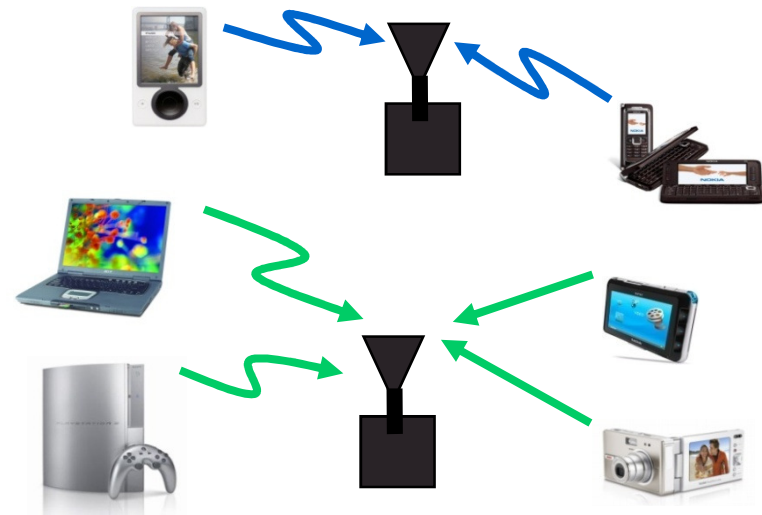
Due to its scarcity, spectrum is *reused*

In licensed bands



Cellular, Wimax

and unlicensed bands



Wifi, BT, UWB,...

Reuse introduces interference

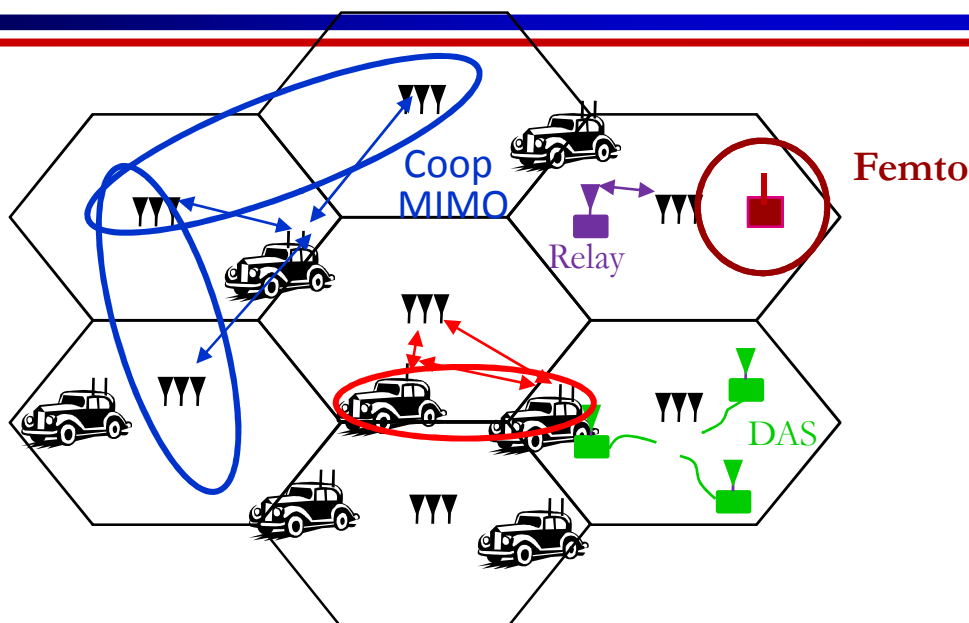
Interference: *Friend or Foe?*

If exploited via
cooperation and cognition

Friend

Especially in a network setting

Rethinking “Cells” in Cellular



How should cellular systems be designed?

Will gains in practice be big or incremental; in capacity or coverage?

- **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
 - Femtocells create a cell within a cell
 - Mobile cooperation via relays, virtual MIMO, network coding.

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

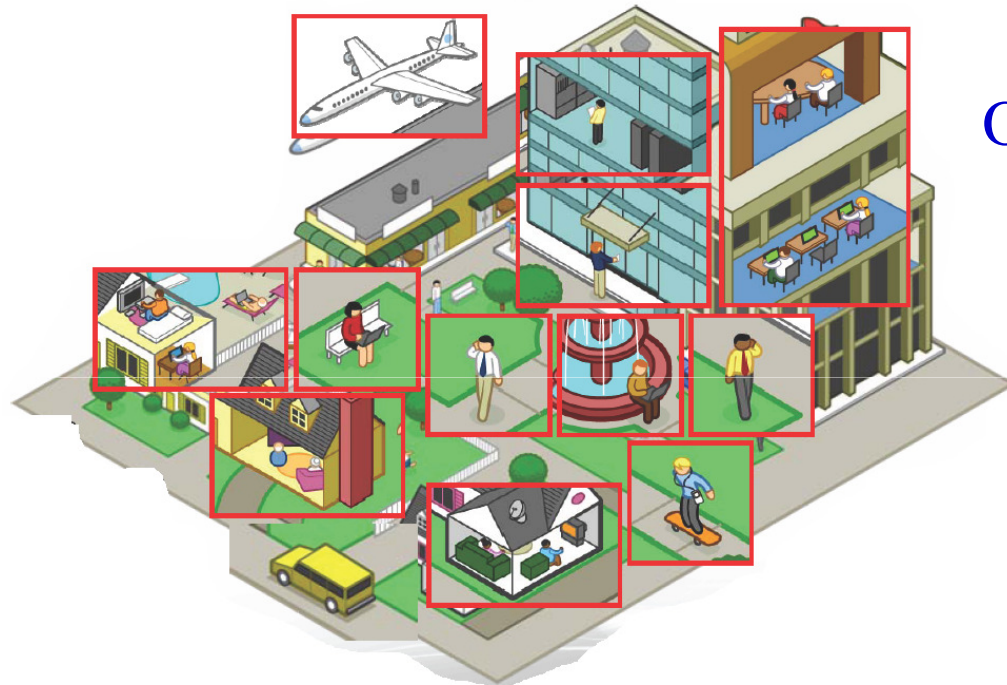
Standards for current systems are summarized in Appendix D.

Emerging Systems*

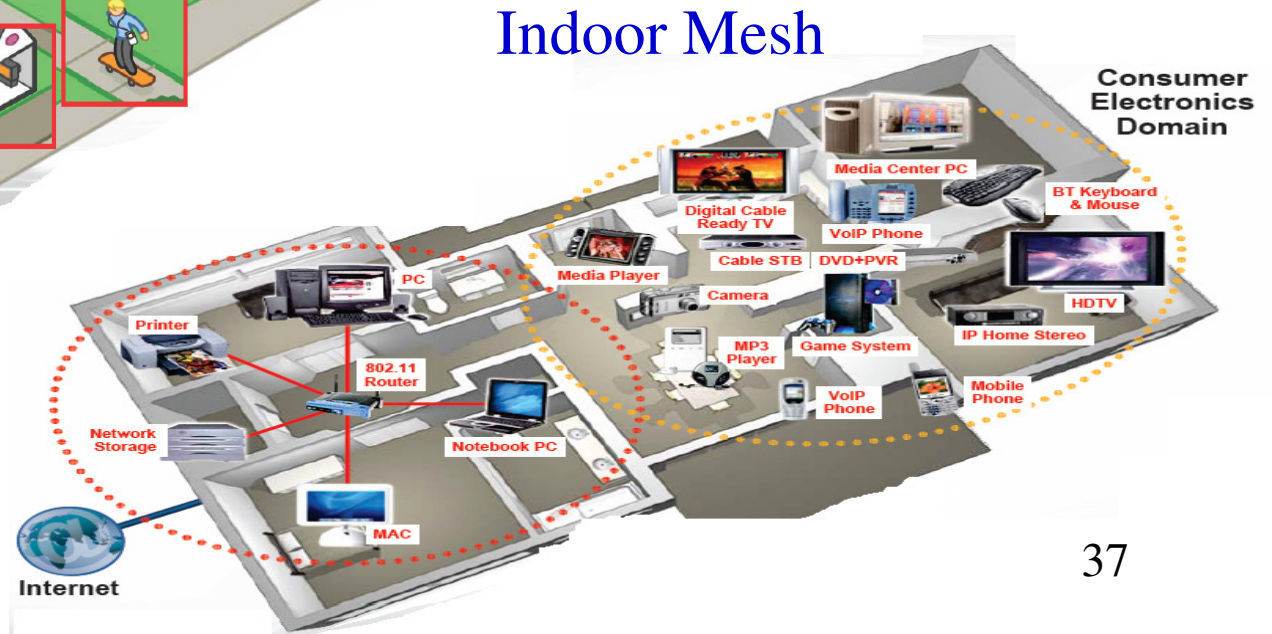
- 4th generation cellular (4G)
 - OFDMA is the PHY layer
 - Other new features and bandwidth still in flux
- Ad hoc/mesh wireless networks
- Cognitive radios
- Sensor networks
- Distributed control networks
- Biomedical networks

*Can have a bonus lecture on this topic late in the quarter if there is interest

Ad-Hoc/Mesh Networks



Outdoor Mesh



Indoor Mesh

Design Issues

- Ad-hoc networks provide a flexible network infrastructure for many emerging applications.
- The capacity of such networks is generally unknown.
- Transmission, access, and routing strategies for ad-hoc networks are generally ad-hoc.
- Crosslayer design critical and very challenging.
- Energy constraints impose interesting design tradeoffs for communication and networking.

Cognitive Radios

- Cognitive radios can support new wireless users in existing crowded spectrum
 - Without degrading performance of existing users
- Utilize advanced communication and signal processing techniques
 - Coupled with novel spectrum allocation policies
- Technology could
 - Revolutionize the way spectrum is allocated worldwide
 - Provide sufficient bandwidth to support higher quality and higher data rate products and services

Cognitive Radio Paradigms

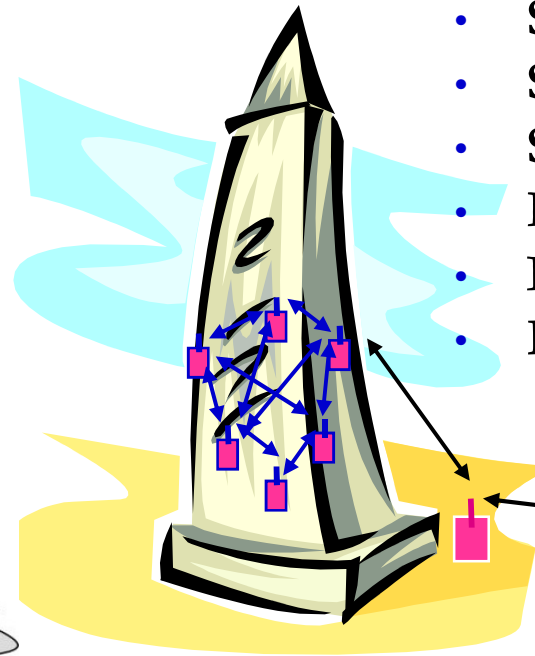
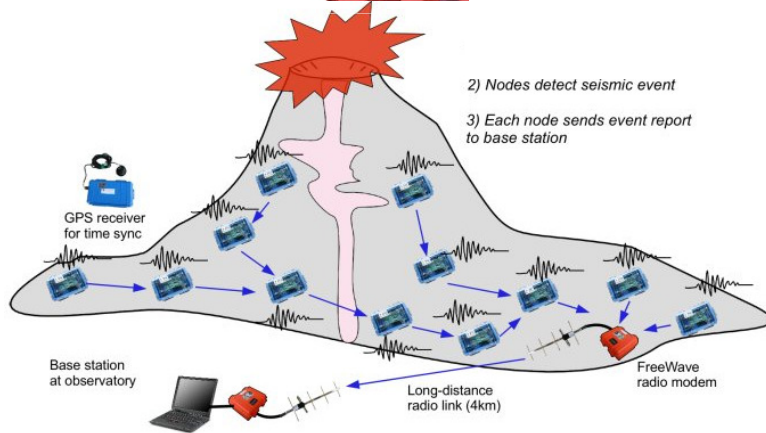
- Underlay
 - Cognitive radios constrained to cause minimal interference to noncognitive radios
- Interweave
 - Cognitive radios find and exploit spectral holes to avoid interfering with noncognitive radios
- Overlay
 - Cognitive radios overhear and enhance noncognitive radio transmissions



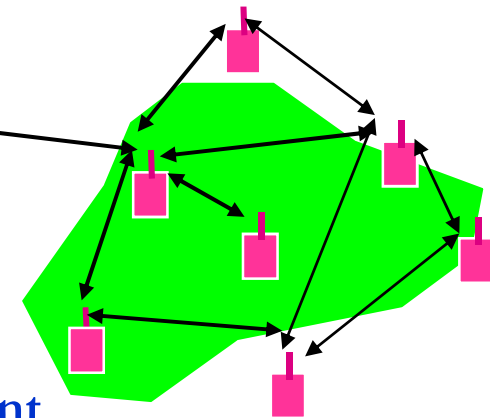
Knowledge
and
Complexity

Wireless Sensor Networks

Data Collection and Distributed Control



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

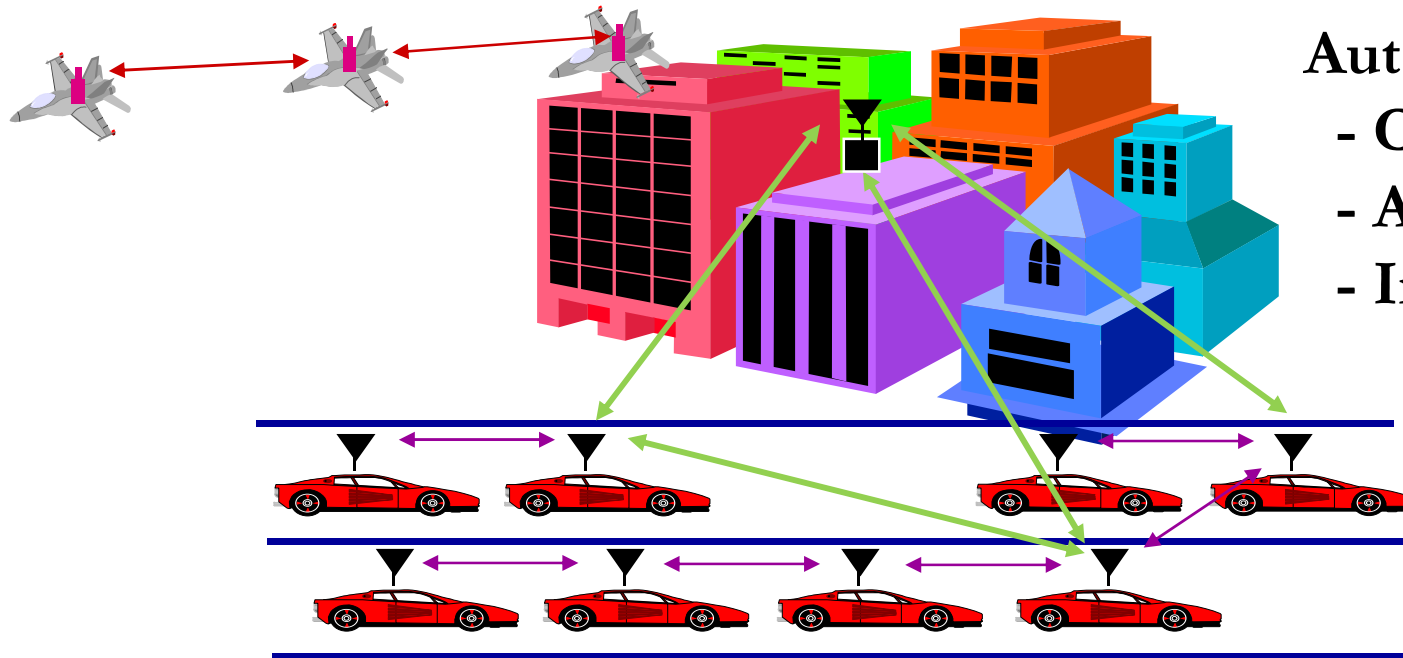


- **Energy (transmit and processing) is the driving constraint**
- **Data flows to centralized location (joint compression)**
- **Low per-node rates but tens to thousands of nodes**
- **Intelligence is in the network rather than in the devices**

Energy-Constrained Nodes

- Each node can only send a finite number of bits.
 - Transmit energy minimized by maximizing bit time
 - Circuit energy consumption increases with bit time
 - Introduces a delay versus energy tradeoff for each bit
- Short-range networks must consider transmit, circuit, and processing energy.
 - Sophisticated techniques not necessarily energy-efficient.
 - Sleep modes save energy but complicate networking.
- Changes **everything** about the network design:
 - Bit allocation must be optimized across all protocols.
 - Delay vs. throughput vs. node/network lifetime tradeoffs.
 - Optimization of node cooperation.

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*

Main Points

- The wireless vision encompasses many exciting systems and applications
- Technical challenges transcend across all layers of the system design.
- Cross-layer design emerging as a key theme in wireless.
- Existing and emerging systems provide excellent quality for certain applications but poor interoperability.
- Standards and spectral allocation heavily impact the evolution of wireless technology