Acknowledgement

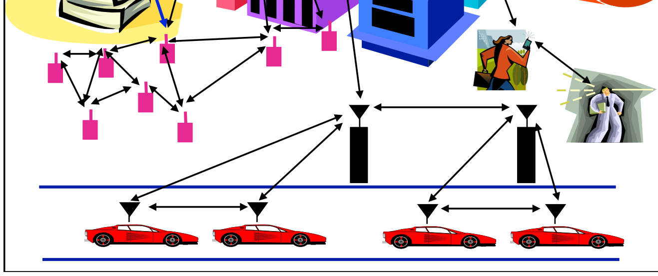
- Slides derived from class material posted by Dr. A. Goldsmith
- www.stanford.edu/class/ee359/lectures.html
- See also: A. Goldsmith, *Wireless Communications*, Cambridge Press

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

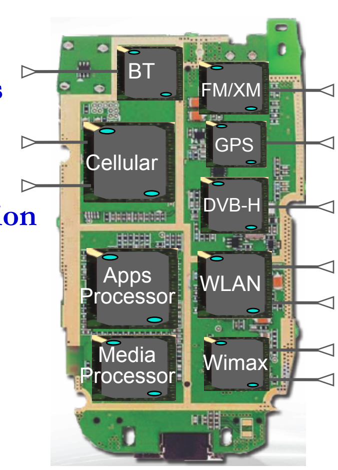
Ubiquitous Communication Among People and Devices



Next-generation Cellular
Wireless Internet Access
Wireless Multimedia
Sensor Networks
Smart Homes/Spaces
Automated Highways
In-Body Networks
All this and more …

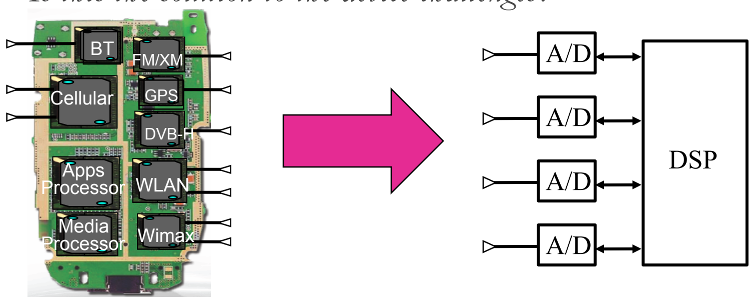
Challenges

- **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**
  - **Coexistance**



Software-Defined (SD) Radio:

Is this the solution to the device challenges?



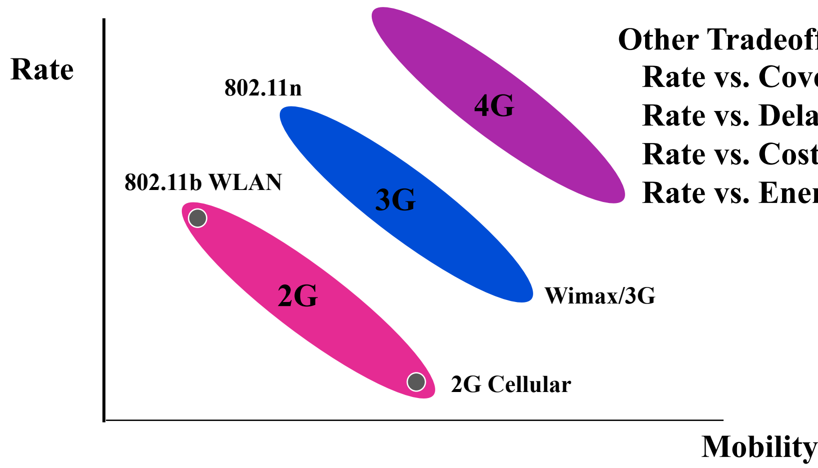
- Wideband antennas and A/Ds span BW of desired signals
- DSP programmed to process desired signal: no specialized HW

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

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



Other Tradeoffs:
- Rate vs. Coverage
- Rate vs. Delay
- Rate vs. Cost
- Rate vs. Energy

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

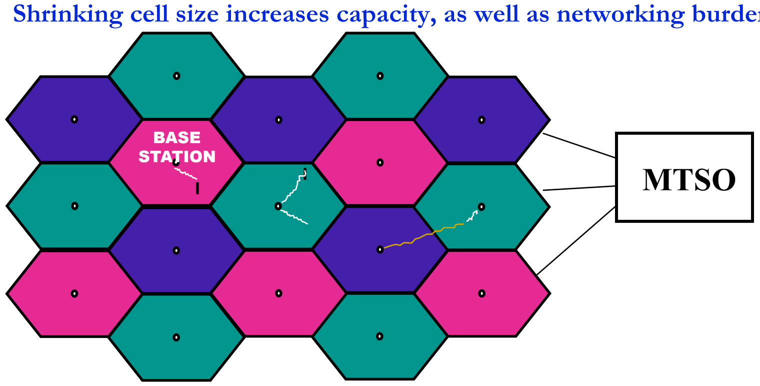
Adapt across design layers
Reduce uncertainty through scheduling
Provide robustness via diversity

Current Wireless Systems

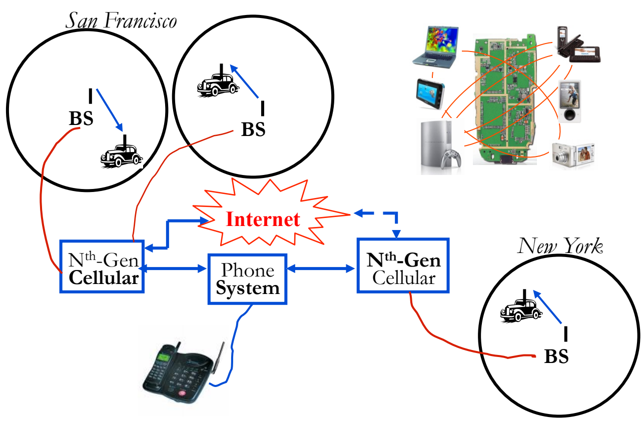
- Cellular Systems
- Wireless LANs
- Wimax
- Satellite Systems
- Paging Systems
- Bluetooth
- Zigbee radios

Cellular 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*

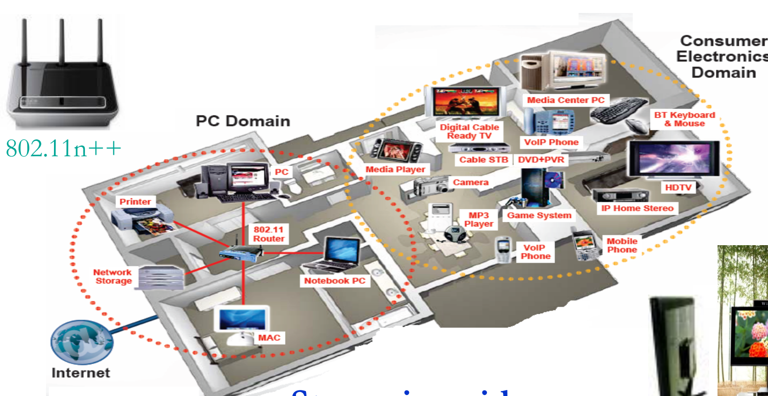
3G Cellular Design:
Voice and Data

- **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

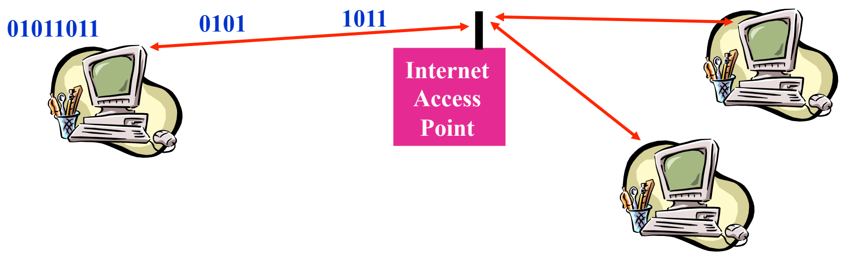


802.11n++

- Streaming video
- Gbps data rates
- High reliability
- Coverage in *every* room

Wireless HDTV and Gaming

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

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

- 802.11n (young pup) What's next? 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.

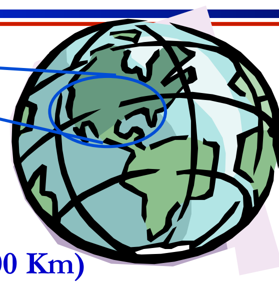
Wimax (802.16)

- 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

Bluetooth

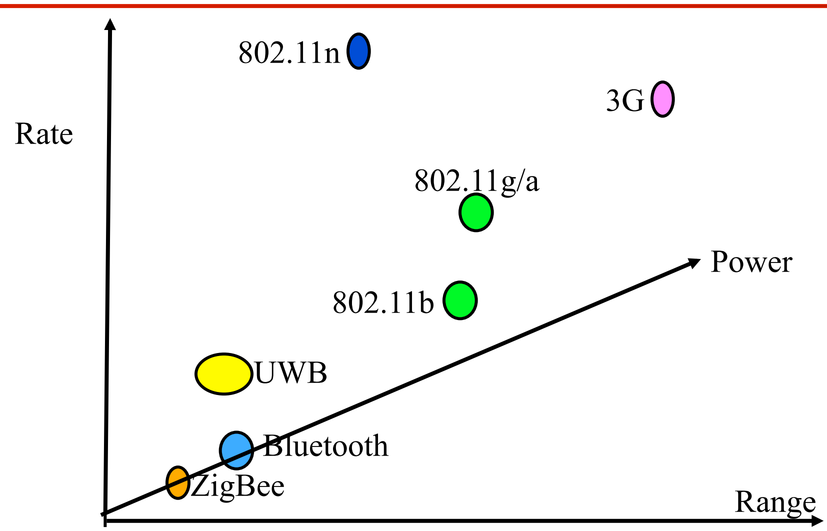
- Cable replacement RF technology (low cost)
- Short range (10m, extendable to 100m)
- 2.4 GHz band (crowded)
- 1 Data (700 Kbps) and 3 voice channels, up to 3 Mbps
- Widely supported by telecommunications, PC, and consumer electronics companies
- Few applications beyond cable replacement

IEEE 802.15.4/ZigBee Radios

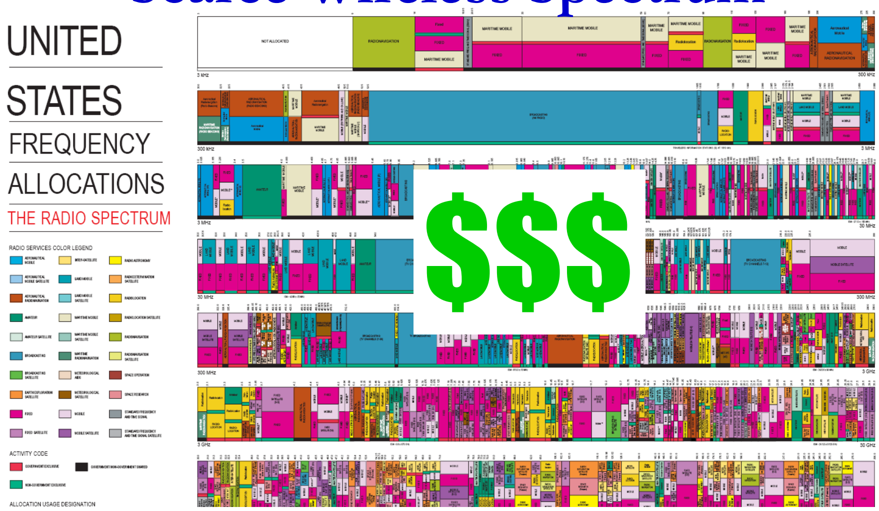
- **Low-Rate WPAN**
- **Data rates of 20, 40, 250 Kbps**
- **Support for large mesh networking or star clusters**
- **Support for low latency devices**
- **CSMA-CA channel access**
- **Very low power consumption**
- **Frequency of operation in ISM bands**

Focus is primarily on low power sensor networks

Tradeoffs



Scarce Wireless Spectrum



and Expensive

Spectrum Regulation

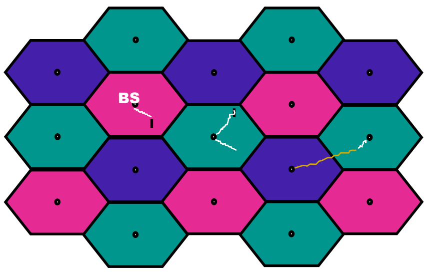
- **Spectrum a scarce public resource, hence allocated**
- **Spectral allocation in US controlled by FCC (commercial) or OSM (defense)**
- **FCC auctions spectral blocks for set applications.**
- **Some spectrum set aside for universal use**
- **Worldwide spectrum controlled by ITU-R**
- **Regulation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

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

Spectral Reuse

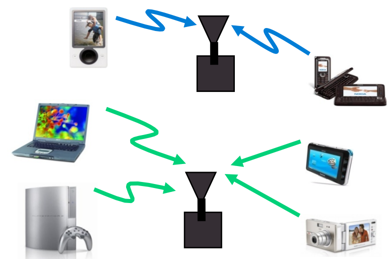
Due to its scarcity, spectrum is *reused*

In licensed bands



Cellular, Wimax

and unlicensed bands



Wifi, BT, UWB,…

Reuse introduces interference

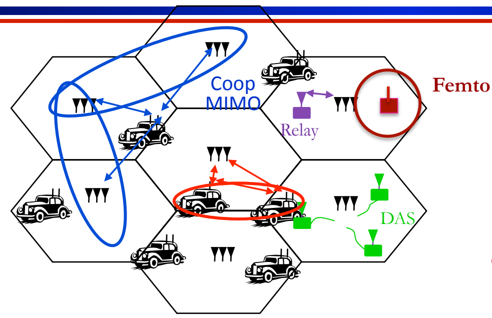
Interference: *Friend or Foe?*

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.**

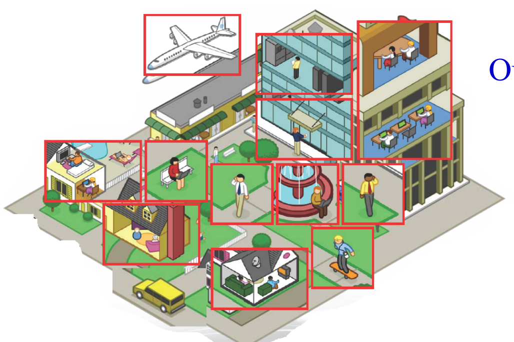
Standards

- **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**

Emerging Systems

- 4^{th} 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

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

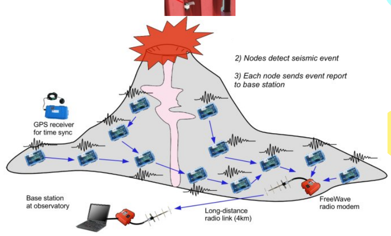
- Cognitive radios can support new wireless users in existing crowded spectrum
  - Without degrading performance of existing users
- Utilize advanced communication and signal processing techniques
  - Coupled with novel spectrum allocation policies
- Technology could
  - Revolutionize the way spectrum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

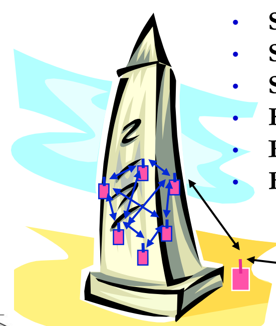
Cognitive Radio Paradigms

- 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

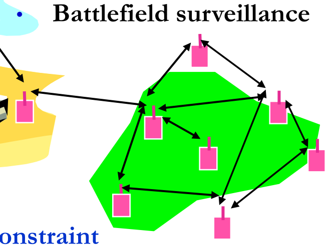
Knowledge and Complexity

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.

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