Wireless Communication Systems

Communication Engineering
Faculty of Electrical engineering
Sahand University of Technology

Lecture1: *Overview of wireless communication*

Course Information

- Required **Textbook**:

  1- *"Wireless Communications", by Andrea Goldsmith, Cambridge University Press, 2005.*

  2- *"Wireless Communications", by T.S. Rappaport, Prentice Hall, 2002.*

  3- *"Fundamentals of Wireless Communication", by D.Tse and P. Viswanath, Cambridge University Press, 2004.*

- Class Homepage: http://fa.ee.sut.ac.ir/ShowCourseDetails.aspx?id=7
- **Whatsapp**: email your mobile numbers. I will create a Whatsapp group for this course.

- Contact info.: emails: aebrahimi@sut.ac.ir, afshinebrahimi@gmail.com

  Tel.: 041-33459374

Important communication media

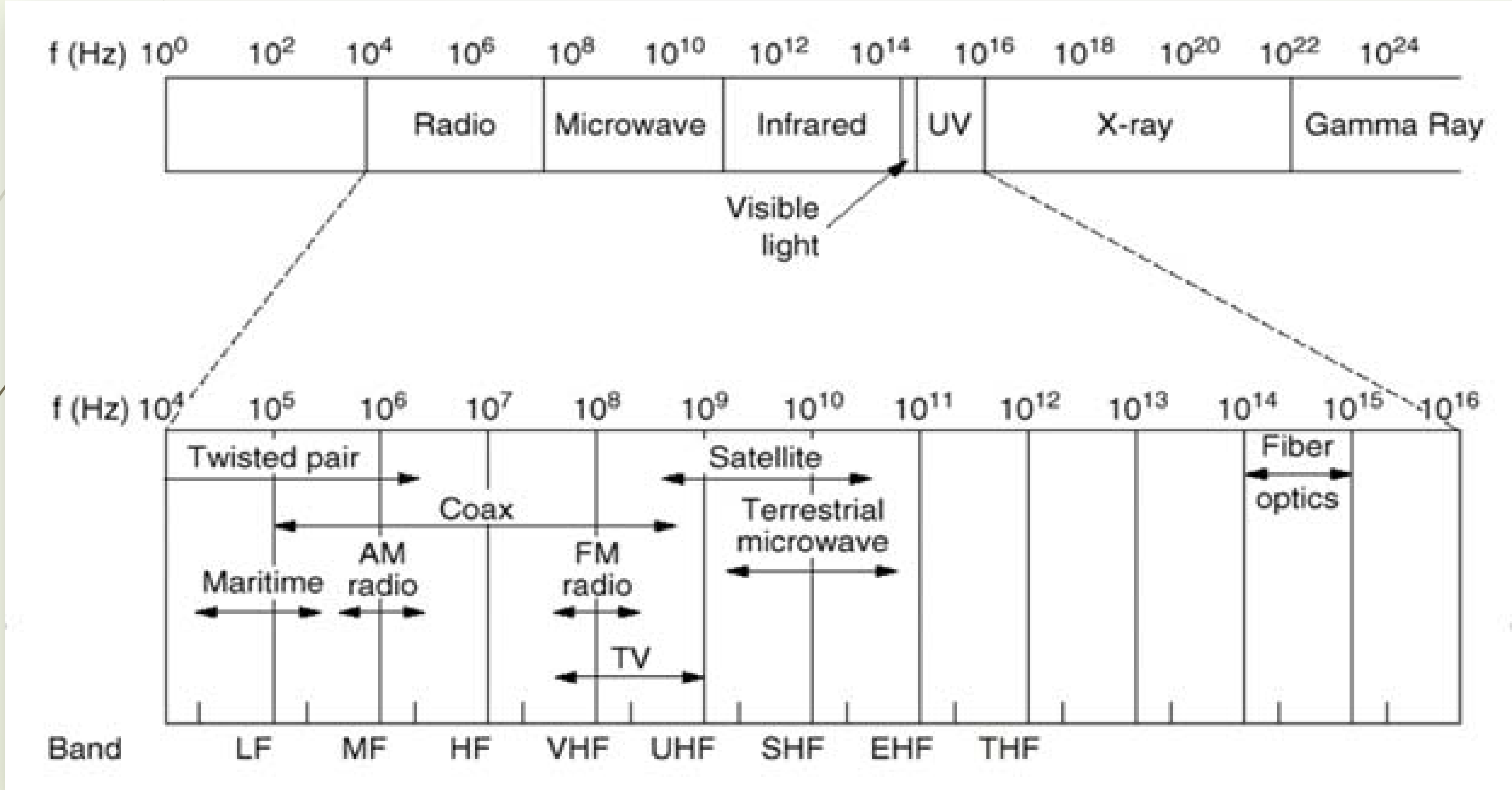
- ***Guided transmission media***

  - ✓ Twisted pair
  - ✓ coaxial cable
  - ✓ power lines
  - ✓ Fiber optics

- ***Wireless transmission***

  - ✓ Radio/microwave transmission
  - ✓ Millimeter wave transmission
  - ✓ Light wave transmission
  - ✓ Satellite communication

Wireless transmission



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 about 6 billion users worldwide today
  - Ignited the wireless revolution
  - Voice, data, and multimedia 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

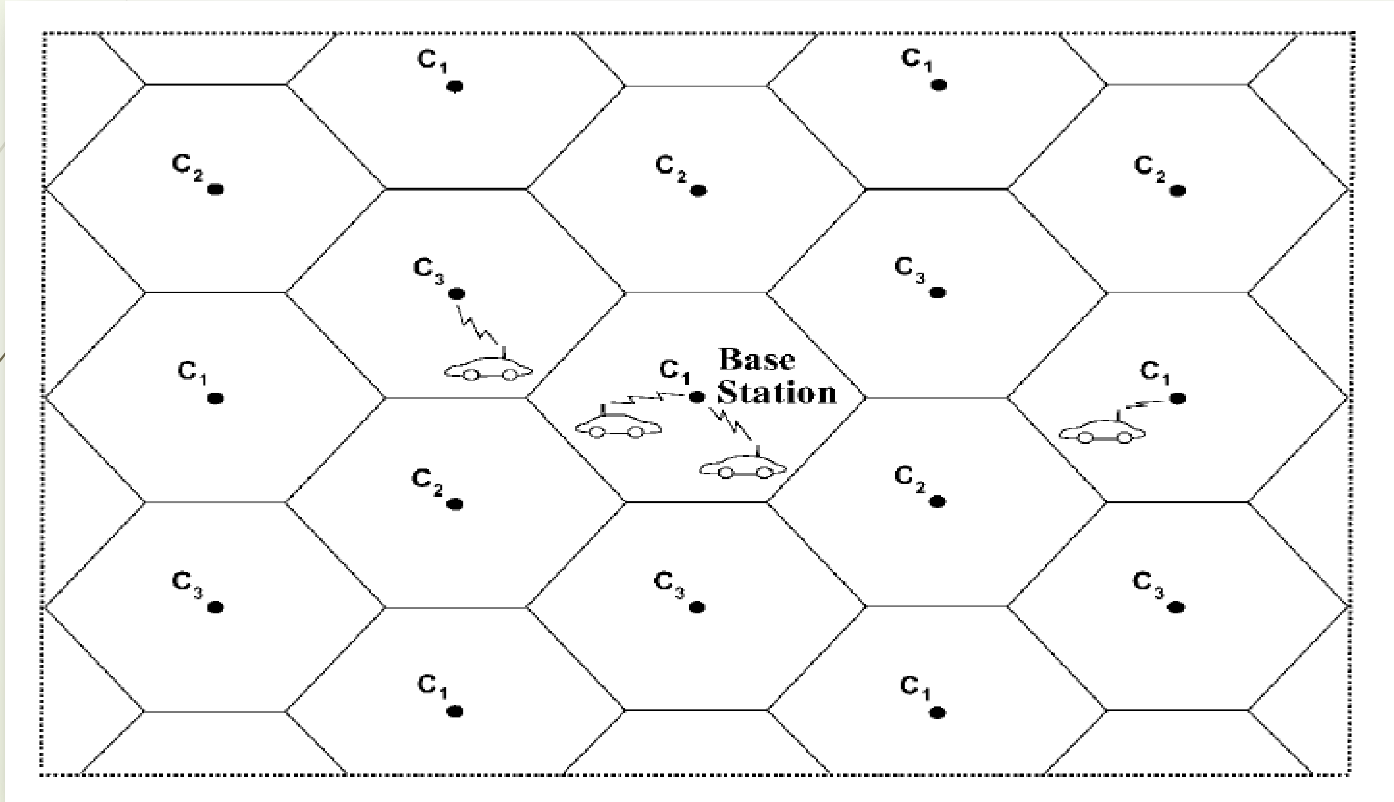
Current Wireless Systems

- ❑ Cellular Telephone Systems
- ❑ Wireless Local Area Networks (LAN)
- ❑ Broadband Wireless Access
- ❑ Low-Cost, Low-Power Radios: Bluetooth and ZigBee

Cellular Telephone Systems

- These systems are extremely **popular and lucrative** worldwide.
- provide two-way **voice and data** communication with regional, national, or international coverage.
- The basic premise behind cellular system design is **frequency reuse**, which exploits the fact that **signal power** falls off with distance to reuse the same frequency spectrum at spatially separated locations.
- the coverage area of a cellular system is divided into **non-overlapping** cells, where some set of **channels** is assigned to each cell.
- This same channel set is used in another cell **some distance away**

Cellular systems



Cellular systems

- The interference caused by users in different cells operating on the same channel set is called *intercell interference*.

- *The spatial separation of cells that reuse the same channel set, the reuse distance, should be as small as possible so that frequencies are reused as often as possible, thereby maximizing spectral efficiency.*

- Initial cellular system designs were mainly driven by the high cost of base stations, approximately $1 million each.

- The cell base stations were placed on tall buildings or mountains and transmitted at very *high power* with cell coverage areas of several square miles. These large cells are called *macrocells*.

Cellular systems

- Signal power radiated uniformly in all directions, so a mobile moving in a circle around the base station would have approximately constant received power.

- *The circular contour of constant power yields a hexagonal cell shape for the system.*

- Cellular systems in urban areas now mostly use smaller cells with base stations *close to street level that are transmitting at much lower power*. These smaller cells are called microcells or *picocells*.

- This evolution to smaller cells occurred for two reasons: *the need for higher capacity in areas with high user density* and *the reduced size and cost of base station electronics*.

Cellular systems

- *Mobiles traverse a small cell more quickly than a large cell, so handoffs must be processed more quickly.*

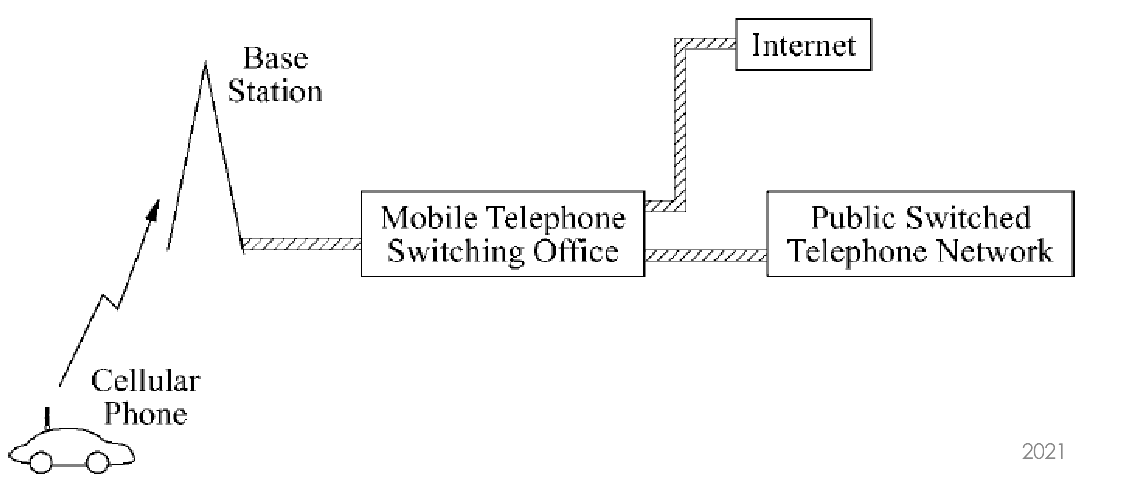
- *It is harder to develop general propagation models for small cells, since signal propagation in these cells is highly dependent on* ***base station placement*** *and* ***the geometry of the surrounding reflectors****.*

- *In particular, a hexagonal cell shape is generally not a good approximation to signal propagation in microcells.*

- Microcellular systems are often designed using square or triangular cell shapes, but these shapes have a *large margin of error in their approximation to microcell signal propagation*.

Cellular systems

- All base stations in a given geographical area are connected via a high-speed communications link to a ***mobile telephone switching office*** **(MTSO).**
- The MTSO acts as a **central controller** for the network: *allocating* ***channels*** *within each cell*, *coordinating* ***handoffs*** *between cells when a mobile traverses a cell boundary*, and ***routing*** *calls to and from mobile users*.
- The MTSO can **route** voice calls through the **public switched telephone network (PSTN)** or provide **Internet access**.



Calling request

1. A new user located in a given cell **requests a channel** by sending a call request to the cell's base station over a separate control channel.
2. The request **is relayed to the MTSO**, which accepts the call request if a channel is available in that cell. If no channels are available then the call request is rejected.
3. *A call **handoff** is initiated when the base station or the mobile in a given cell detects that the received signal power for that call is approaching a given minimum threshold.*
4. *If **no channels** are available in the cell with the new base station then the handoff **fails** and the call is terminated.*
5. *A call will also be **dropped** if the **signal strength** between a mobile and its base station falls below the minimum threshold needed for communication as a result of random signal variations.*

Cellular systems

- The first generation of cellular systems used **analog communications**; these systems were primarily designed in the **1960s**, before digital communications became prevalent.

- Second generation systems moved from analog to digital because of the latter's many **advantages**:

    - The components are **cheaper**, faster, and smaller, and they require less power.

    - *The degradation of voice quality caused by channel impairments can be mitigated with* ***error correction coding*** *and* ***signal processing****.*

    - Digital systems also have ***higher capacity*** than analog systems because they can use more *spectrally efficient* ***digital modulation*** and *more efficient techniques to share* ***the cellular*** *spectrum*.

Cellular systems

- They can also take advantage of advanced **compression** techniques and voice activity factors.

- In addition, **encryption** techniques can be used *to secure digital signals against eavesdropping*.

- Digital systems can also offer data services in addition to voice, including short messaging, email, **Internet access**, and imaging capabilities (camera phones).

- *Because of their lower cost and higher efficiency, service providers used aggressive **pricing tactics** to encourage user migration from analog to digital systems.*

Cellular systems

- *today analog systems are **primarily** used in areas with no digital service.*
- *Digital systems do not always work as well as the analog ones.*
- *Users can experience poor **voice quality**, frequent call dropping, and spotty coverage in certain areas.*
- *In some areas cellular phones provide almost the same quality as wireline service.*

Cellular systems

- ***Spectral sharing*** *in communication systems, also called* ***multiple access****, is done by dividing the signaling dimensions along the time, frequency, and/or code space axes.*

- *In frequency division multiple access (****FDMA****) the total system bandwidth is divided into orthogonal frequency channels.*

- In *time-division multiple access* (**TDMA**), *time is divided orthogonally and each channel occupies the entire frequency band over its assigned timeslot*.

- *TDMA is more difficult to* ***implement*** *than FDMA because the users must be time-synchronized.*

- *Code-division multiple access* (**CDMA**) *is typically implemented with either* ***orthogonal*** *or nonorthogonal codes.*

Cellular systems

- The **first-generation** (1G) cellular systems in the United States, called the **Advance Mobile Phone Service (AMPS)**, used FDMA with *30-kHz **FM-modulated** voice channels*.

- *The FCC(Federal Communications Commission-USA) initially allocated **40 MHz** of spectrum to this system, which was increased to **50 MHz** shortly after service introduction to support more users.*

- *This total bandwidth was **divided** into two 25-MHz bands, one for mobile-to-base station channels and the other for base station-to-mobile channels.*

- *The FCC divided these channels into two sets that were assigned to two different service providers in each city to encourage **competition**.*

Cellular systems

- A similar system, the Total Access Communication System (**TACS**), emerged in **Europe**.

- *AMPS was deployed worldwide in the **1980s** and remains the only cellular service in some areas, including rural parts of the United States.*

- Many of the first-generation cellular systems in Europe were **incompatible**, and the Europeans quickly converged on a uniform standard for second-generation (**2G**) digital systems called ***GSM (Global System for Mobile communication)***.

- *The GSM standard uses a combination of **TDMA** and slow frequency hopping with **frequency-shift keying** for the **voice** modulation.*

Cellular systems

- the standards activities in the United States surrounding the second generation of digital cellular provoked a raging debate on spectrum-sharing techniques, resulting in several **incompatible** standards.

- there are two standards in the **900-MHz** cellular frequency band.

- ***IS-136***, *which uses a combination of TDMA and FDMA and phase-shift keyed modulation*.
- ***IS-95***, *which uses direct-sequence CDMA with **phase-shift keyed** modulation and coding.*

- *The incompatible standards in the United States and world, makes it impossible to roam between systems nationwide or **globally** without a **multimode** phone and/or multiple phones (and phone numbers).*

Cellular systems

- *All of the second-generation digital cellular standards have been* ***enhanced*** *to support high-rate packet data services:*

- ***GSM*** *systems provide data rates of up to* ***140 kbps*** *by aggregating all timeslots together for a single user. This enhancement is called* ***GPRS****.*

- A more fundamental enhancement, *Enhanced Data rates for GSM Evolution* (**EDGE**), further increases data rates up to **384 kbps** by using a *high-level modulation format combined with coding*.

- *EDGE defines* ***nine*** *different modulation and coding combinations, each optimized to a different value of received* ***SNR*** *(signal-to-noise ratio).*

- *The* ***IS-136*** *systems also use GPRS and EDGE enhancements to support data rates up to 384 kbps.*

Cellular systems

- *The **third-generation (3G)** cellular systems are based on a wideband **CDMA** standard developed under the auspices of the International Telecommunications Union (ITU).*

- *The standard, called International Mobile Telecommunications 2000 **(IMT-2000),** provides different **data rates** depending on mobility and location, from 384 kbps for pedestrian use* to *144 kbps for vehicular use* to *2 Mbps for indoor office use.*

- *The 3G standard is **incompatible** with 2G systems, so service providers must invest in a new **infrastructure** before they can provide 3G service.*

- *The first 3G systems were deployed in **Japan**.*

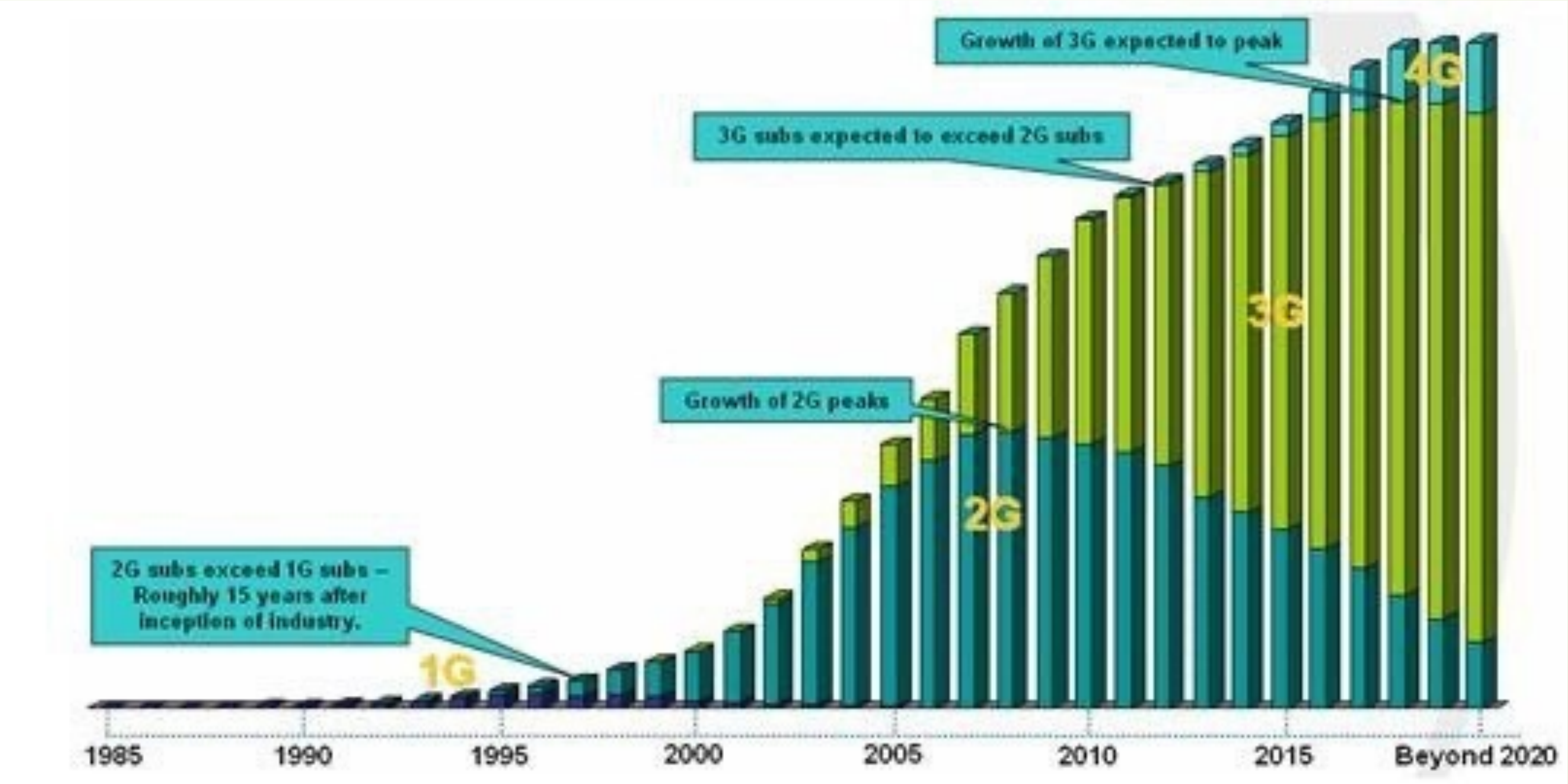
Cellular systems

- *The 3G spectrum in both Europe and the United States is allocated based on **auctioning**, thereby requiring a huge initial investment for any company wishing to provide 3G service.*

- *European companies collectively paid over **$100 billion** (American) in their 3G spectrum auctions.*

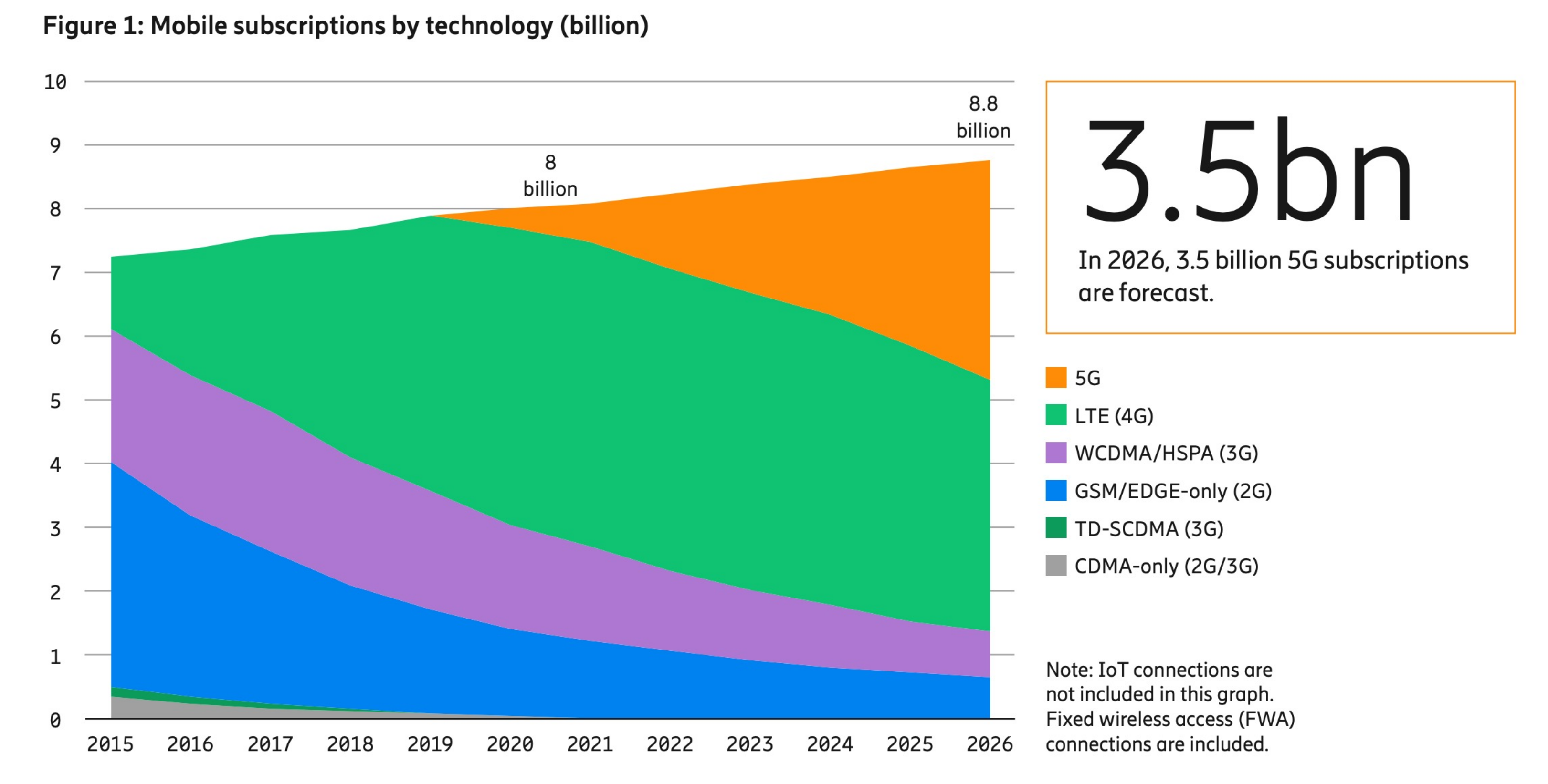
- *In fact, 3G systems have not grown as anticipated in Europe, and it appears that data **enhancements to 2G** systems may suffice to satisfy user demands at least for some time.*

Cellular systems

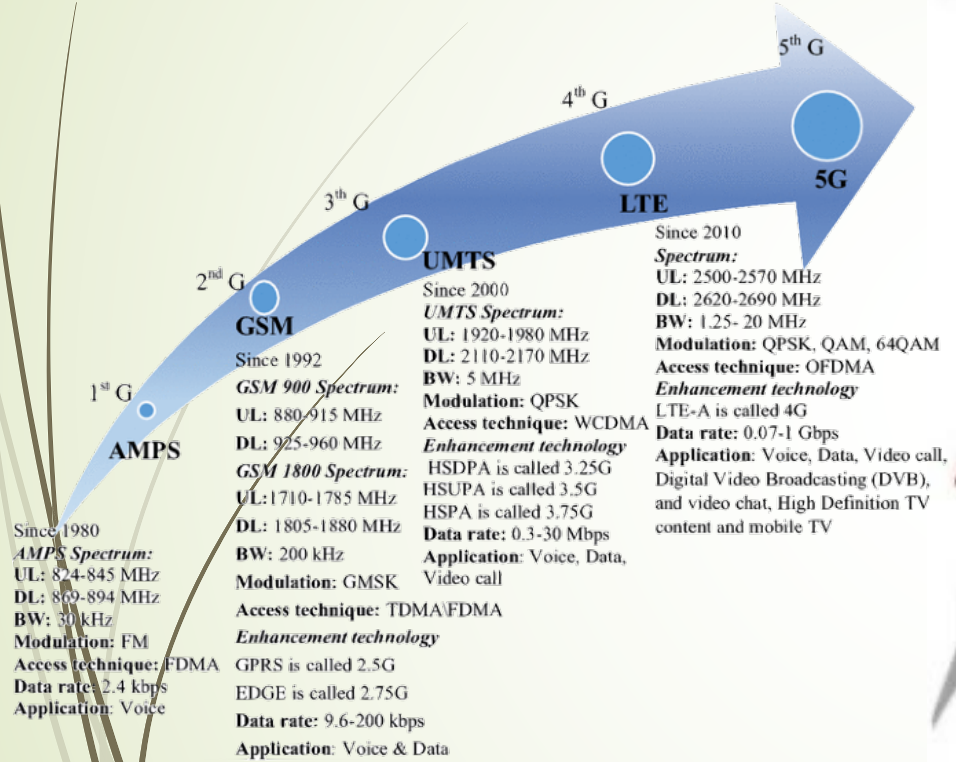


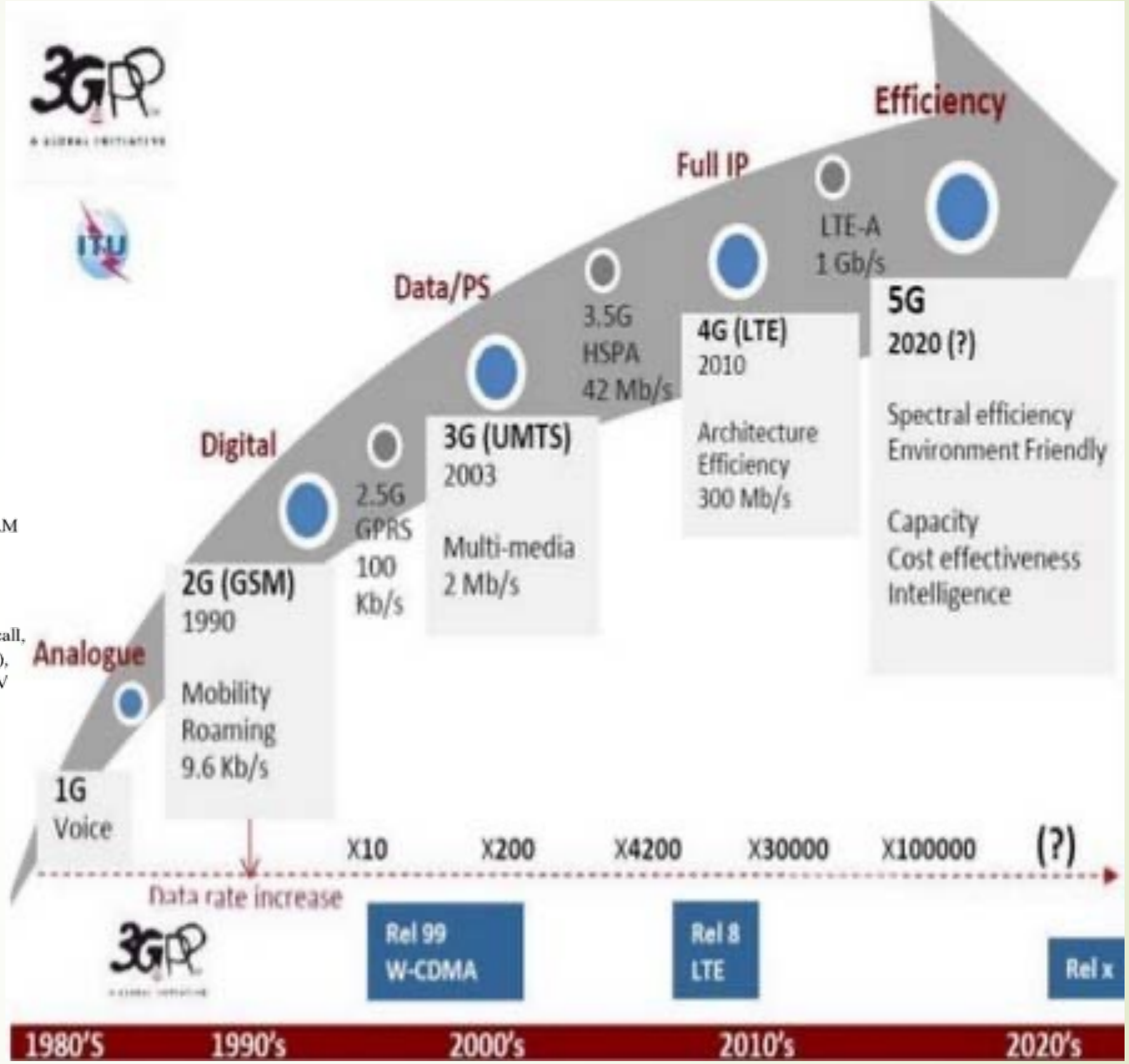
https://www.ericsson.com/4a03c2/assets/local/reports-papers/mobility-report/documents/2021/june-2021-ericsson-mobility-report.pdf

Mobile siubscriptions by technology



Cellular systems



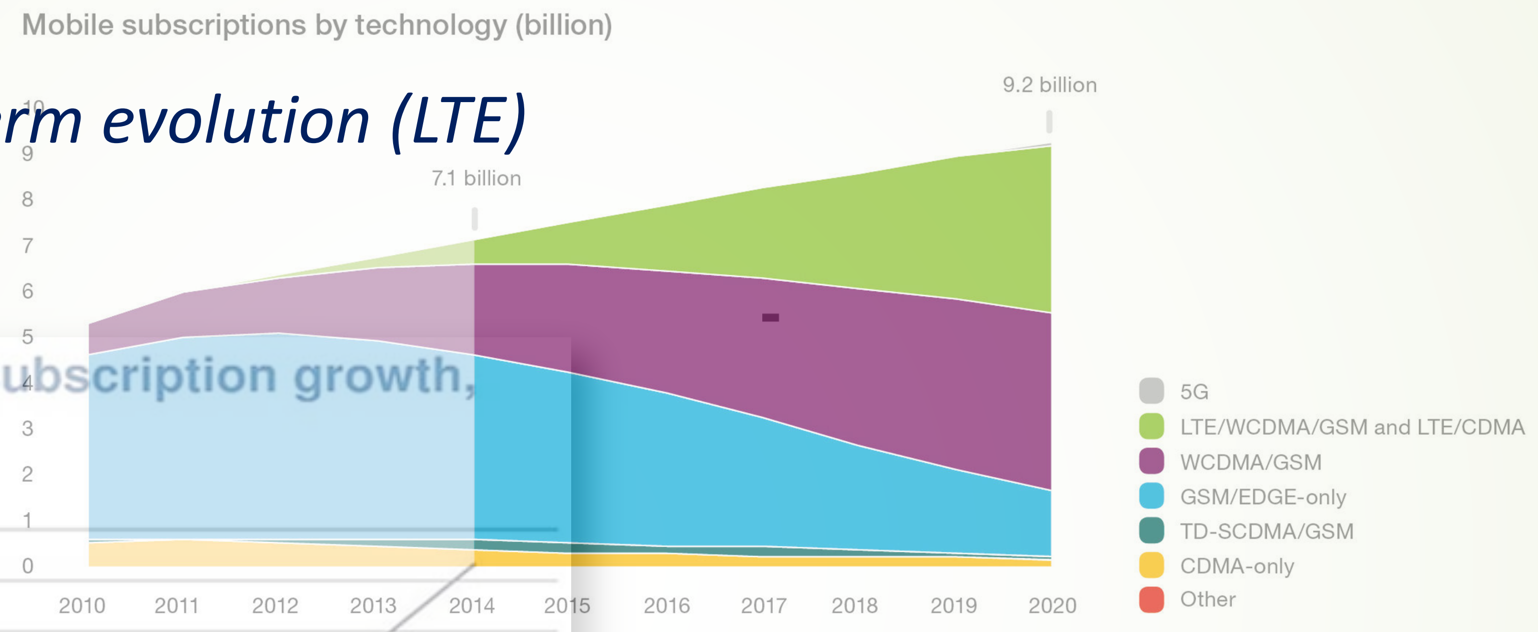


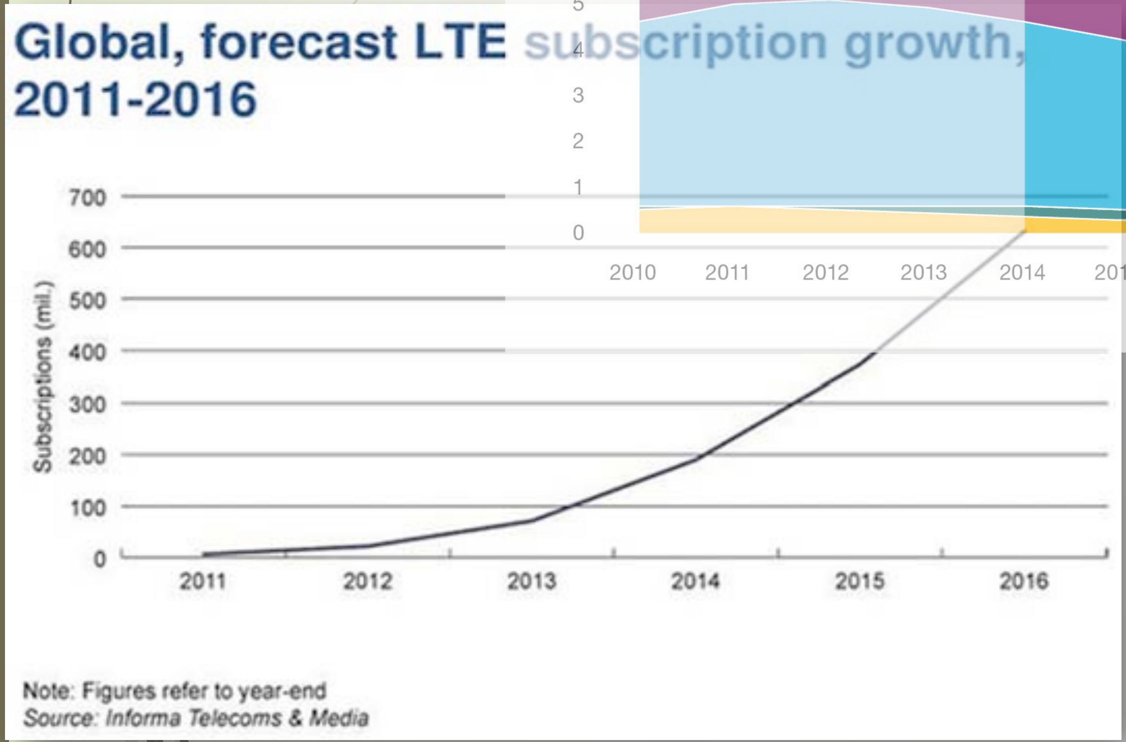
https://link.springer.com/article/10.1007/s11235-016-0195-x

Long term evolution (LTE)

- *Downlink peak rates of at least 100 Mbit/s for a single antenna, Peak download rates of **326.4 Mbit/s for 4x4 antenna**, and 172.8 Mbit/s for 2x2 antenna (utilizing 20 MHz of spectrum)*
- Peak **upload** rates of 86.4 Mbit/s for every 20 MHz of spectrum using a single antenna
- Scalable carrier bandwidths, from 1.4 MHz to 20 MHz.
- Greater spectral efficiency (bits/s/Hz)
- Adaptive MIMO-OFDM
- Low packet latency (<5ms)

Long term evolution (LTE)





https://telecoms.com/424181/ericsson-forecasts-lte-subscriptions-to-increase-seven-fold-by-2020/

Wireless Local Area Networks

- *Wireless LANs support high-speed data transmissions **within a small region** (e.g., a campus or small building) as users move from place to place.*

- *Wireless devices that access these LANs are typically **stationary** or moving at pedestrian speeds.*

- *All wireless LAN standards in the United States operate in **unlicensed** frequency bands.*

- *The primary unlicensed bands are the **ISM bands** at 900 MHz, 2.4 GHz, and 5.8 GHz and the Unlicensed National Information Infrastructure **(U-NII) band** at 5 GHz. An FCC license is not required to operate in either the ISM or U-NII bands.*

Wireless Local Area Networks

- *Wireless LANs can have either a **star architecture**, with wireless access points or hubs placed throughout the coverage region, or a **peer-to-peer architecture**, where the wireless terminals self-configure into a network.*

- *first-generation wireless LANs were based on proprietary and **incompatible** protocols.*

- *they operated within the 26- MHz spectrum of the **900-MHz ISM band** using direct-sequence spread spectrum, with data rates on the order of **1–2 Mbps.***

- *Only one of the first-generation wireless LANs, **Motorola's Altair**, operated outside the 900-MHz band. This system, operating in the licensed **18-GHz band**, had data rates on the order of **6 Mbps**.*

Wireless Local Area Networks

- *The **second-generation** wireless LANs in the United States operate with 83.5 MHz of spectrum in the 2.4-GHz ISM band.*

- *A wireless LAN standard for this frequency band, the **IEEE 802.11b standard**, was developed to avoid some of the problems with the proprietary first-generation systems.*

- *The standard has data rates of around **1.6 Mbps** (raw data rates of 11 Mbps) and a range of approximately **100 m.***

- *Many laptops come with integrated 802.11b wireless LAN cards. Companies and universities have installed 802.11b **base stations** throughout their locations, and many coffee houses, airports, and hotels offer wireless access, often for free, to increase their appeal.*

Wireless Local Area Networks

- *Two additional standards in the 802.11 family were developed to provide higher data rates than 802.11b:*

*1- The IEEE 802.11a wireless LAN standard operates **with 300 MHz** of spectrum in the 5-GHz U-NII band.*

- *The 802.11a standard is based on **multicarrier modulation** and provides **54-Mbps** data rates at a range of about **30 m.***

- *Because 802.11a has much more bandwidth and consequently many more channels than 802.11b, it can support **more users** at higher data rates.*

*2- The other standard, **802.11g**, has the same design and data rates as 802.11a, but it operates in the **2.4-GHz** band with a range of about **50 m**.*

Wireless Local Area Networks

- *Many wireless LAN cards and access points support all three standards to avoid* ***incompatibilities****.*

- *In Europe, wireless LAN development revolves around the* ***HIPERLAN*** *(high-performance radio LAN) standards. The HIPERLAN/2 standard is* ***similar to the IEEE 802.11a*** *wireless LAN standard.*

- *it has a similar link layer design and also operates in a 5-GHz frequency band similar to the U-NII band. Hence it has the same maximum data rate of 54 Mbps and the same range of approximately 30 m as 802.11a.*

Wireless Local Area Networks: IEEE 802.11x

IEEE Standard	802.11a	802.11b	802.11g	802.11n	802.11ac	802.11ax
Year Released	1999	1999	2003	2009	2014	2019
Frequency	5Ghz	2.4GHz	2.4GHz	2.4Ghz & 5GHz	2.4Ghz & 5GHz	2.4Ghz & 5GHz
Maximum Data Rate	54Mbps	11Mbps	54Mbps	600Mbps	1.3Gbps	10-12Gbps

https://netspeedtest.in/wi-fi-standards-wi-fi-4-wi-fi-5-and-wi-fi-6/

Broadband Wireless Access

Broadband wireless access provides high-rate wireless communications between a fixed access point and multiple terminals.

- *These systems were initially proposed to support interactive **video** service to the home, but the application emphasis then shifted to providing both high-speed **data access** (tens of Mbps) to the Internet and the World Wide Web as well as high-speed data **networks** for homes and businesses.*

- In the United States, *two frequency bands* were set aside for these systems: *part of the **28-GHz** spectrum for **local** distribution systems* (local multipoint distribution service, **LMDS**) and *a band in the **2-GHz** spectrum for **metropolitan*** distribution service (multi Channel multipoint distribution services, **MMDS**).

Broadband Wireless Access

- *MMDS is a television and telecommunication delivery system with transmission ranges of **30–50 km**.*

** MMDS has the capability of delivering more than **a hundred digital video TV channels** along with telephony and access to the Internet.*

- *MMDS will compete mainly with existing **cable and satellite systems.***

- *Europe is developing a standard similar to MMDS called **Hiperaccess***.*

- ***WiMax** is an emerging broadband wireless technology based on the **IEEE 802.16 standard.***
- *The core 802.16 specification is a standard for broadband wireless access systems operating at radio frequencies **between 2 GHz and 11 GHz for non–line-of-sight operation**, and between **10 GHz and 66 GHz for line-of-sight** operation.*

* https://www.etsi.org/deliver/etsi_ts/102000_102099/102000/01.04.01_60/ts_102000v010401p.pdf

Broadband Wireless Access

*<u>Data rates of around **40 Mbps** will be available for fixed users and **15 Mbps** for mobile users, with a range of several kilometers.</u>*

- Many manufacturers of laptops and PDAs (personal digital assistants) are planning to incorporate WiMax once it becomes available to satisfy demand for constant **Internet access** and email exchange from any location.

- WiMax will compete with wireless LANs, 3G cellular services, and possibly **wireline** services like cable and DSL (digital subscriber line). ?????????

- The ability of WiMax to *challenge* or supplant these systems will depend on its relative performance and **cost**.

Wimax IEEE 802.16 standard

Standard	802.16	802.16a/802.16REVd	802.16e
Spectrum	10 to 66 GHz	< 11 GHz	< 6 GHz
Channel Conditions	Line-of-Sight only	None-Line-of-Sight	Non-Line-of-Sight
Speed (bit rate)	32 to 134 Mbps	75 Mbps max, 20-MHz channelization	15 Mbps max, 5-MHz channelization
Modulation	QPSK 16QAM 64QAM	OFDM 256 subcarrier QPSK 16QAM 64QAM	same as 802.16a
Mobility	Fixed	Fixed	Pedestrian mobility, regional roaming
Channel Bandwidths	20, 25 and 28 MHz	Selectable between 1.25 and 20 MHz	same as 802.16a with sub-channels
Typical Cell Radius	1 – 3 miles	3-5 miles (up to 30 miles, depending on tower height, antenna gain and transmit power)	1-3 miles

https://www.cse.wustl.edu/~jain/cse571-09/ftp/wimax2/

Low-Cost, Low-Power Radios: Bluetooth and ZigBee

- *As radios decrease their cost and power consumption, it becomes feasible to **embed** them into more types of electronic devices, which can be used to create smart homes, sensor networks, and other compelling applications. Two radios have emerged to support this trend: Bluetooth and ZigBee.*

- Bluetooth radios provide **short-range** connections between wireless devices along with rudimentary networking capabilities.

- The Bluetooth standard is based on a tiny microchip incorporating a **radio transceiver** that is built into digital devices.

Low-Cost, Low-Power Radios: Bluetooth and ZigBee

- Bluetooth is mainly for *short-range communications* – for example, from a laptop to a nearby printer or from a cell phone to a **wireless headset**.

- *Its normal range of operation is 10 m (at 1-mW transmit power), and this range can be increased to 100 m by increasing the transmit power to 100 mW.*

- The system operates in the *unlicensed **2.4-GHz** frequency band*, so it can be used worldwide without any licensing issues.

- *The Bluetooth standard provides one asynchronous data channel at **723.2 kbps.***

Low-Cost, Low-Power Radios: Bluetooth and ZigBee

The Bluetooth standard was developed jointly by 3 Com, Ericsson, Intel, IBM, Lucent, Microsoft, Motorola, Nokia, and Toshiba.

- The standard has now been adopted by over 1,300 manufacturers, and many consumer electronic products incorporate Bluetooth. These include wireless headsets for cell phones, **wireless USB** or RS232 connectors and **wireless set-top boxes**.

*The **ZigBee** radio specification is designed for lower cost and power consumption than Bluetooth.*

- Its specification is based on the **IEEE 802.15.4** standard. The radio operates in the same ISM band as Bluetooth.

Low-Cost, Low-Power Radios: Bluetooth and ZigBee

- *The specification supports data rates of up **to 250 kbps** at a range of up to **30 m**.*

- *These data rates are slower than Bluetooth, but in exchange the radio consumes significantly **less power** with a larger transmission range.*

*The goal of ZigBee is to provide radio operation for months or years without **recharging**, thereby targeting applications such as **sensor networks.***

Comparison of Bluetooth, UWB, ZigBee, and Wi-Fi

COMPARISON OF THE BLUETOOTH, UWB, ZIGBEE, AND WI-FI PROTOCOLS

Standard	Bluetooth	UWB	ZigBee	Wi-Fi
IEEE spec.	802.15.1	802.15.3a *	802.15.4	802.11a/b/g
Frequency band	2.4 GHz	3.1-10.6 GHz	868/915 MHz; 2.4 GHz	2.4 GHz; 5 GHz
Max signal rate	1 Mb/s	110 Mb/s	250 Kb/s	54 Mb/s
Nominal range	10 m	10 m	10 - 100 m	100 m
Nominal TX power	0 - 10 dBm	-41.3 dBm/MHz	(-25) - 0 dBm	15 - 20 dBm
Number of RF channels	79	(1-15)	1/10; 16	14 (2.4 GHz)
Channel bandwidth	1 MHz	500 MHz - 7.5 GHz	0.3/0.6 MHz; 2 MHz	22 MHz
Modulation type	GFSK	BPSK, QPSK	BPSK (+ ASK), O-QPSK	BPSK, QPSK COFDM, CCK, M-QAM
Spreading	FHSS	DS-UWB, MB-OFDM	DSSS	DSSS, CCK, OFDM
Coexistence mechanism	Adaptive freq. hopping	Adaptive freq. hopping	Dynamic freq. selection	Dynamic freq. selection, transmit power control (802.11h)
Basic cell	Piconet	Piconet	Star	BSS
Extension of the basic cell	Scatternet	Peer-to-peer	Cluster tree, Mesh	ESS
Max number of cell nodes	8	8	> 65000	2007
Encryption	E0 stream cipher	AES block cipher (CTR, counter mode)	AES block cipher (CTR, counter mode)	RC4 stream cipher (WEP), AES block cipher
Authentication	Shared secret	CBC-MAC (CCM)	CBC-MAC (ext. of CCM)	WPA2 (802.11i)
Data protection	16-bit CRC	32-bit CRC	16-bit CRC	32-bit CRC

* Unapproved draft.

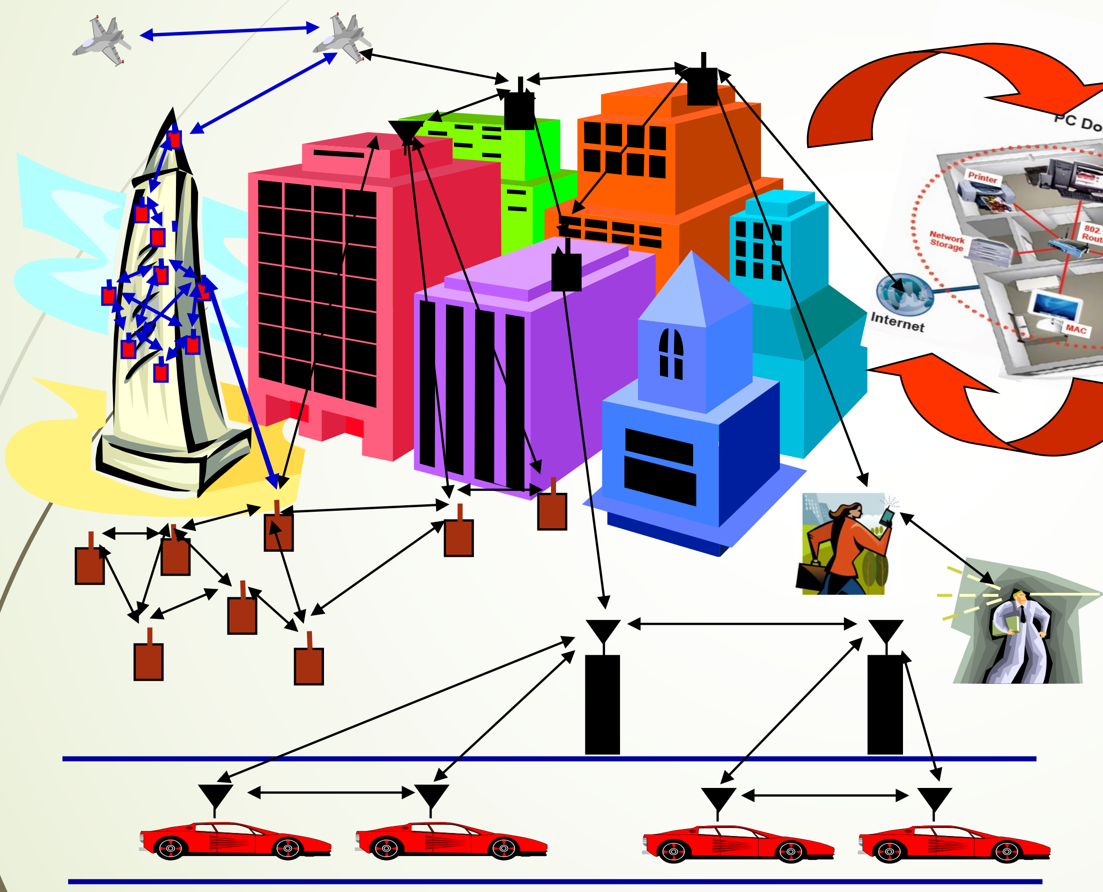
• Acronyms: ASK (amplitude shift keying), GFSK (Gaussian frequency SK), BPSK/QPSK (binary/quardrature phase SK), O-QPSK (offset-QPSK), OFDM (orthogonal frequency division multiplexing), COFDM (coded OFDM), MB-OFDM (multiband OFDM), M-QAM (M-ary quadrature amplitude modulation), CCK (complementary code keying), FHSS/DSSS (frequency hopping/direct sequence spread spectrum), BSS/ESS (basic/extended service set), AES (advanced encryption standard), WEP (wired equivalent privacy), WPA (Wi-Fi protected access), CBC-MAC (cipher block chaining message authentication code), CCM (CTR with CBC-MAC), CRC (cyclic redundancy check).

https://ieeexplore.ieee.org/document/4460126

Future Wireless Networks

Ubiquitous Communication Among People and Devices

https://web.stanford.edu/class/ee359/

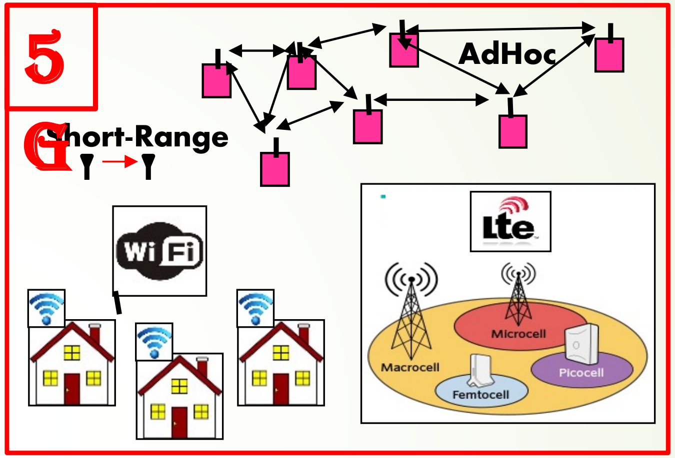


- Next-generation Cellular
- Wireless Internet Access
- Wireless Multimedia
- Sensor Networks
- Smart Homes/Spaces
- Automated Highways
- In-Body Networks
- All this and more …

Challenges

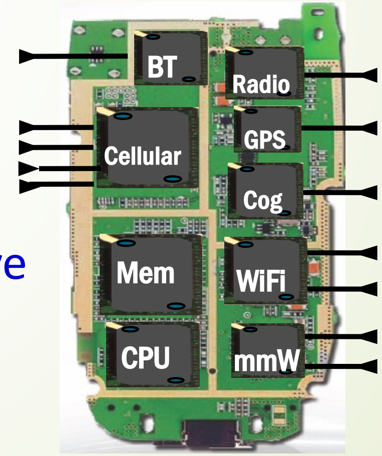
Network/Radio Challenges

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



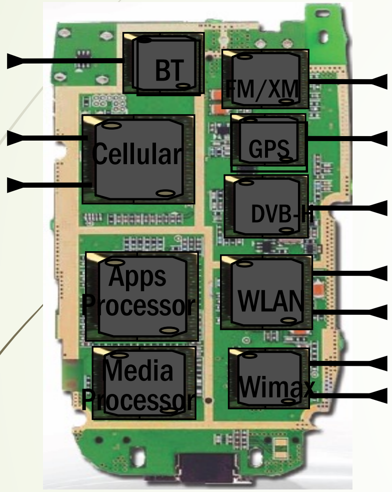
Device/SoC Challenges

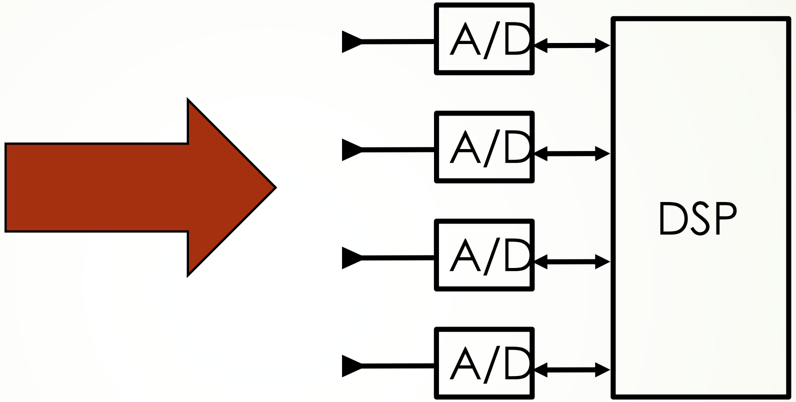
- Performance
- Complexity
- Size, Power, Cost
- High frequencies/mmWave
- Multiple Antennas
- Multiradio Integration
- Coexistance



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

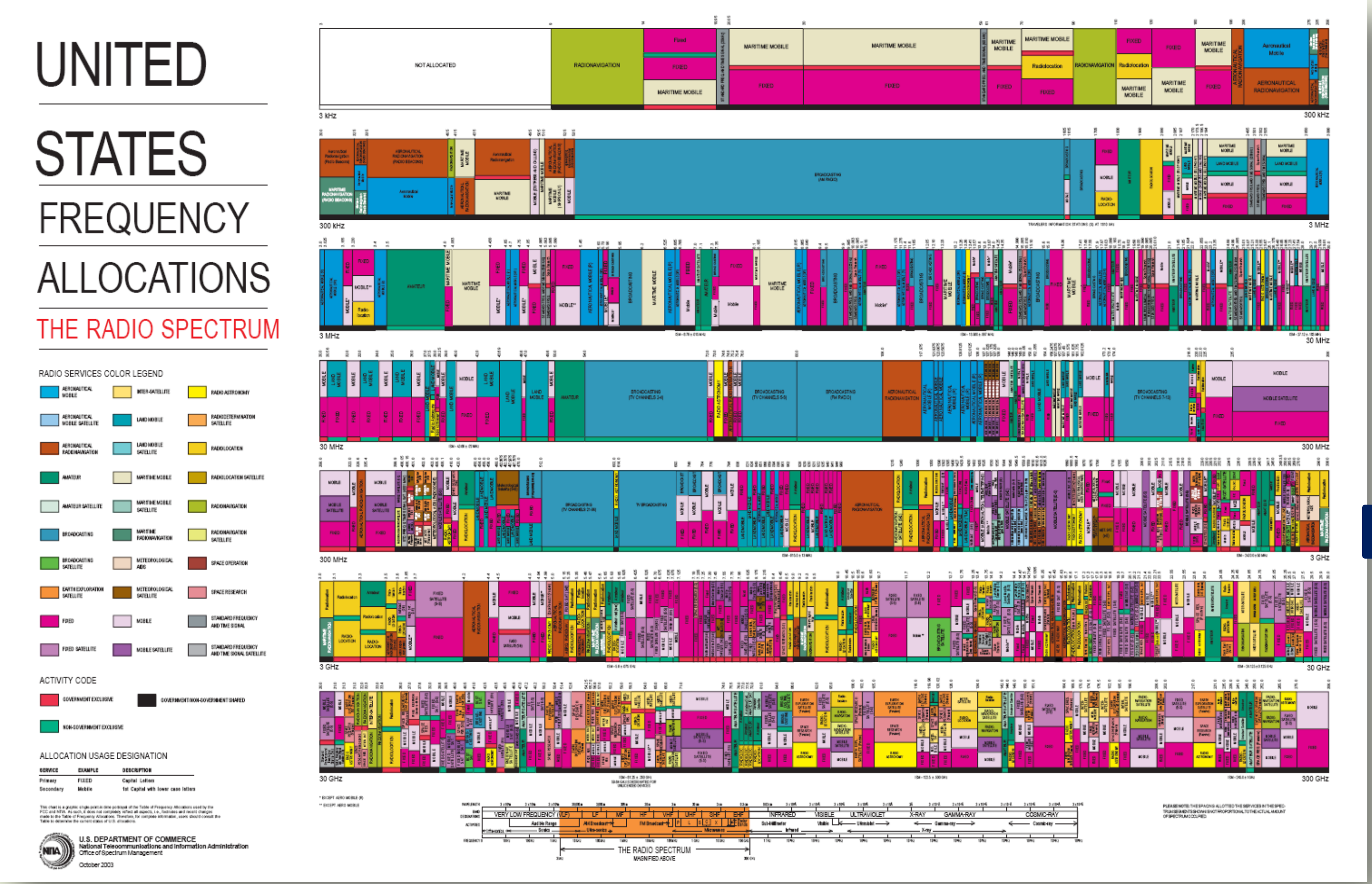
Today, this is not cost, size, or power efficient

- *Compressed sensing may be a solution for sparse signals*

Current Wireless Systems

- Cellular Systems
- Wireless LANs
- WiGig and mmWave Communications
- Cognitive Radios
- Satellite Systems
- Zigbee radios

Driving Constraint in Wireless System Design: Scarce Spectrum



Licensed Bands Scarce & Expensive

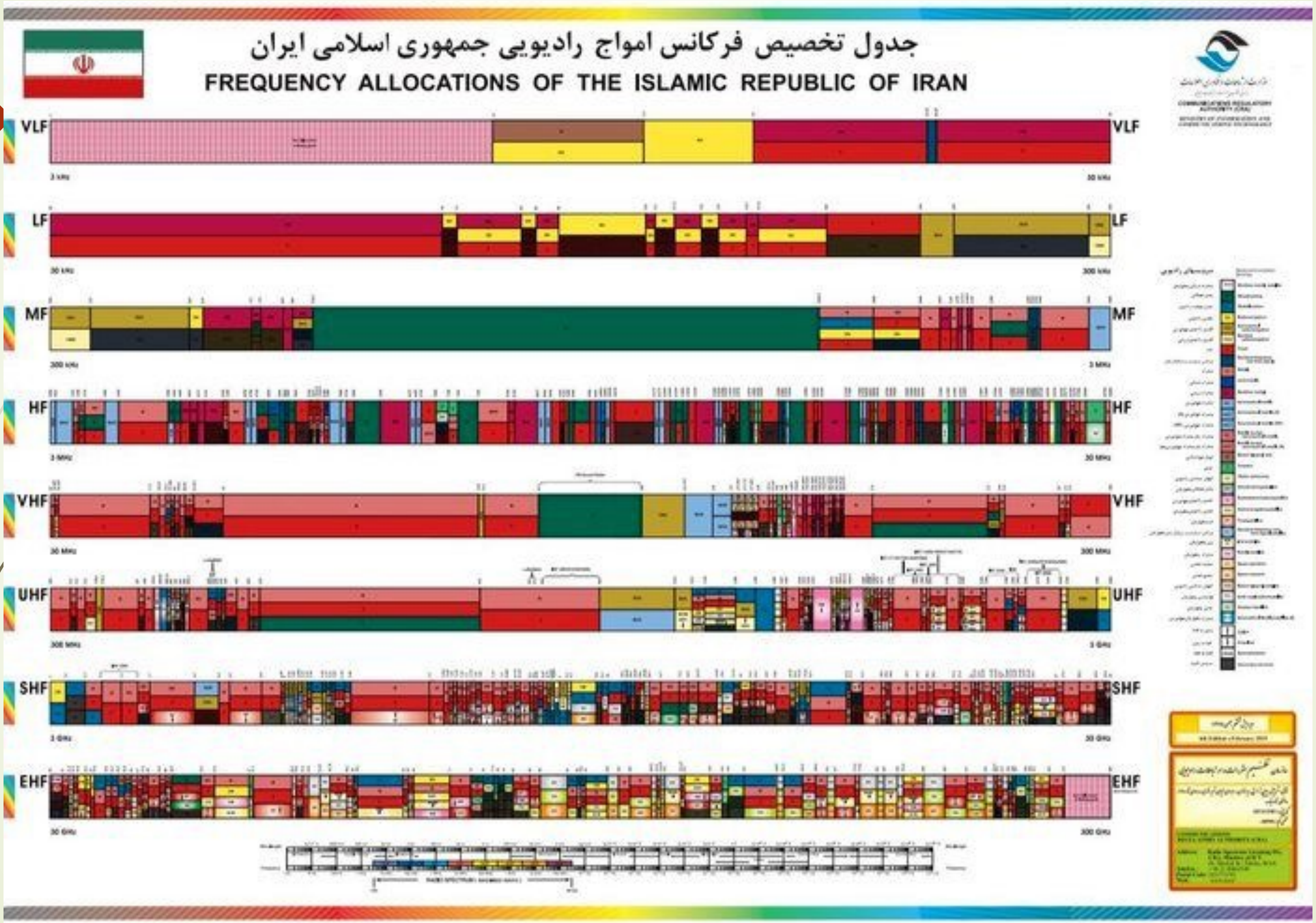
The Wireless Spectrum

In the United States, spectrum is allocated by the *Federal Communications Commission* (**FCC**) for commercial use and by the *Office of Spectral Management* (**OSM**) for military use.

Commercial spectral allocation is governed in Europe by the *European Telecommunications Standards Institute* (**ETSI**) and globally by the *International Telecommunications Union* (**ITU**).

In IRAN: Communications Regulatory Authority of The I.R. of Iran
https://www.cra.ir/

The FCC and regulatory bodies in other countries still allocate spectral blocks for specific purposes, but these blocks are now commonly assigned through spectral ***auctions*** *to the highest bidder.*



https://asnad.cra.ir/fa/File?id=edd3816d-57d8-e911-967d-0050569b0899

The Wireless Spectrum

*In addition to spectral auctions, spectrum can be set aside in specific frequency bands that are free to use **without a license** according to a specific set of etiquette rules.*

- *The rules may correspond to a specific communications standard, power levels, and so forth. The purpose of these **unlicensed bands** is to encourage **innovation** and low-cost implementation.*

Many extremely successful wireless systems operate in unlicensed bands, including wireless LANs, **Bluetooth**, and cordless phones.

*A major difficulty of unlicensed bands is that they can be killed by their own success. If many unlicensed devices in the same band are used in close proximity then they **interfere** with each other, which can make the band unusable.*

The Wireless Spectrum

- **Underlay** systems are *another alternative for allocating spectrum*.

*An underlay system operates as a secondary user in a frequency band with other **primary** users.*

- *Operation of secondary users is typically restricted so that primary users experience minimal **interference**. This is usually accomplished by restricting the **power** per hertz of the secondary users.*

- *Satellite systems cover large areas spanning many countries and sometimes the globe. For wireless systems that span multiple countries, spectrum is allocated by the International Telecommunications Union Radio Communications group (**ITU-R**).*

- ***ITU-T**, adopts telecommunication **standards** for global systems that must interoperate across national boundaries.*

The Wireless Spectrum

Most wireless applications reside in the radio spectrum between ***30 MHz and 40 GHz.***

- Note that the ***required antenna size*** *for good reception is inversely proportional to the signal* ***frequency***, so *moving systems to a higher frequency allows for more compact antennas*.

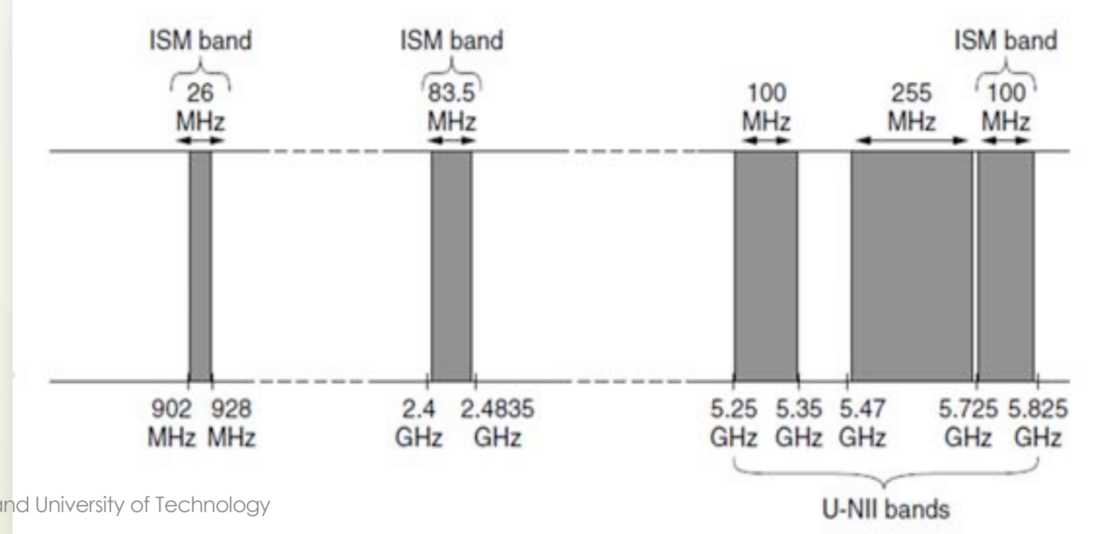
received signal ***power*** *with non-directional antennas is proportional to the inverse of frequency squared, so it is harder to cover large distances with higher-frequency signals.*

Licensed U.S. spectrum allocations

Service/system	Frequency span
AM radio	535–1605 kHz
FM radio	88–108 MHz
Broadcast TV (channels 2–6)	54–88 MHz
Broadcast TV (channels 7–13)	174–216 MHz
Broadcast TV (UHF)	470–806 MHz
Broadband wireless	746–764 MHz, 776–794 MHz
3G broadband wireless	1.7–1.85 MHz, 2.5–2.69 MHz
1G and 2G digital cellular phones	806–902 MHz
Personal communication systems (2G cell phones)	1.85–1.99 GHz
Wireless communications service	2.305–2.32 GHz, 2.345–2.36 GHz
Satellite digital radio	2.32–2.325 GHz
Multichannel multipoint distribution service (MMDS)	2.15–2.68 GHz
Digital broadcast satellite (satellite TV)	12.2–12.7 GHz
Local multipoint distribution service (LMDS)	27.5–29.5 GHz, 31–31.3 GHz
Fixed wireless services	38.6–40 GHz

Unlicensed U.S. spectrum allocations

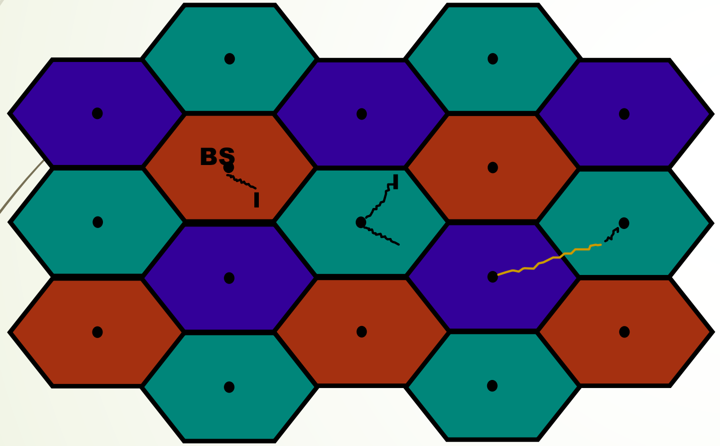
Band	Frequency
ISM band I (cordless phones, 1G WLANs)	902–928 MHz
ISM band II (Bluetooth, 802.11b and 802.11g WLANs)	2.4–2.4835 GHz
ISM band III (wireless PBX)	5.725–5.85 GHz
U-NII band I (indoor systems, 802.11a WLANs)	5.15–5.25 GHz
U-NII band II (short-range outdoor systems, 80211a WLANs)	5.25–5.35 GHz
U-NII band III (long-range outdoor systems, 80211a WLANs)	5.725–5.825 GHz



Spectral Reuse

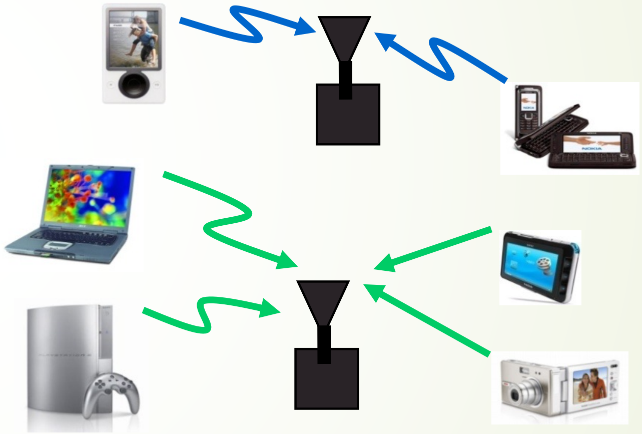
<u>Due to its scarcity, spectrum is *reused*</u>

In licensed bands



Cellular

and unlicensed bands

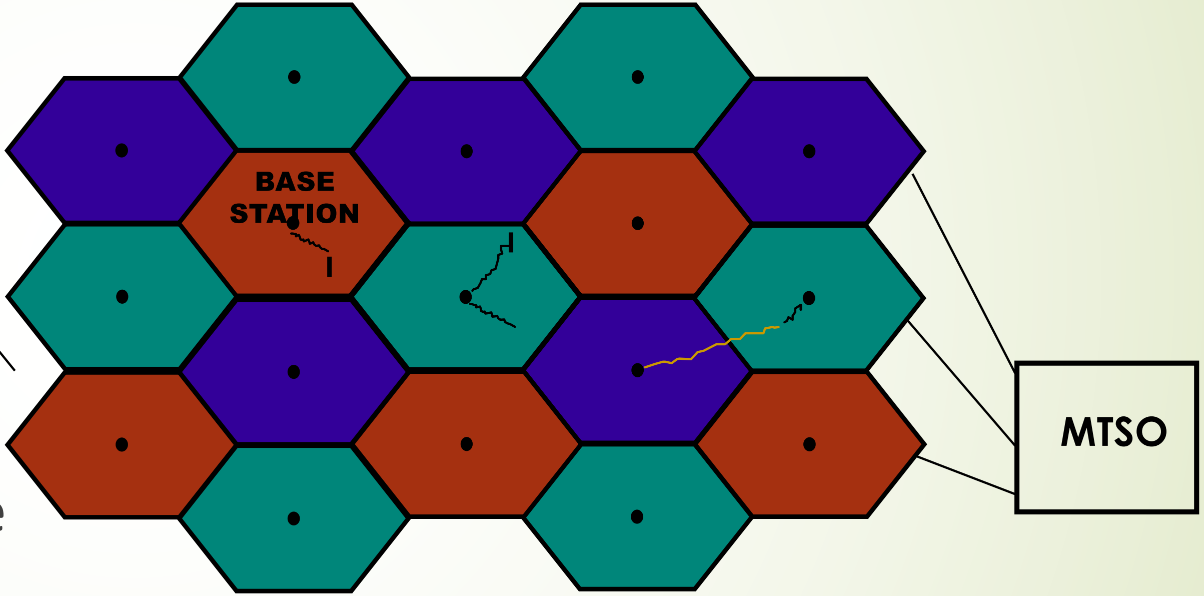


Wifi, BT, UWB,…

Reuse introduces interference

Cellular Systems:
Reuse channels to maximize capacity

- Geographic region divided into cells
- Frequency/timeslots/codes reused at spatially-separated locations.
- Co-channel interference between same color cells (reuse 1 common now).
- Base stations/MTSOs coordinate handoff and control functions
- Shrinking cell size increases capacity, as well as networking burden

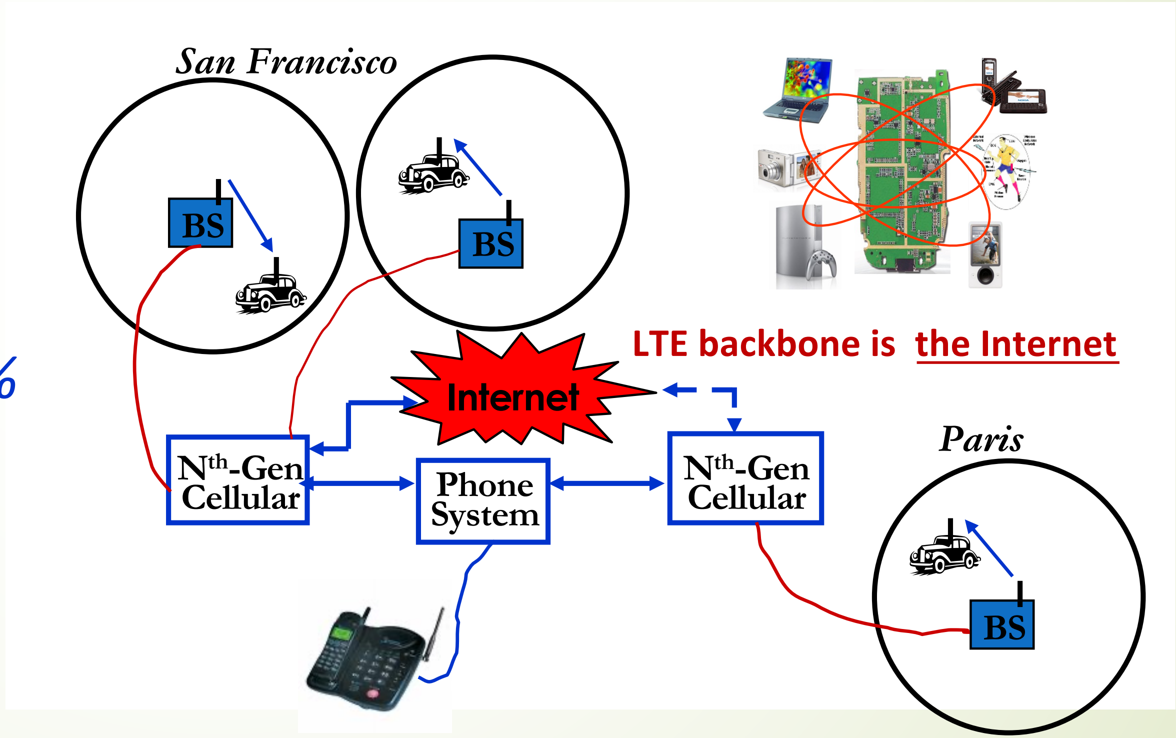


Future Cellular Phones

Burden for this performance is on the backbone network

Much better performance and reliability than today

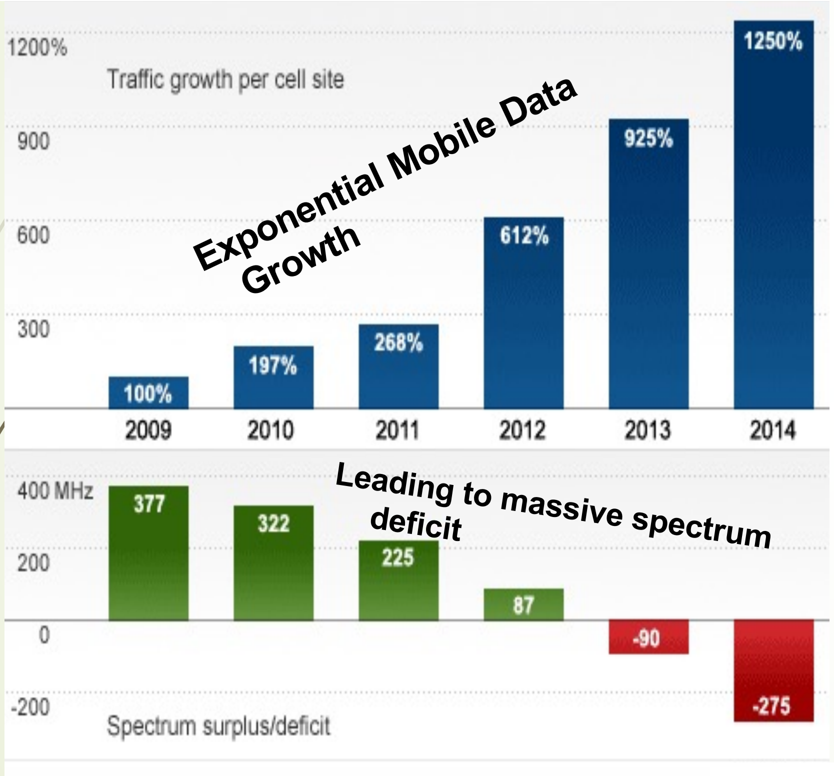
- Gbps rates, low latency, 99% coverage indoors and out



4G/LTE Cellular

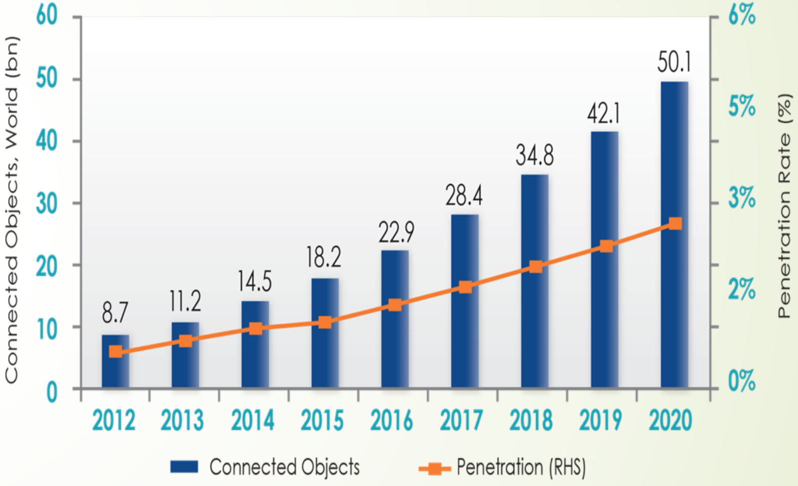
- Much higher data rates than 3G (50-100 Mbps)
  - 3G systems has 384 Kbps peak rates
- Greater spectral efficiency (bits/s/Hz)
  - More bandwidth, adaptive OFDM-MIMO, reduced interference
- Flexible use of up to 100 MHz of spectrum
  - 20 MHz spectrum allocation common
- Low packet latency (<5ms).
- Reduced cost-per-bit
- All IP network

"Sorry America, your airwaves are full*"



Source: FCC

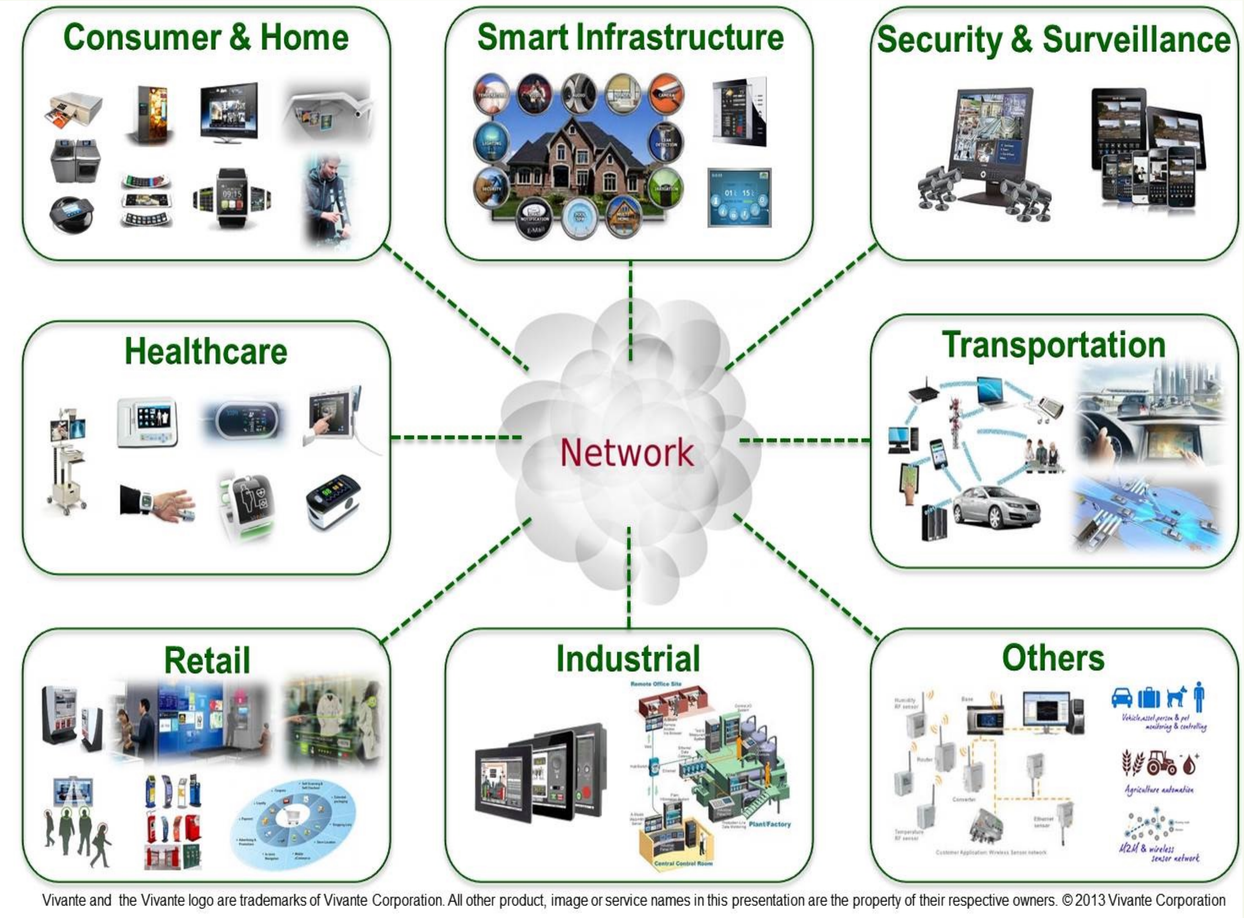
On the Horizon:
"The Internet of Things"



50 billion devices by 2020

[*CNN MoneyTech – Feb. 2012]

IoT is not (completely) hype



Different requirements than smartphones: low rates/energy consumption

Number of Connected Objects Expected to Reach 50bn by 2020

Are we at the Shannon limit of the Physical Layer?

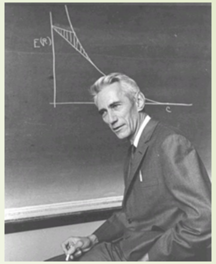
We are at the Shannon Limit

- "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?

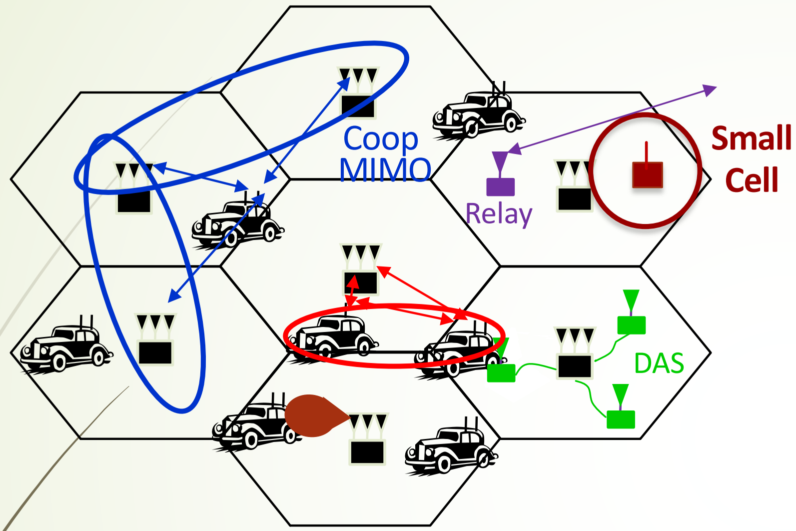


We don’t know the Shannon capacity of most wireless channels

- 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

Rethinking "Cells" in Cellular



How should cellular systems be designed?

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

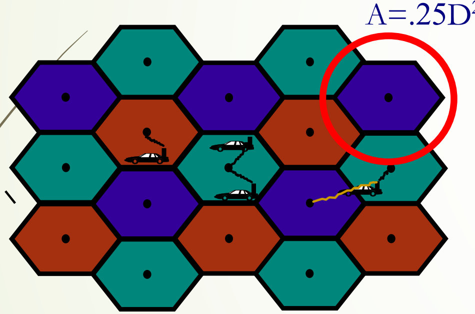
Traditional cellular design "interference-limited"

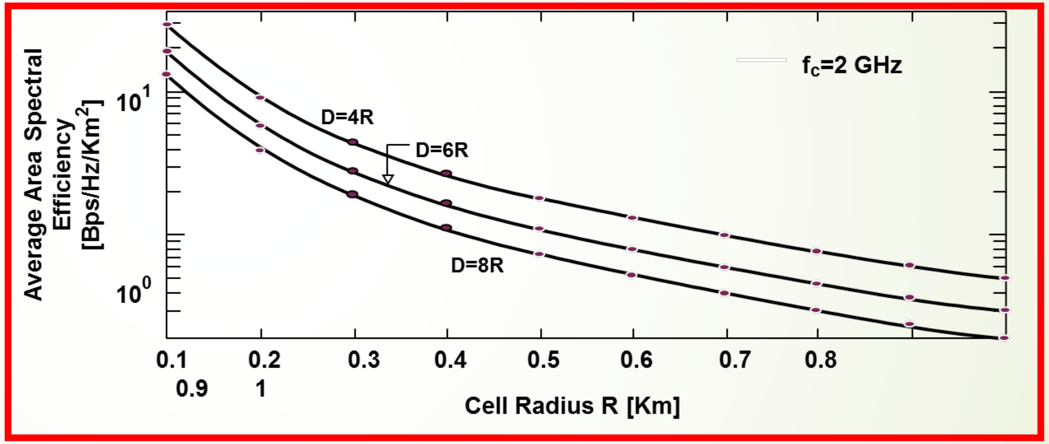
- MIMO/multiuser detection can remove interference
- Cooperating BSs form a MIMO array: what is a cell?
- Relays change cell shape and boundaries
- Distributed antennas move BS towards cell boundary
- Small cells create a cell within a cell
- Mobile cooperation via relays, virtual MIMO, network coding.

Are small cells the solution to increase cellular system capacity?

Yes, with reuse one and adaptive techniques (Alouini/Goldsmith 1999)

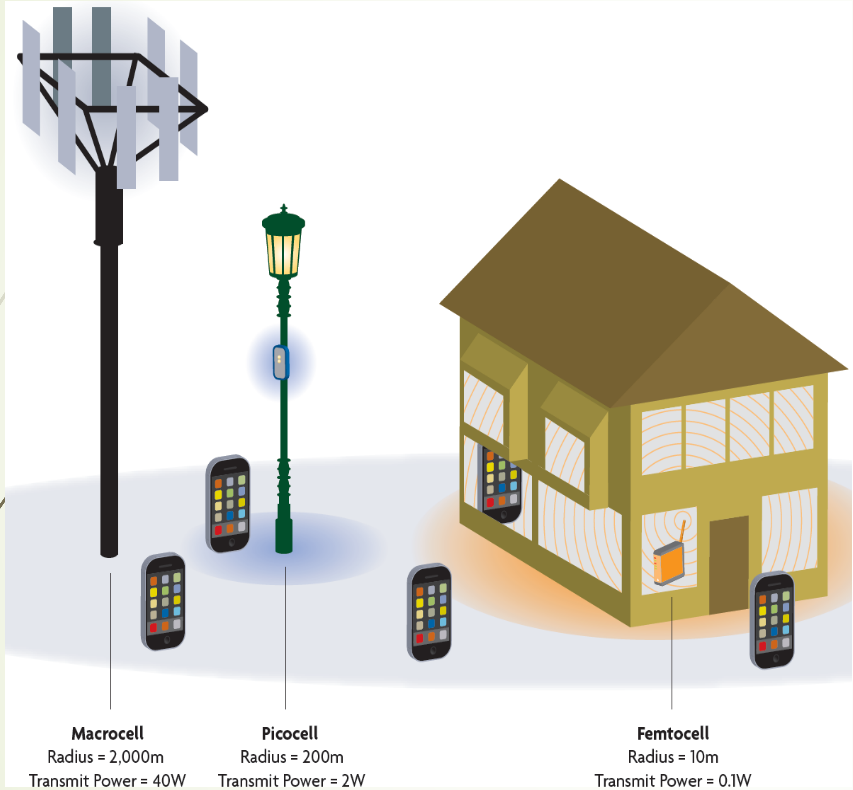
Area Spectral Efficiency

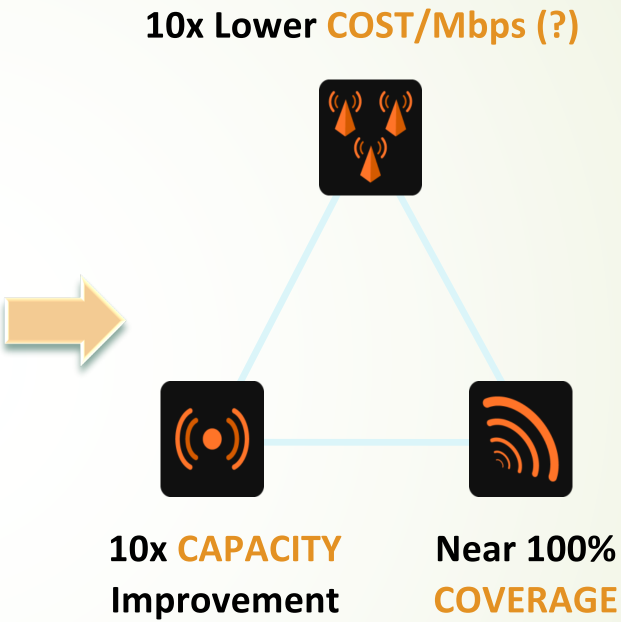




- S/I increases with reuse distance (increases link capacity).
- Tradeoff between reuse distance and link spectral efficiency (bps/Hz).
- Area Spectral Efficiency: $A_e=\Sigma R_i/(.25D^2\pi)$ bps/Hz/Km^2.

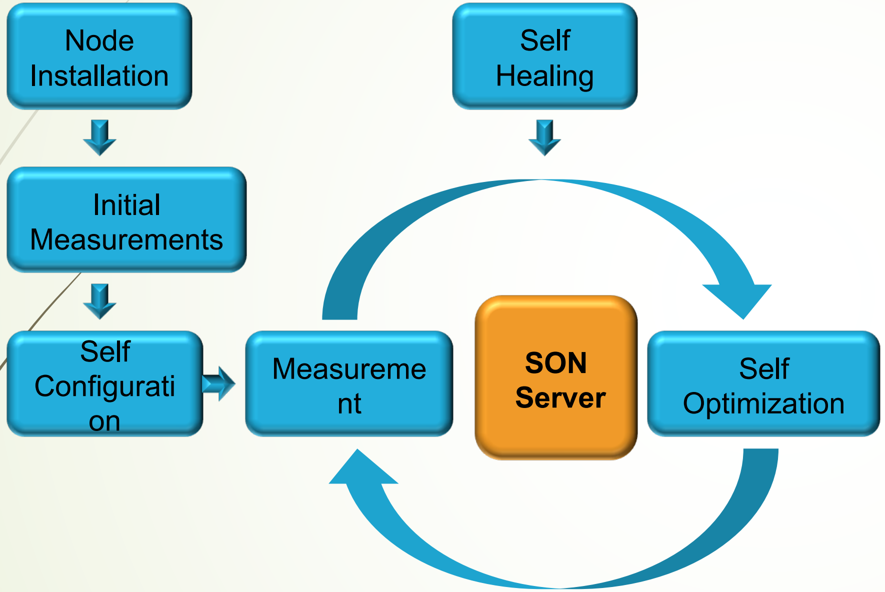
The Future Cellular Network: Hierarchical Architecture

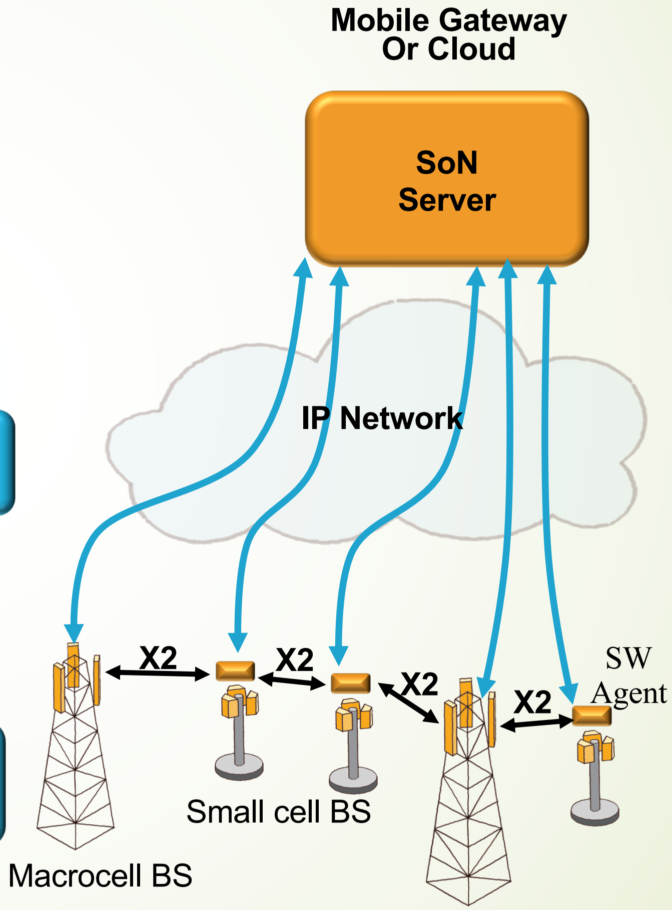




Future systems require Self-Organization (SON) and WiFi Offload

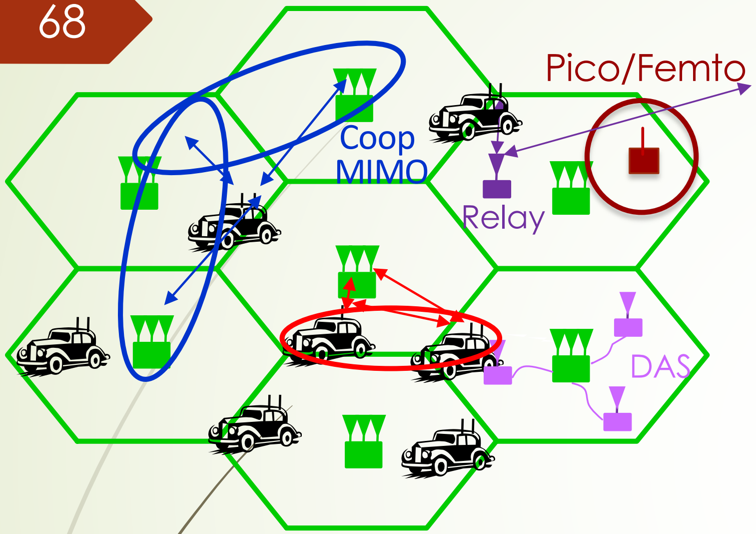
SON Premise and Architecture





- **SON is part of 3GPP/LTE standard**
- **Small cells not widely deployed today**

Green" Cellular Networks



How should cellular systems be redesigned for minimum energy?

Research indicates that significant savings is possible

Minimize energy at both the mobile *and* base station via

- New Infrastructures: cell size, BS placement, DAS, Picos, relays
- New Protocols: Cell Zooming, Coop MIMO, RRM, Scheduling, Sleeping, Relaying
- Low-Power (Green) Radios: Radio Architectures, Modulation, coding, MIMO

Wifi Networks
Multimedia Everywhere, Without Wires

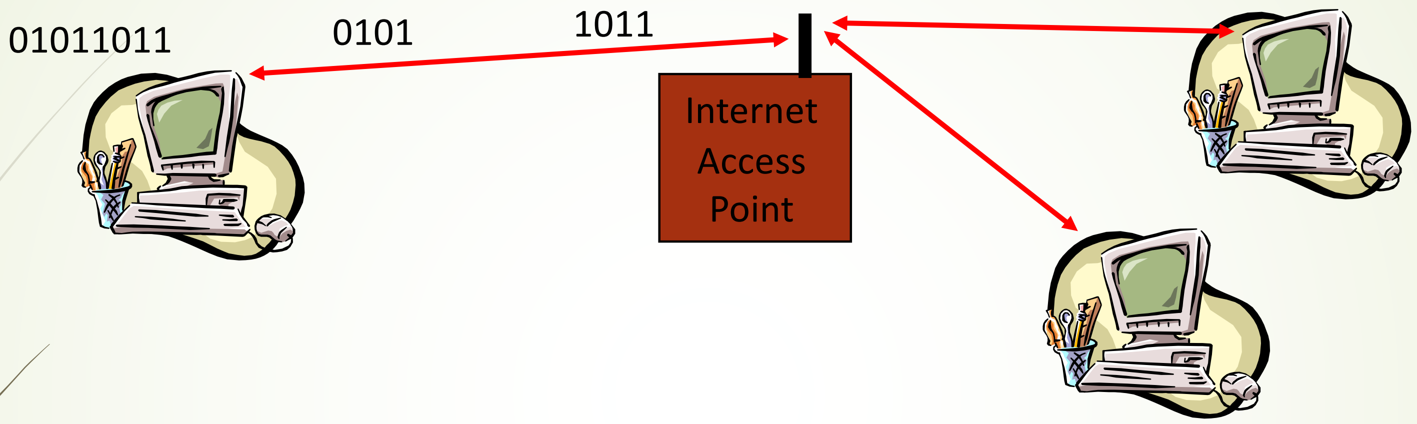
Wifi is today's small cell

802.11ac

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

Wireless HDTV and Gaming

Wireless Local Area Networks (WLANs)



- WLANs connect “local” computers (100m 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

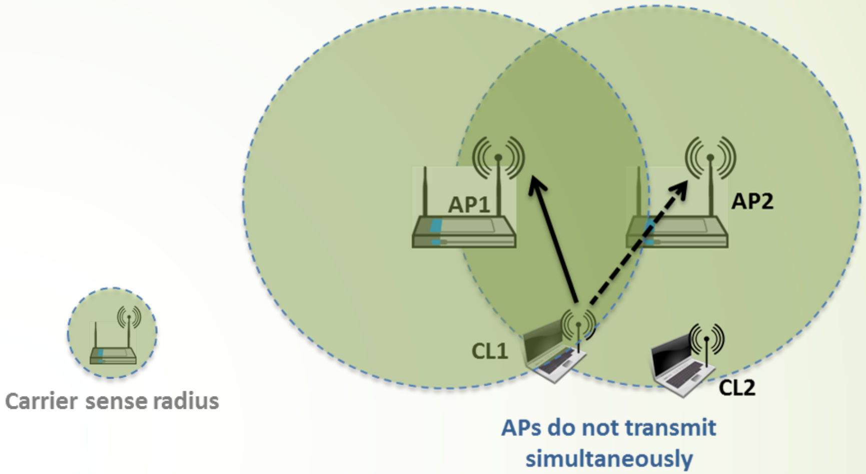
- 802.11b (Old – 1990s)
  - Standard for 2.4GHz ISM band (80 MHz)
  - Direct sequence spread spectrum (DSSS)
  - Speeds of 11 Mbps, approx. 500 ft range
- 802.11a/g (Middle Age– mid-late 1990s)
  - Standard for 5GHz band (300 MHz)/also 2.4GHz
  - OFDM in 20 MHz with adaptive rate/codes
  - Speeds of 54 Mbps, approx. 100-200 ft range
- 802.11n/ac (Current)
  - 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 600Mbps/10 Gbps, approx. 200 ft range
  - Other advances in packetization, antenna use, multiuser MIMO

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

Why does WiFi performance suck?

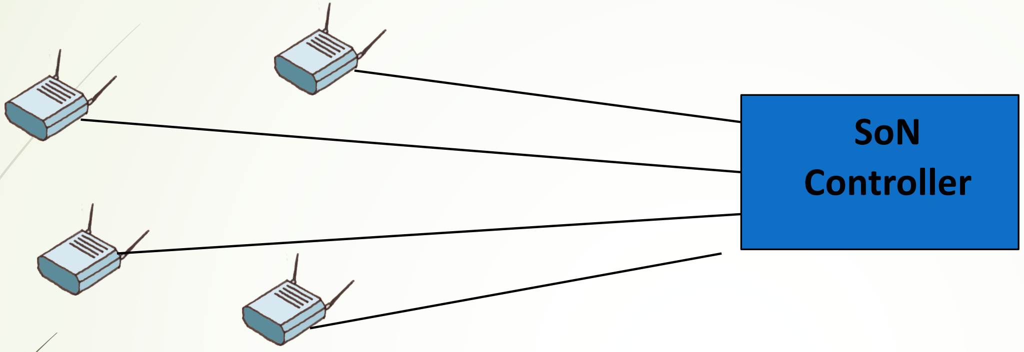
Carrier Sense Multiple Access: if another WiFi signal detected, random backoff

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

Why not use SoN for WiFi?

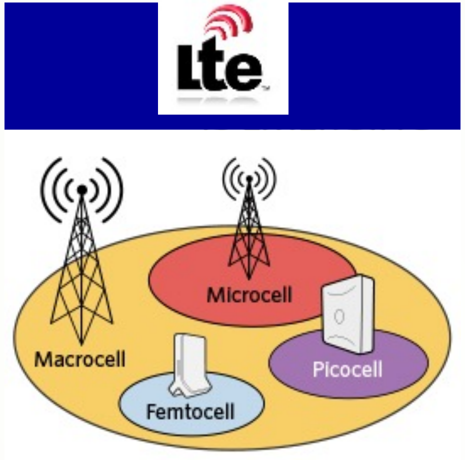


- Channel Selection
- Power Control
- etc.

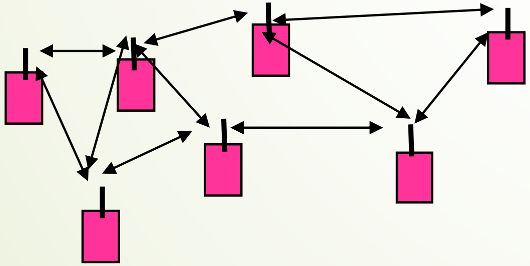
- SoN-for-WiFi: dynamic self-organization network software to manage of WiFi APs.
- Allows for capacity/coverage/interference mitigation tradeoffs.
- Also provides network analytics and planning.

In fact, why not use SoN for all wireless networks?

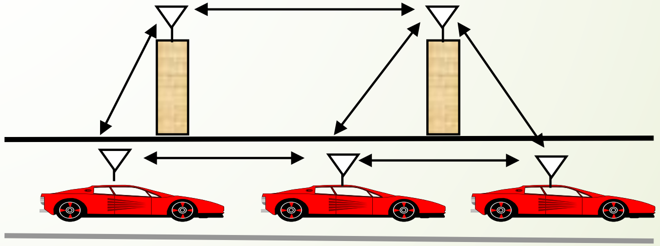
TV White Space &
Cognitive Radio



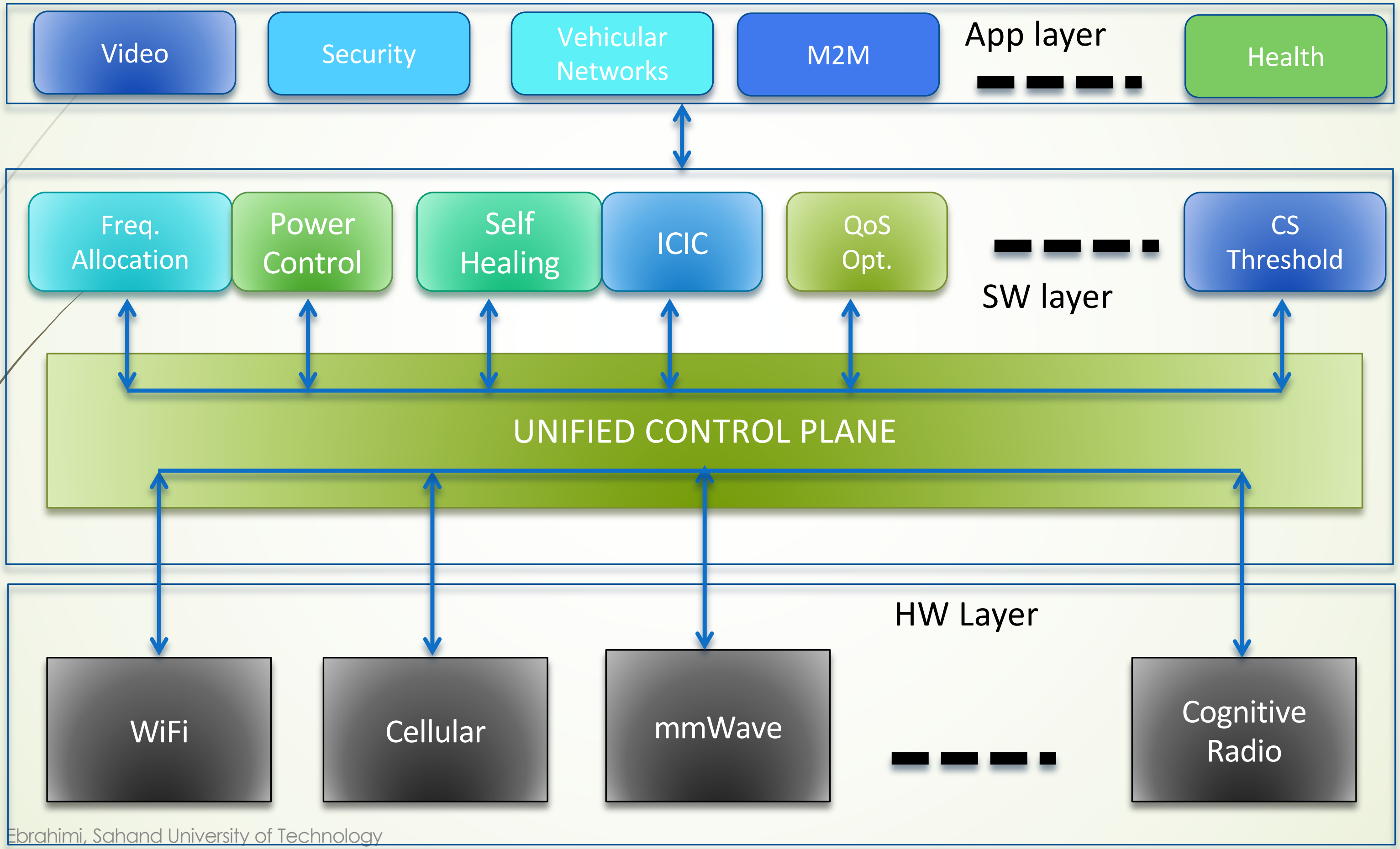
mmWave networks



Vehicle networks



Software-Defined Wireless Network (SDWN) Architecture



WiGig and mmWave

WiGig

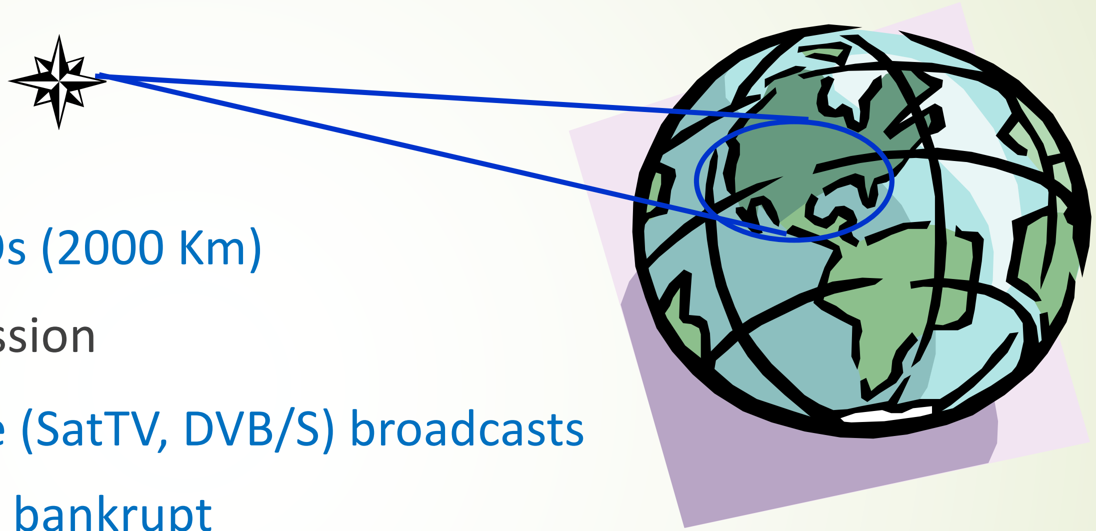
- Standard operating in 60 GHz band
- Data rates of 7-25 Gbps
- Bandwidth of around 10 GHz (unregulated)
- Range of around 10m (can be extended)
- Uses/extends 802.11 MAC Layer
- Applications include PC peripherals and displays for HDTVs, monitors & projectors

mmWave

- Couples 60GHz with massive MIMO and better MAC
- Promises long-range communication w/Gbps data rates
- Hardware, propagation and system design challenges
- Much research on this topic today

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



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”

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

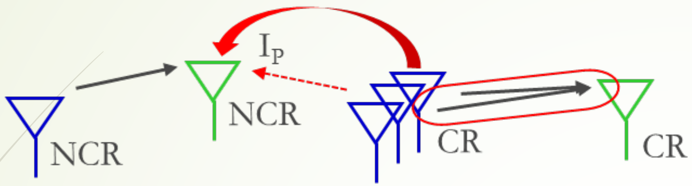
- Interacting systems require standardization
- Companies want their systems adopted as standard
  - Alternatively try for de-facto standards
- Standards determined by TIA/CTIA in US
  - IEEE standards often adopted
  - Process fraught with inefficiencies and conflicts
- Worldwide standards determined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

Standards for current systems are summarized in Goldsmith's book (Appendix D).

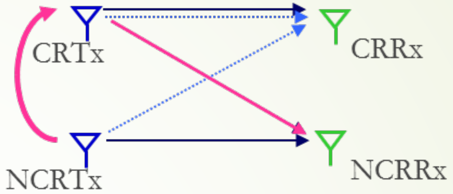
Emerging Systems

- Cognitive radio networks
- Ad hoc/mesh wireless networks
- Sensor networks
- Distributed control networks
- The smart grid
- Biomedical networks

Cognitive Radios



MIMO Cognitive Underlay



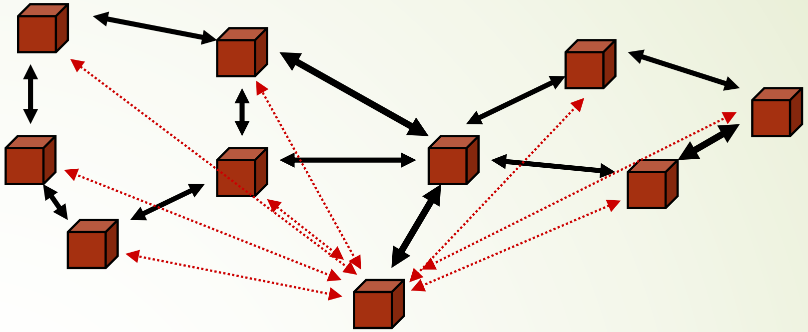
Cognitive Overlay

- Cognitive radios support new users in existing crowded spectrum without degrading licensed users
  - 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)

Compressed Sensing in Communications

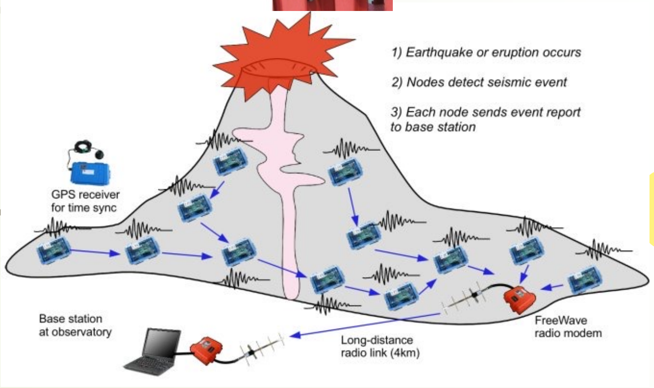
- Compressed sensing ideas have found widespread application in signal processing and other areas
- Basic premise: exploit sparsity to approximate high-dimensional system/signal in a few dimensions.
- We ask: how can sparsity be exploited to reduce the complexity of communication system design
  - **Sparse signals: e.g. white-space detection**
  - **Sparse samples: e.g. sub-Nyquist sampling**
  - **Sparse users: e.g. reduced-dimension multiuser detection**
  - **Sparse state space: e.g reduced-dimension network control**

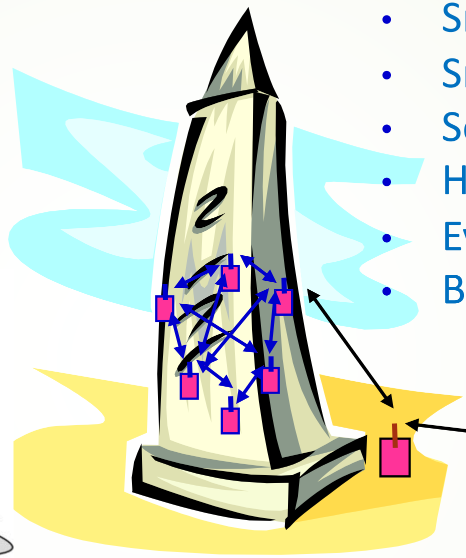
Ad-Hoc Networks



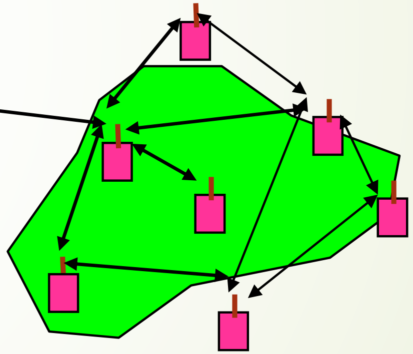
- Peer-to-peer communications
  - No backbone infrastructure or centralized control
- Routing can be multihop.
- Topology is dynamic.
- Fully connected with different link SINRs
- Open questions
  - Fundamental capacity region
  - Resource allocation (power, rate, spectrum, etc.)
  - Routing

Wireless Sensor Networks
Data Collection and Distributed Control



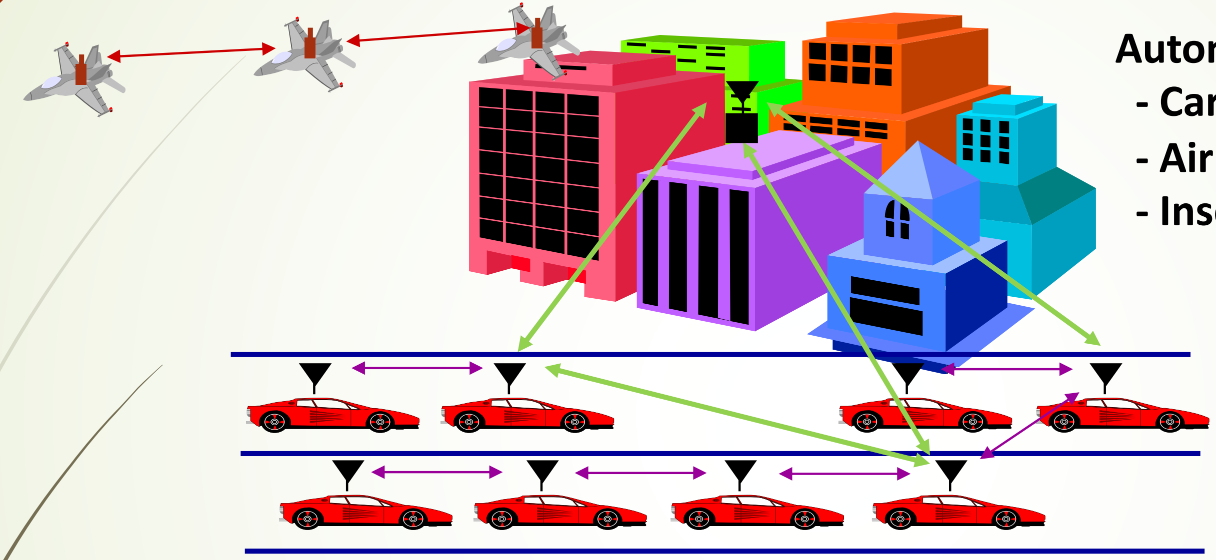


- Smart homes/buildings
- Smart structures
- Search and rescue
- Homeland security
- Event detection
- Battlefield surveillance



- 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

Distributed Control over Wireless

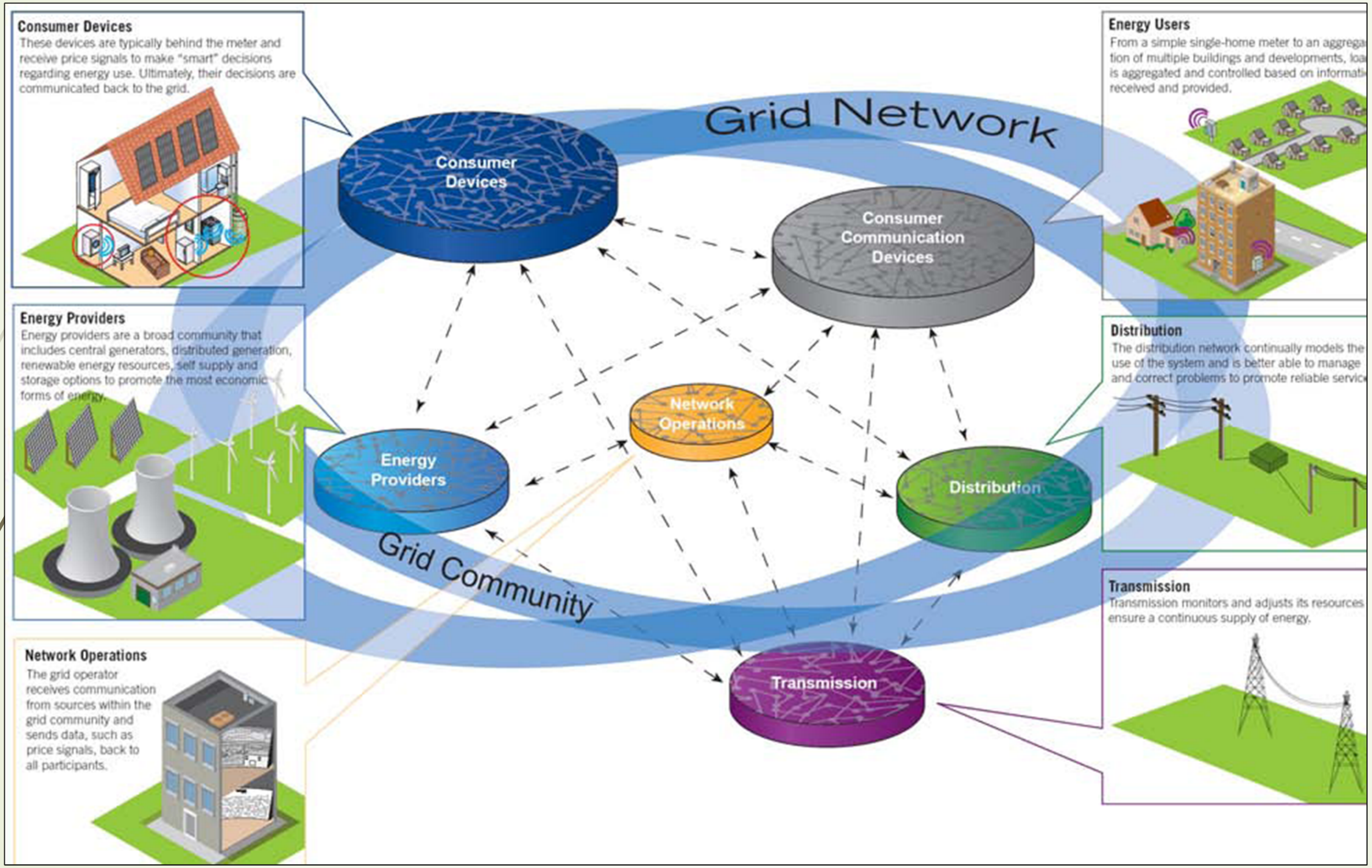


Automated Vehicles
- Cars
- Airplanes/UAVs
- Insect flyers

Interdisciplinary design approach

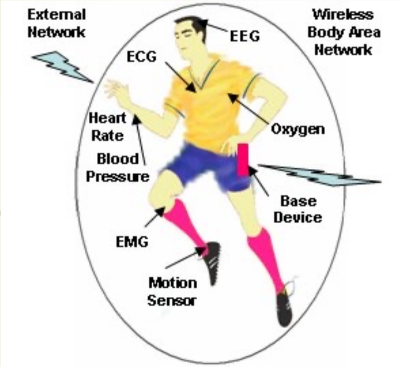
- Control requires fast, accurate, and reliable feedback.
- Wireless networks introduce delay and loss
- Need reliable networks and robust controllers
- Mostly open problems: ***Many design challenges***

The Smart Grid:
Fusion of Sensing, Control, Communications



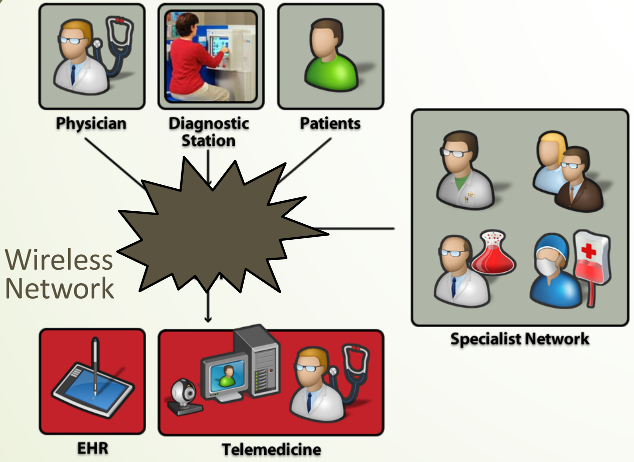
Open problems:
- Optimize sensor placement in the grid
- New designs for energy routing and distribution
- Develop control strategies to robustify the grid
- Look at electric cars for storage and path planning

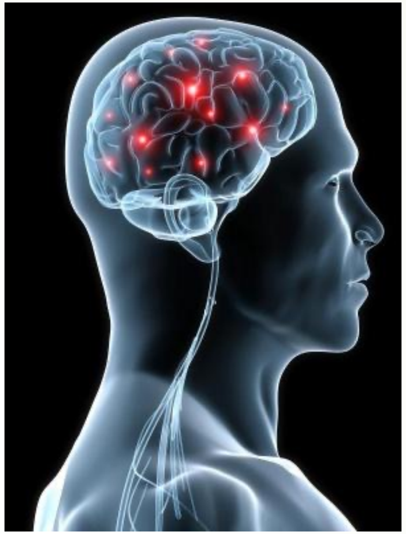
Applications in Health, Biomedicine and Neuroscience



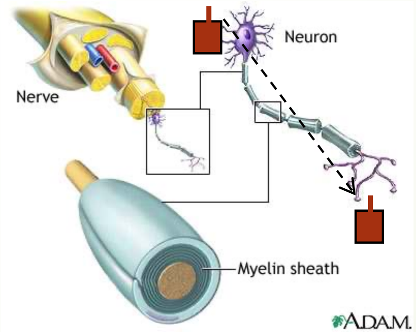
Body-Area Networks

Doctor-on-a-chip





Neuro/Bioscience
- EKG signal reception/modeling
- Brain information theory
- Nerve network (re)configuration
- Implants to monitor/generate signals
-In-brain sensor networks
- SP/Comm applied to bioscience



Recovery from Nerve Damage

Main Points

- The wireless vision encompasses many exciting systems and applications
- Technical challenges transcend across all layers of the system design.
- Existing and emerging systems provide excellent quality for certain applications but poor interoperability.
- Innovative wireless design needed for mmWave systems, massive MIMO, SDWN, and Internet of Things connectivity
- Standards and spectral allocation heavily impact the evolution of wireless technology