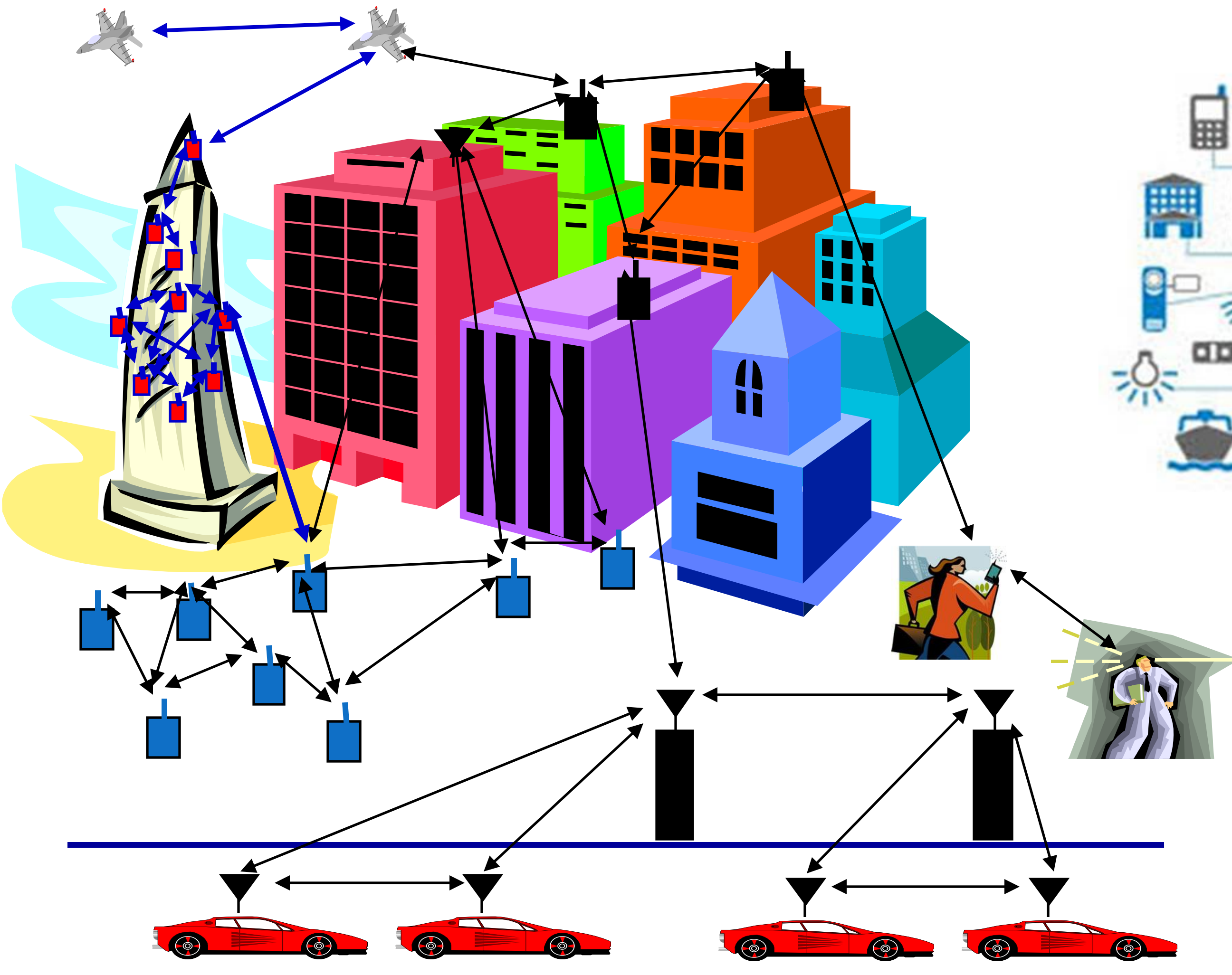
EE 458: Wireless Communications

Prof. Dr. Adnan Kavak



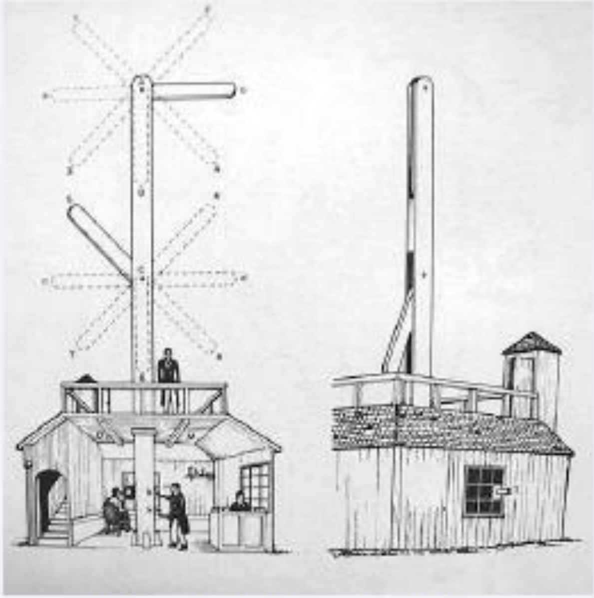
Next-Gen Cellular/WiFi
Smart Homes/Spaces
Autonomous Cars
Smart Cities
Body-Area Networks
Internet of Things
All this and more …

Early Wireless Communications

- Visual Communication
  - Line of Sight (LOS) communication
  - LOS distance further extended by telescopes
  - e.g. Smoke signals, Heliographs and Semaphore

Heliograph signaling

[Source: Wikipedia]



Semaphore signaling

[Source: Portsdown Tunnels]

Semaphore wheel

[Source: ThinkQuest]

Origin of Wireless Communications

Electromagnatic Waves

- 1831: Faraday demonstrated electromagnetic induction
- 1865: Maxwell predicted and developed theory of electromagnetic fields
- 1888: Hertz demonstrated with an experiment the wave character of electrical transmission through space

Wireless Begins

- 1893: Tesla made the first public demonstration of "wireless" radio communication
- 1894: Lodge demonstrated the reception of Morse code signaling using radio waves using a detecting device
- 1896: Marconi was awarded a patent for radio, which was recognized as the world's first patent for radio, though it used various earlier techniques of Tesla.
- 1907: Commercial Trans-Atlantic Wireless Service

History of Wireless Communications

Radio Broadcasting

- 1906: Reginald Fessenden transmitted the first radio audio broadcast
- 1915: Wireless voice transmission New York to San Francisco
- 1920: First commercial radio broadcast; Marconi discovers shortwave radio
- 1924: Spark gap radio was forbidden
- 1928: Many TV broadcast trials

Wireless & Mobile Communication System

- 1921: Police car dispatch radios, Detroit
- 1928: First mobile receiver was installed, one-way communication
- 1932: First mobile communication system allowing two-way communications
- 1933: Edwin H. Armstrong invented FM radio and patented
- 1946: Public mobile telephone service was introduced to 25 cities across US
- 1971: First network based on packet radio, ALOHANET, was developed
- 1973: Fundamental patent on UWB communications
- 1982: FCC granted cellular service authorization; Start of GSM specification

Booming of Wireless & Mobile Communication

- 1983: First analog cellular system (AMPS) deployed in Chicago
- 1985: FCC authorized the public use of the Industrial, Scientific and Medical (ISM) frequency band for wireless LAN products.
- 1992: First GSM system deployed
- 1994: First unclassified UWB communication program
- 1996: HiperLAN (High Performance Radio Local Area Network)
- 1997: Wireless LAN - IEEE802.11
- 1998: UMTS (Universal Mobile Telecommunication System) as European proposals for IMT-2000
- 1999: Standardization of additional wireless LANs (IEEE 802.11b) Bluetooth for piconets
- 2000: First GPRS trial
- 2001: Start of 3G systems: cdma2000 in Korea, UMTS tests in Europe
- 2002: FCC Report & Order for Part 15 acceptance of UWB systems

Wireless vs. Mobile Communications

Wireless Communication

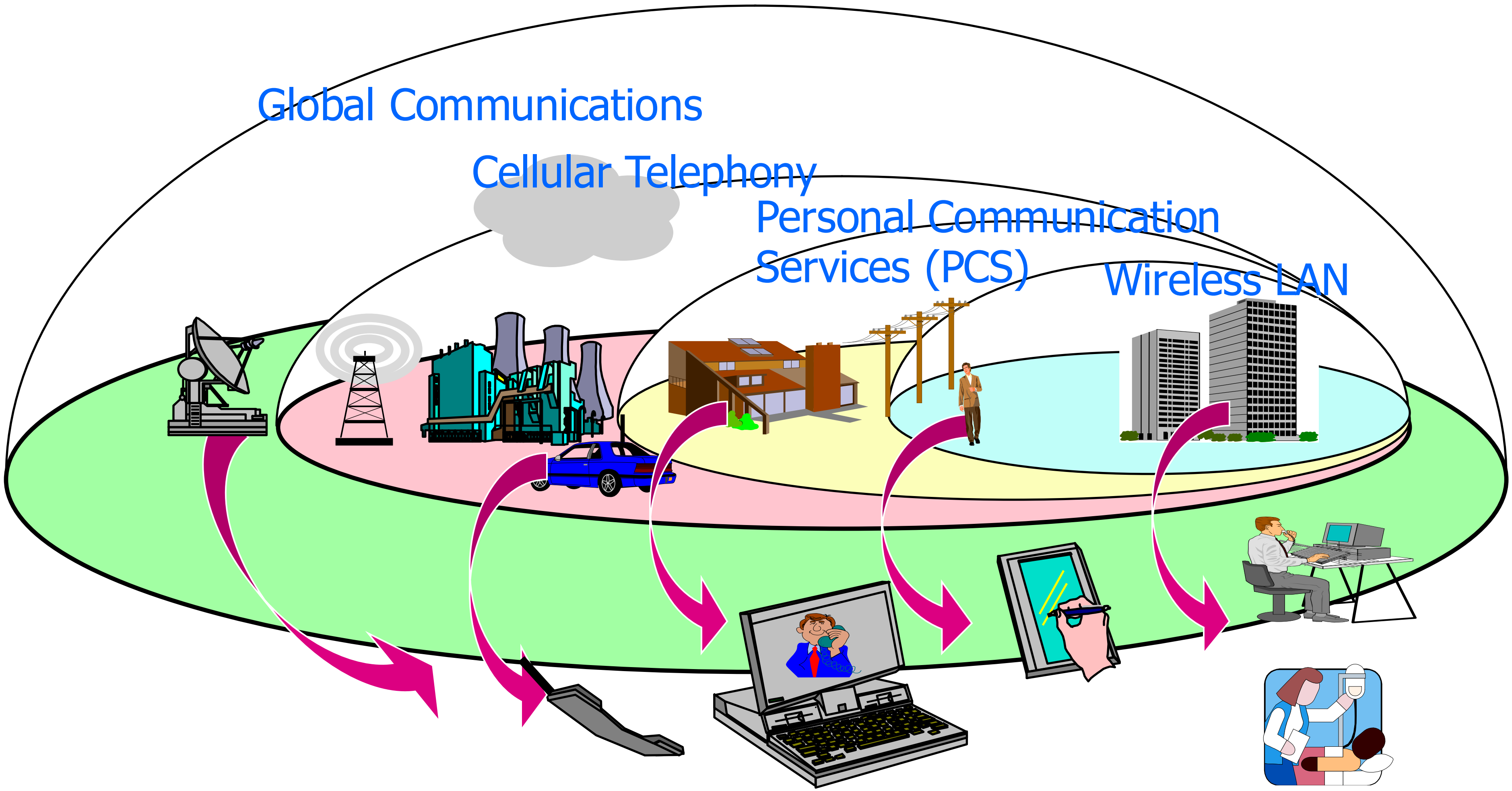
Information exchange between *people* or *devices* without wires.
Three segments of wireless communications:

- **Applications:** voice, data and video transmission, short messages, internet access, paging and short messages
- **Systems:** cellular telephone systems, wireless LANs, ad hoc wireless networks
- **Coverage regions**: in-door, campus, city, regional and global

Mobile Communication

Information exchange between people with mobility or portable devices anytime and anywhere.

The Wireless Vision

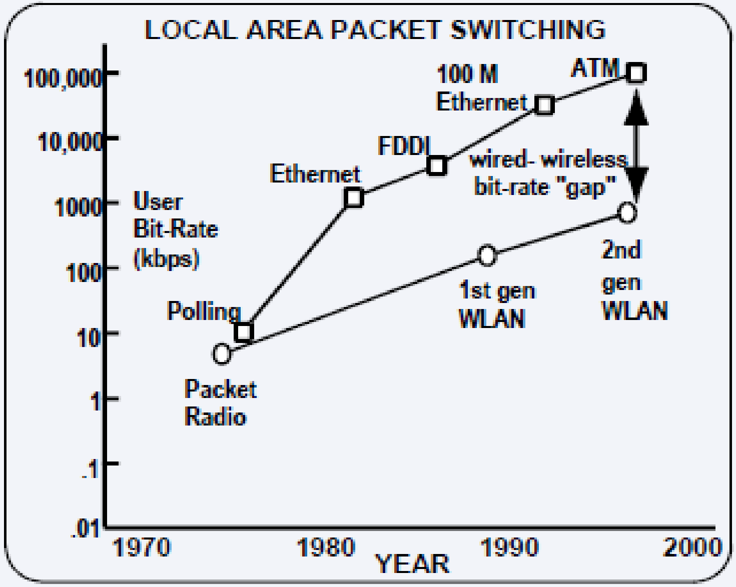


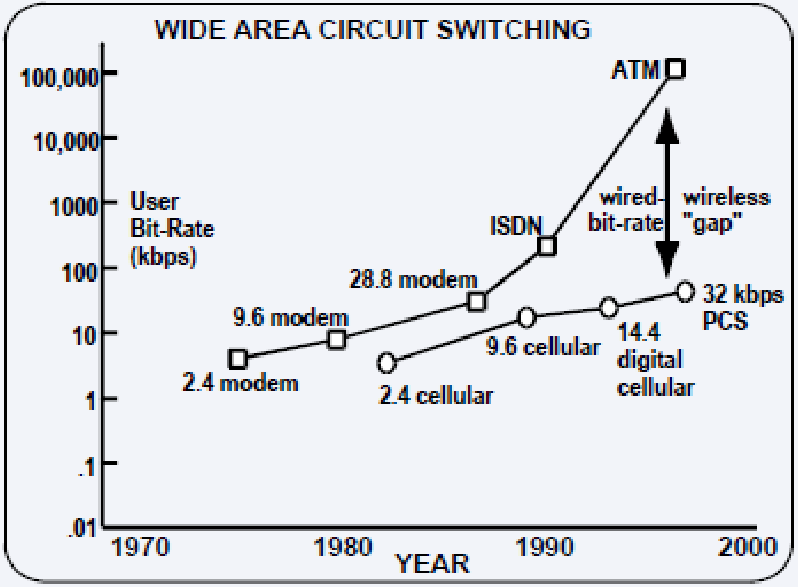
- **Communication Anywhere-Anytime-Anytype**
  - **Increasing Demand for Wireless Services**
  - **Unique Problems Compared to Wireline Communications**

Heterogeneous Wireless Network Access

Wireless v.s. Wired Networks

- Higher loss-rates due to interference, lower reliability
- Restrictive regulations of frequencies
- Lower transmission rates
- Higher delays, higher jitter
- Lower security, simpler active attacking
- **Flexibility and freedom**





[Source: Andrea Goldsmith, Wireless Communications]

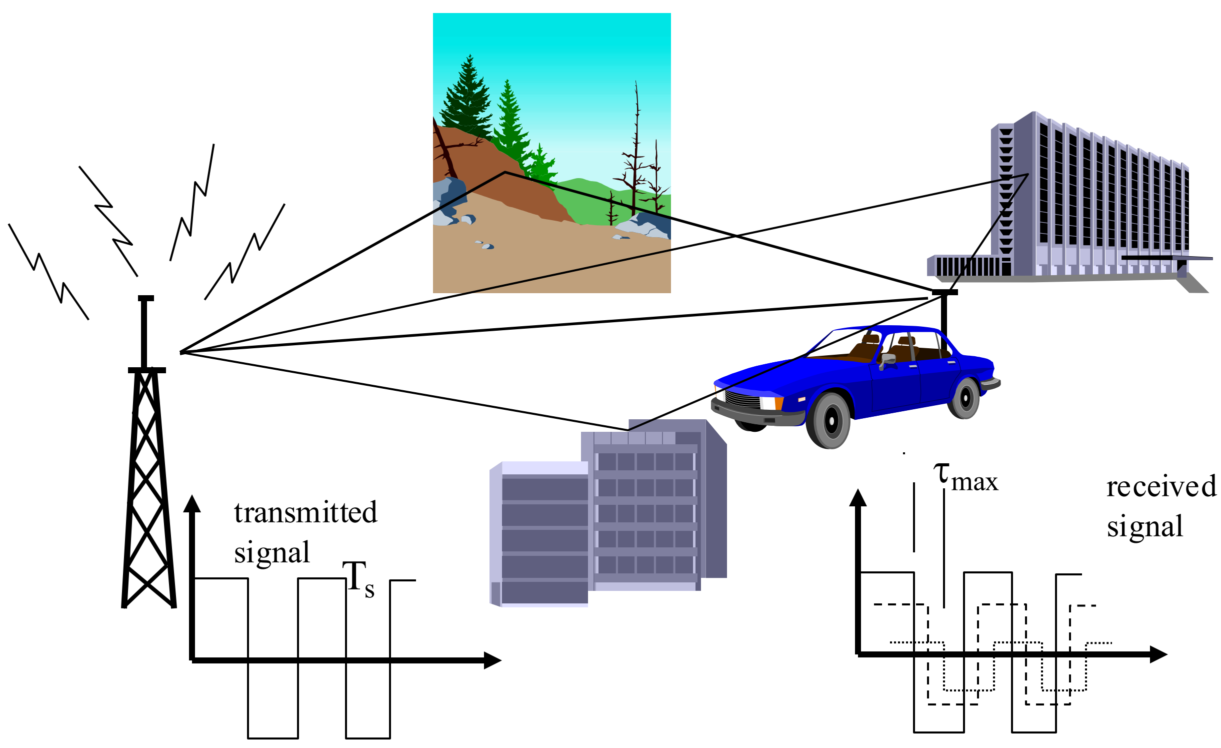
Challenges in Wireless Communications

- **Spectrum is scarce** → License fee
- **High data rates** → Multimedia applications
- **Reliability** → Quality of service
- **Mobility** → Channel characteristics
- **Portability** → Low power consumption
- **Connectivity** in various wireless networks → Multimode
- **Interference** from other users → Limited user capacity
- **Security** → Mobile commerce

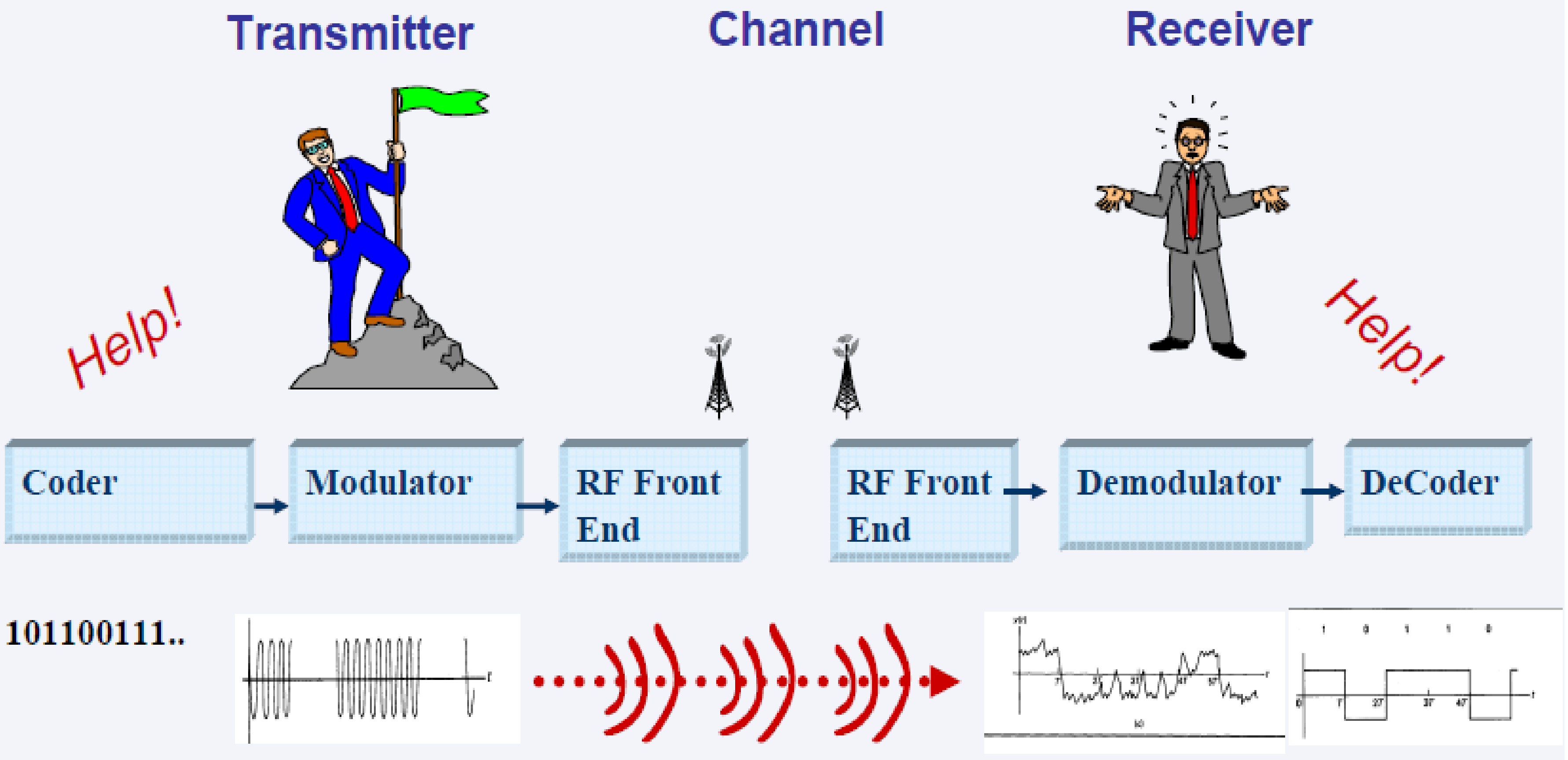
Wireless Environment

- Scarce (Limited) Radio Spectrum
- Co-channel Interference

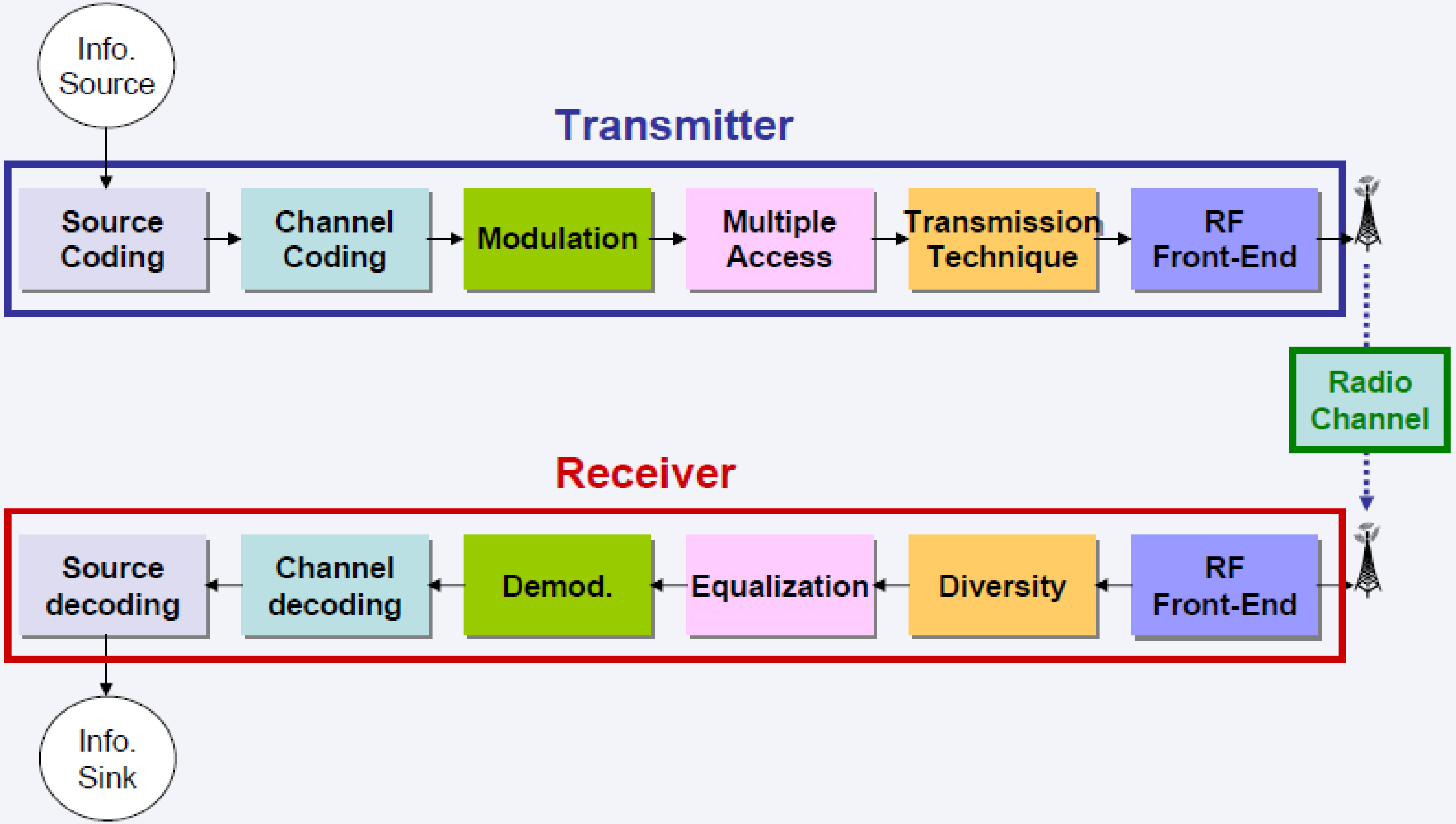
- Multipath
  - Different times of arrival at the receiver
- Coverage/Range
  - Propogation loss



Wireless Communications in Physical Layer

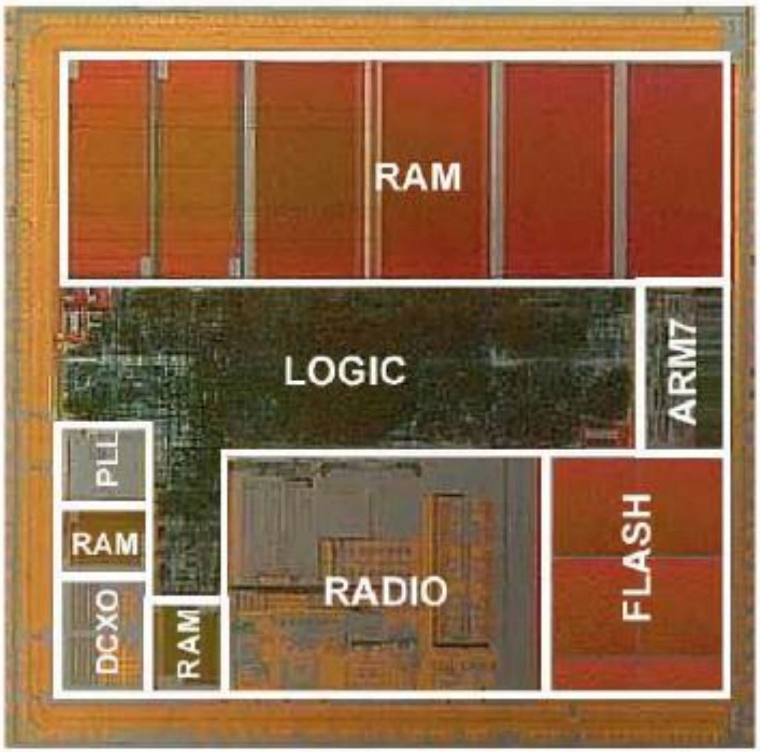


Wireless Transceiver Elements



Wireless SOC

1st Single-Chip Bluetooth SOC



Ref: Alcatel, ISSCC 2001

Wireless LAN SOC

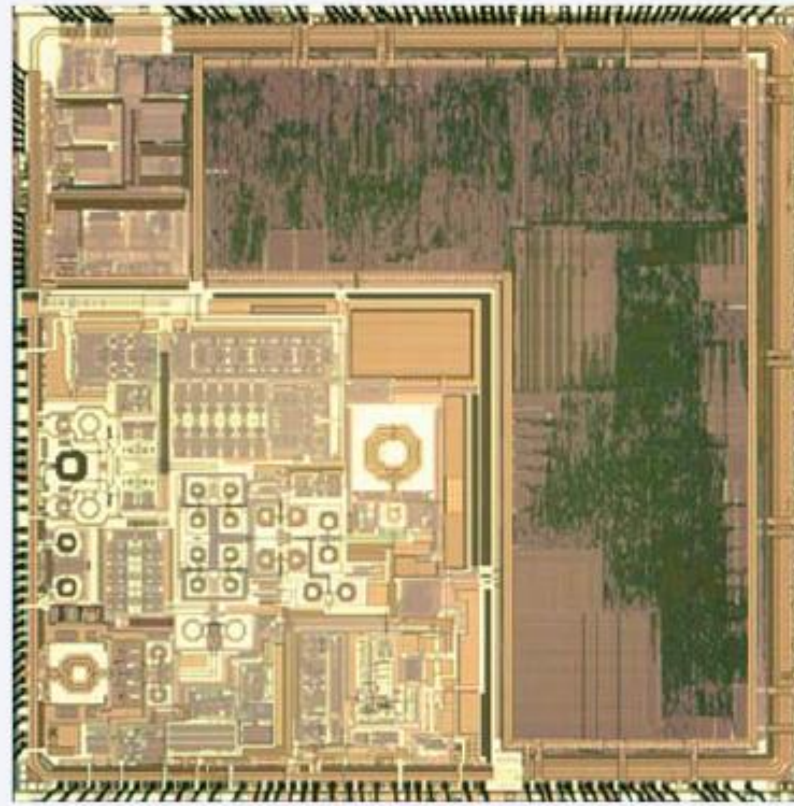


Figure 6. *Die photo of BCM4317 SOC: a fully integrated WLAN chip including the MAC, PHY, radio, power amplifier, and TR and diversity switches.*

Ref: A. Reza Rofougaran et al, IEEE Microwave Magazine, Mar 2005

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

Spectrum Regulation Agencies

- Since frequency spectrum is scarce, the application of spectrum is regulated by governments.
  - Taiwan: National Communications Commission (**NCC**)
  - Japan: Ministry of Internal Affairs and Communication (**MIC**)
  - United States: Federal Communications Commission (**FCC**)
  - Europe: European Telecommunications Standards Institute (**ESTI**)
  - Global: Internal Telecommunications Union (**ITU**)

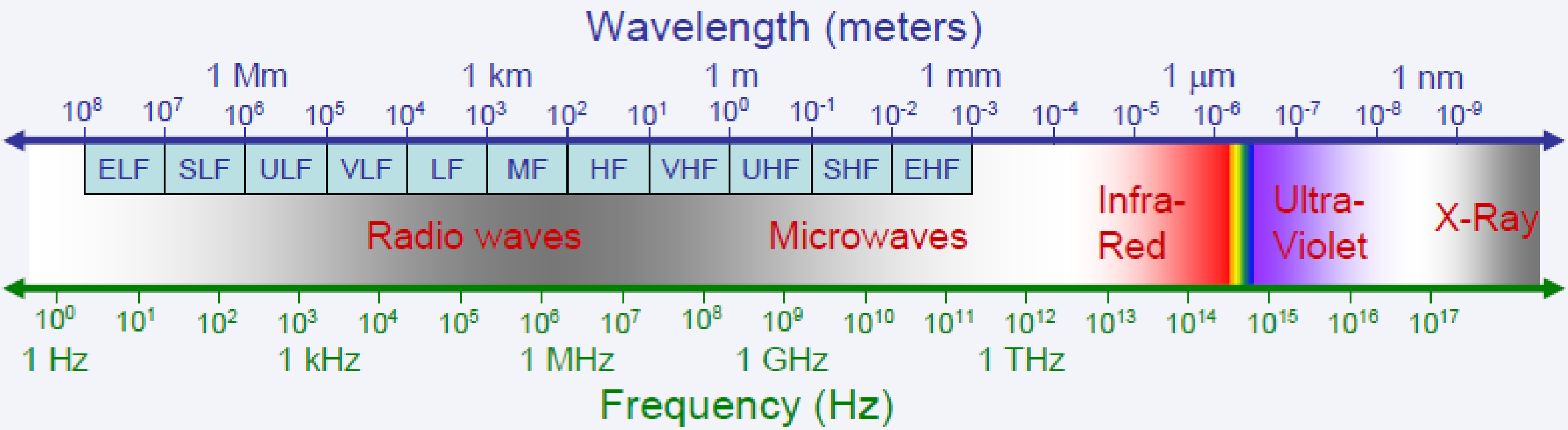
Standards

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

Standard Organizations

- **Telecommunications Industry Association**
  - represents providers of communications and information technology products and services for the global marketplace through its core competencies in standards development, domestic and international advocacy, as well as market development and trade promotion programs.
- **IEEE**
  - leads the way in developing open, leading-edge consensus standards for Wireless Local Area Networks (Wireless LANs), Wireless Personal Area Networks (Wireless PANs), and Wireless Metropolitan Area Networks (Wireless MANs).
- **ETSI**
  - is officially responsible for standardization of Information and Communication Technologies (ICT) within Europe.

Electromagnetic Spectrum



Radio Frequency Bands

Name	Frequency	Wave length	Principle Applications
ELF	3-30 Hz	10-100 Mm	
SLF	30-300 Hz	1-10 Mm	Power grids
ULF	300-3000 Hz	0.1-1 Mm	
VLF	3-30 kHz	10-100 km	Submarines
LF	30-300 kHz	1-10 km	Beacons
MF	300-3000 kHz	0.1-1km	AM Broadcast
HF	3-30 MHz	10-100 m	Shortwave Broadcast
VHF	30-300 MHz	1-10 m	FM, TV
UHF	300-3000 MHz	0.1-1 m	TV, LAN, cellular, GPS
SHF	3-30 GHz	10-100 mm	Radar, GSO satellite
EHF	30-300 GHz	1-10 mm	Radar, automative

Microwave Bands

Old	New	Frequency
L	D	1-2 GHz
S	E,F	2-4 GHz
C	G,H	4-8 GHz
X	I,J	8-12 GHz
Ku	J	12-18 GHz
K	J	18-26 GHz
Ka	K	26-40 GHz

Mobile Radio Standards Around the World

1) Major Mobile Radio Standards in North America

Standard	**Type**	**Year**	**Multiple Access**	**Frequency Band**	**Modulation**	**Channel Bandwidth**
AMPS (1G)	Cellular	1983	FDMA	824-894 MHz	FM	30 KHz
USDC (IS-54) (2G)	Cellular	1991	TDMA	824-894 MHz	Π/4-DQPSK	30 KHZ
IS-95 (2G)	Cellular/PC S	1993	CDMA	824-894 MHz/ 1.8-2 GHz	DQPSK/ BPSK	1.25 MHz
DCS-1900 (GSM) (2G)	PCS	1994	TDMA	1.85-1.99 GHz	GMSK	200 KHz
PACS	Cordless/P CS	1994	TDMA/ FDMA	1.85-1.99 GHz	Π/4-DQPSK	300 KHz
MIRS	SMR/PCS	1994	TDMA	Several	16-QAM	25 KHz
Cdma2000 (3G)	Cellular/PC S	After 2003	WCDMA	1710–1755 MHz and 2110–2155 MHz	QPSK	5 MHz
HSPA (3.5G)	Cellular/PC S		WCDMA	1710–1755 MHz and 2110–2155 MHz	64 QAM	5MHz
LTE Rel.10 4G			OFDMA			5-20 MHz

Mobile Radio Standards Around the World

2) Major Mobile Radio Standards in Europe

Standard	Type	Year	Multiple Access	Frequency Band	Modulation	Channel Bandwidth
NMT-450 NMT-900	Cellular Cellular	1981 1986	FDMA FDMA	450-470 MHz 890-960 MHz	FM FM	25 KHz 12.5 KHz
ETACS	Cellular	1985	FDMA	900 MHz	FM	25 KHz
GSM	Cellular/ PCS	1990	TDMA	890-960 MHz	GMSK	200 KHZ
CT2 DECT	Cordless	1989 1993	FDMA TDMA	864-868 MHz 1.88-1.9 GHz	GFSK GFSK	100 KHz 1.728 MHz
DCS-1800	CordlessPCS	1993	TDMA	1710-1900 MHz	GMSK	200 KHz
WCDMA (UTRA)	Cellular/PCS	After 2003	CDMA	1885–2025 MHz and 2110–2200 MHz	QPSK	5 MHz
HSPA (3.5G)	Cellular/PCS		WCDMA	1710–1755 MHz and 2110–2155 MHz	64 QAM	5MHz
LTE Rel.10 4G						

Current/Next-Gen Wireless Systems

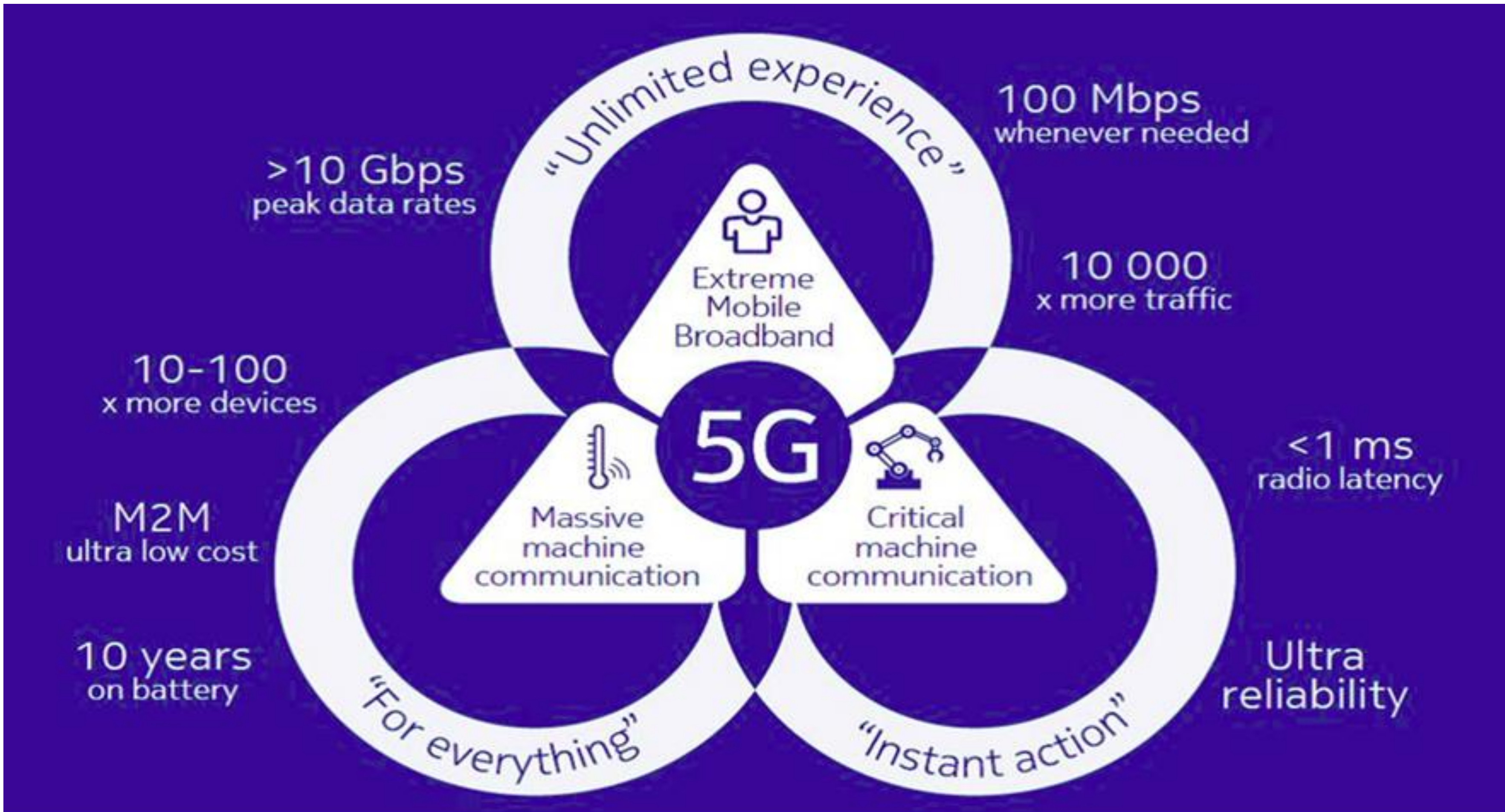
- Current:
  - 4G Cellular Systems (LTE-Advanced)
  - 4G Wireless LANs/WiFi (802.11ac)
  - mmWave massive MIMO systems
  - Satellite Systems
  - Bluetooth
  - Zigbee
  - WiGig
- Emerging
  - 5G Cellular and WiFi Systems
  - Ad/hoc and Cognitive Radio Networks
  - Energy-Harvesting Systems
  - Chemical/Molecular

Much room
For innovation

4G/LTE Cellular

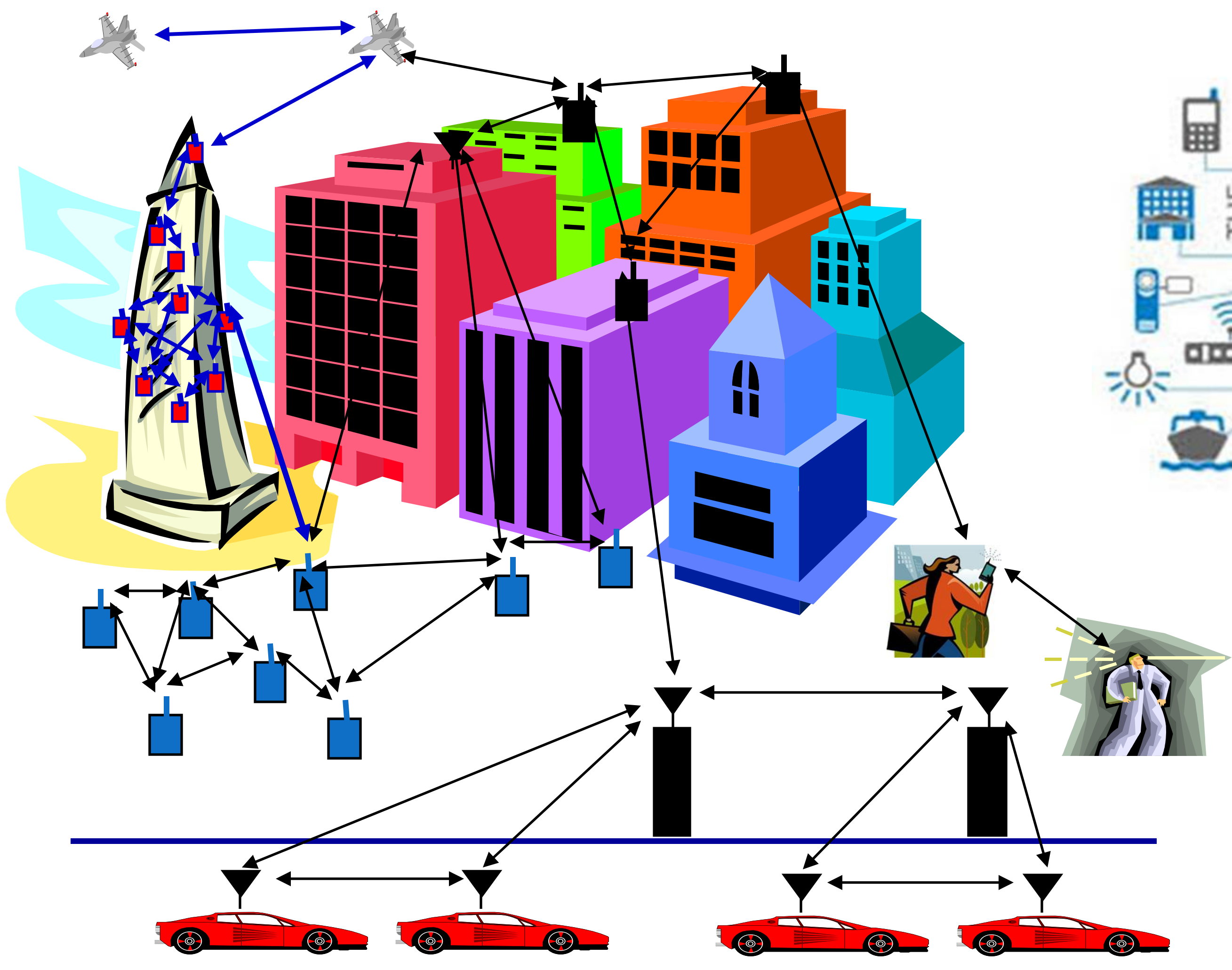
- Much higher data rates than 3G (50-100 Mbps)
  - 3G systems has 384 Kbps peak rates
- Greater spectral efficiency (bits/s/Hz)
  - More bandwidth, adaptive OFDM-MIMO, reduced interference
- Flexible use of up to 100 MHz of spectrum
  - 10-20 MHz spectrum allocation common
- Low packet latency (<5ms).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

5G Upgrades from 4G



Future Wireless Networks

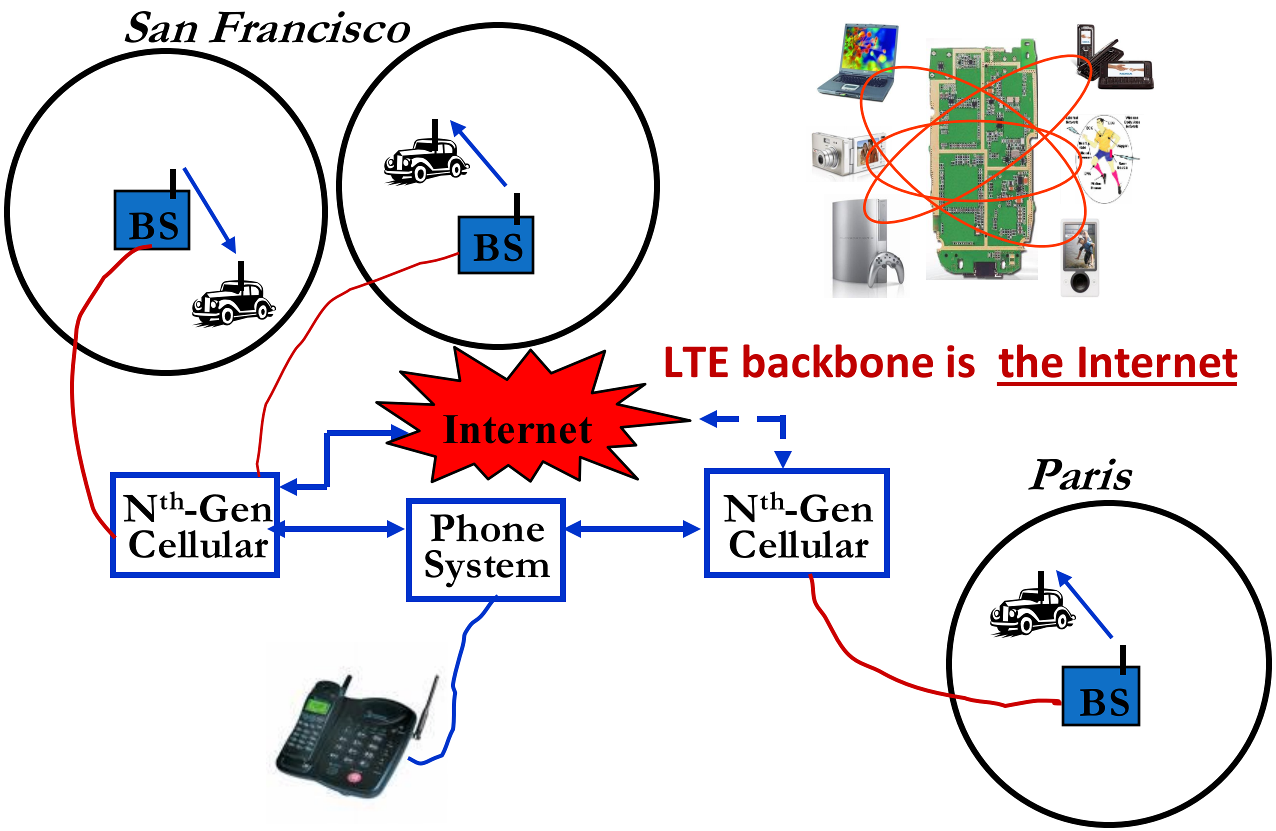
Ubiquitous Communication Among People and Devices



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

Future Cellular Phones

Burden for this performance is on the backbone network

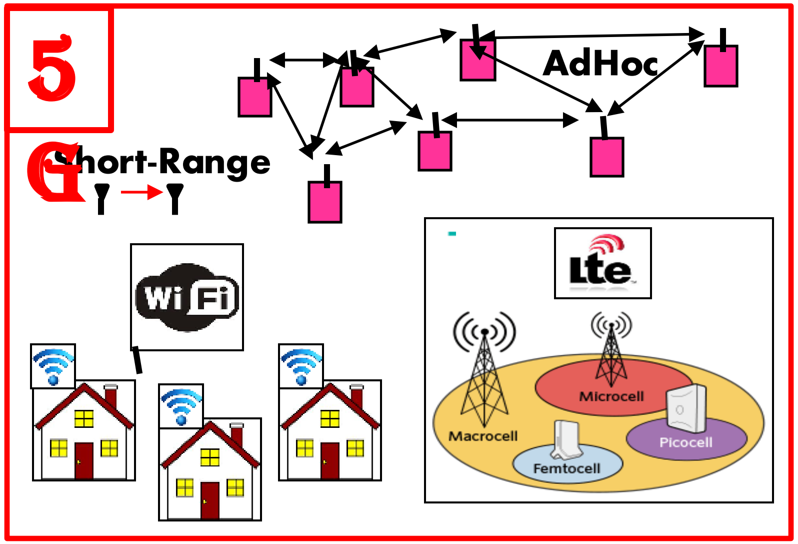


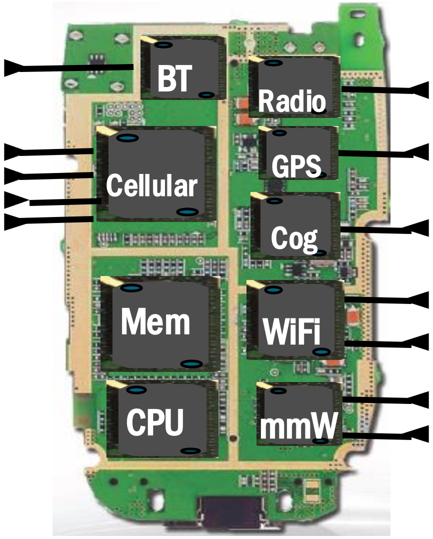
Much better performance and reliability than today

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

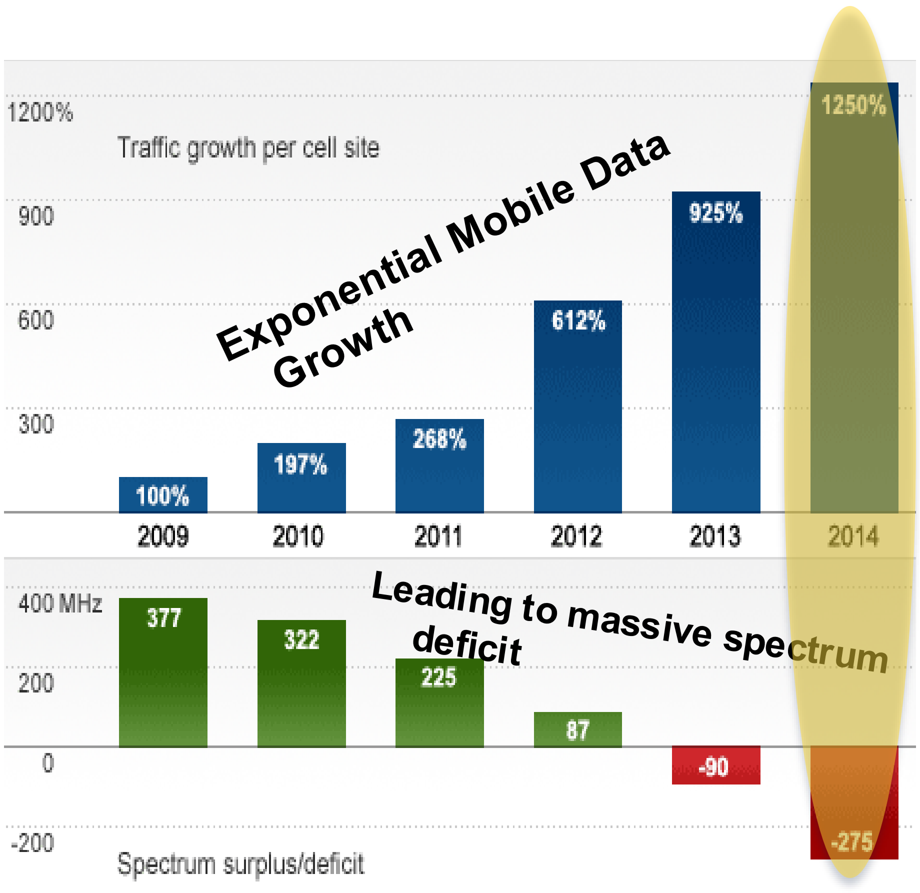
Challenges

- 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



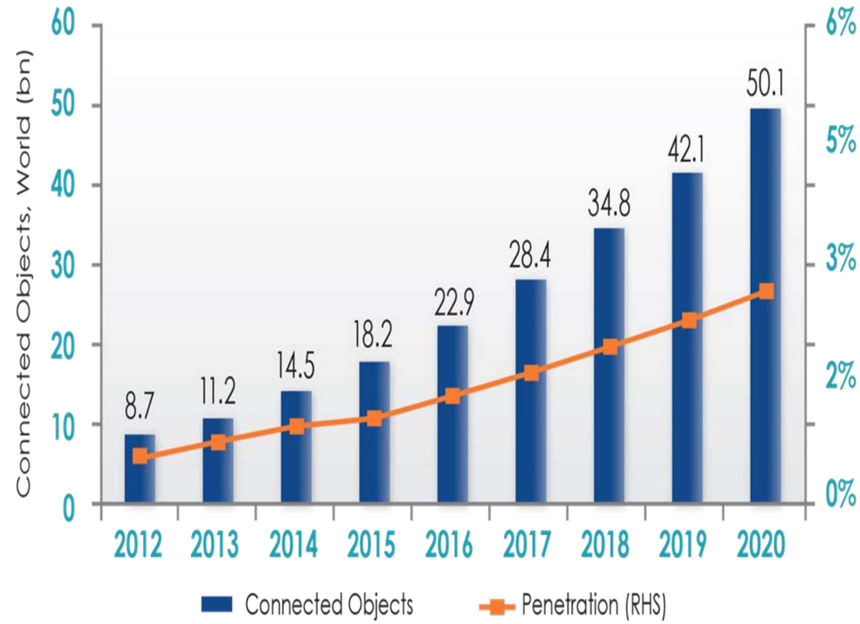


“Sorry, your airwaves are full*”



Source: FCC

On the Horizon:
“The Internet of Things”



50 billion devices by 2020

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

Wifi Networks

Multimedia Everywhere, Without Wires

802.11ac

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

Wireless HDTV and Gaming

Wireless LAN Standards

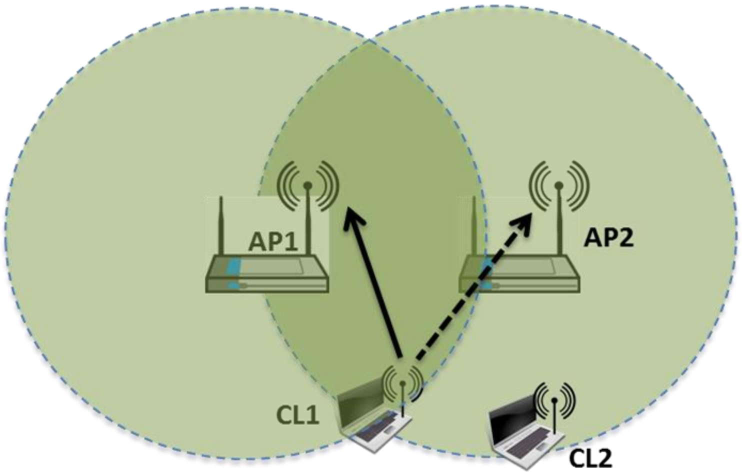
- 802.11b (Old – 1990s)
  - Standard for 2.4GHz ISM band (80 MHz)
  - Direct sequence spread spectrum (DSSS)
  - Speeds of 11 Mbps, approx. 500 ft range
- 802.11a/g (Middle Age– mid-late 1990s)
  - Standard for 5GHz band (300 MHz)/also 2.4GHz
  - OFDM in 20 MHz with adaptive rate/codes
  - Speeds of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

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

Why does WiFi performance suck?

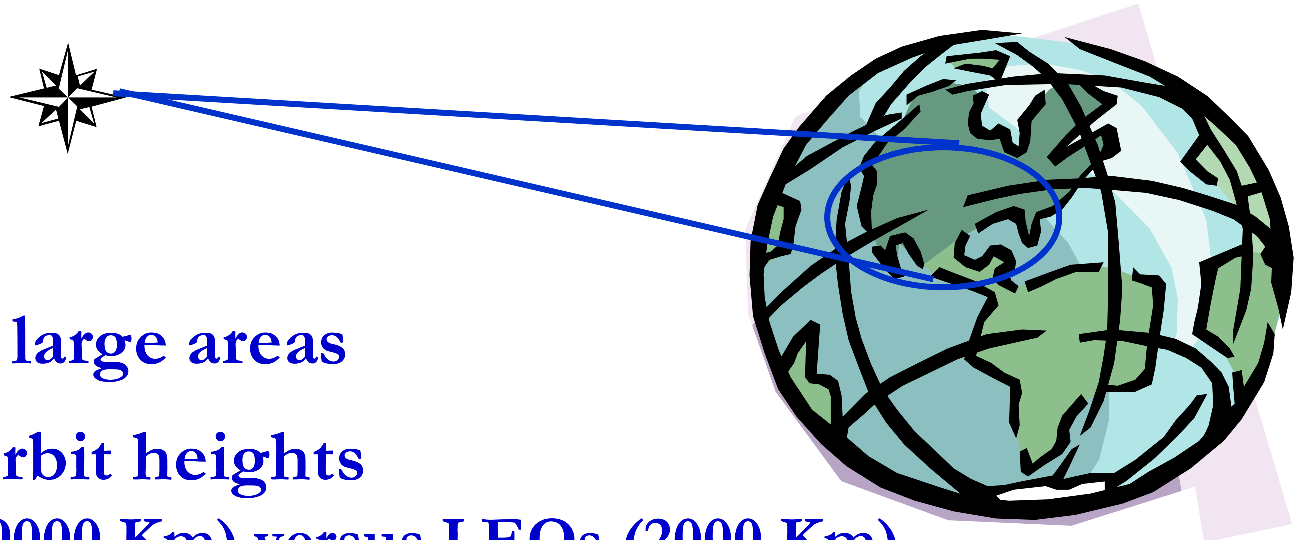
Carrier Sense Multiple Access: if another WiFi signal detected, random backoff

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
  - Multiuser MIMO will help each AP, but not interfering APs

Satellite Communication



- 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

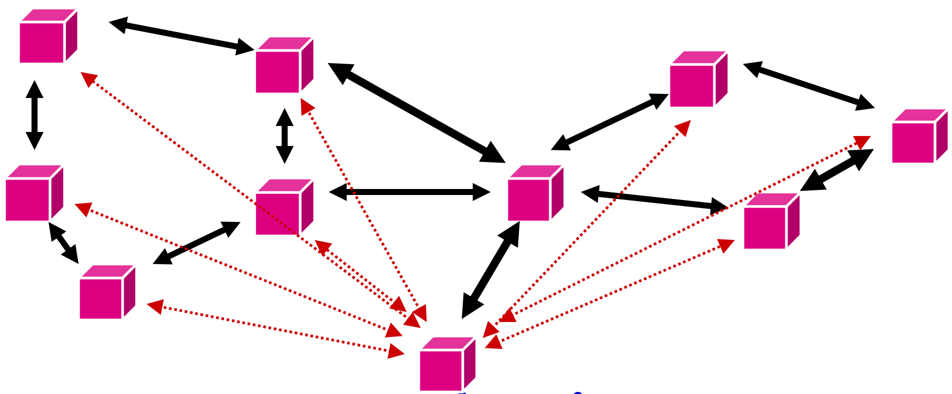
Bluetooth

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

IEEE 802.15.4/ZigBee Radios

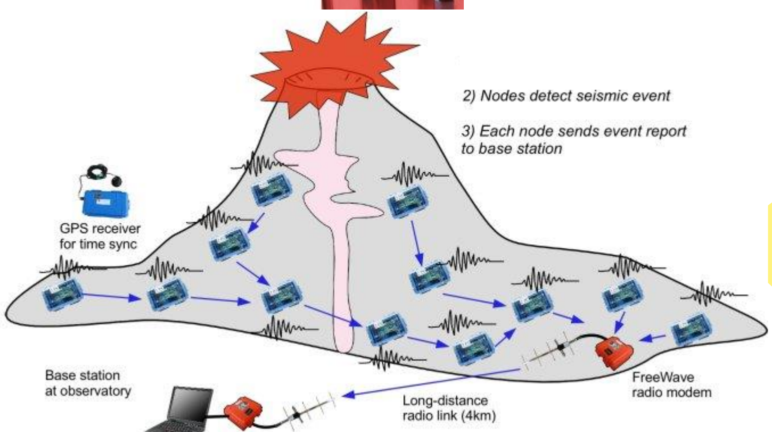
- Low-rate low-power low-cost secure radio
  - Complementary to WiFi and Bluetooth
- Frequency bands: 784, 868, 915 MHz, 2.4 GHz
- Data rates: 20Kbps, 40Kbps, 250 Kbps
- Range: 10-100m line-of-sight
- Support for large mesh networking or star clusters
- Support for low latency devices
- CSMA-CA channel access
- Applications: light switches, electricity meters, traffic management, and other low-power sensors.

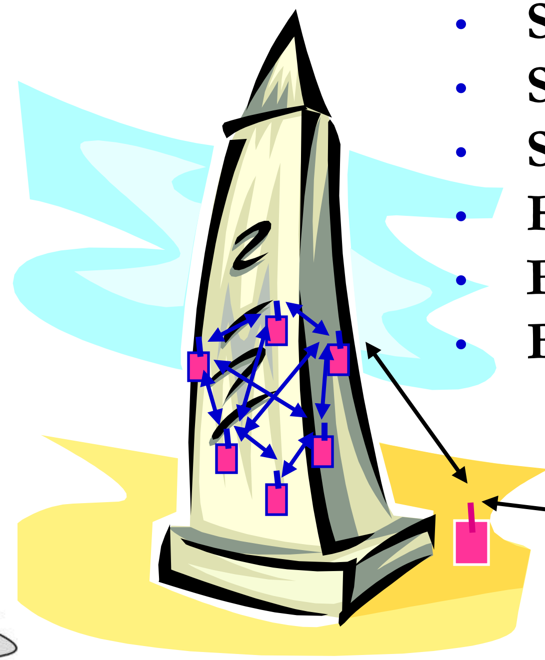
Ad-Hoc Networks



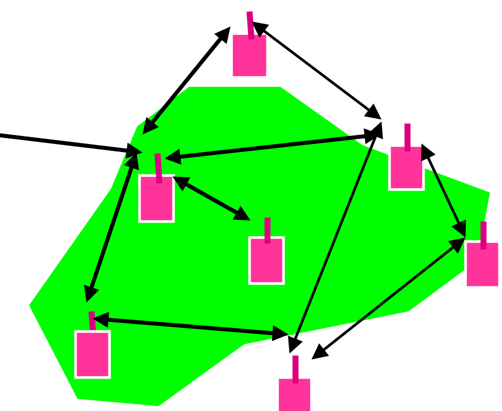
- Peer-to-peer communications
  - No backbone infrastructure or centralized control
- Routing can be multihop.
- Topology is dynamic.
- Fully connected with different link SINRs
- Open questions
  - Fundamental capacity region
  - Resource allocation (power, rate, spectrum, etc.)
  - Routing

Wireless Sensor Networks
Data Collection and Distributed Control



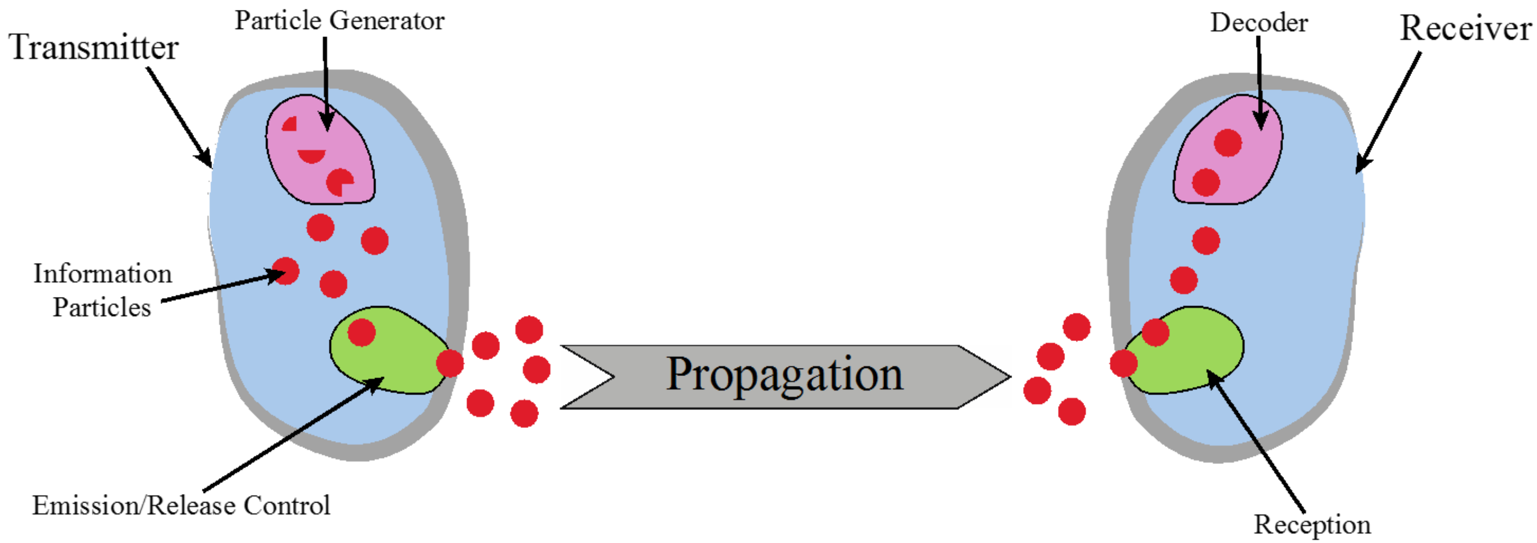


- Smart homes/buildings
- Smart structures
- Search and rescue
- Homeland security
- Event detection
- Battlefield surveillance



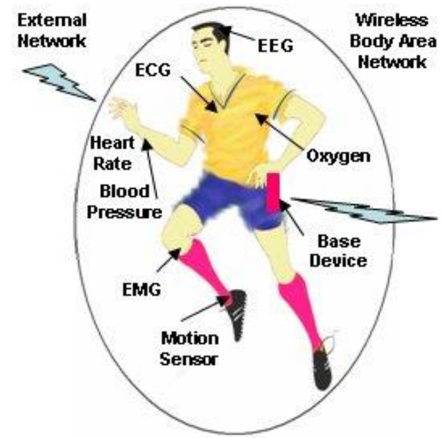
- Energy (transmit and processing) is the driving constraint
- Data flows to centralized location (joint compression)
- Low per-node rates but tens to thousands of nodes
- Intelligence is in the network rather than in the devices

Chemical Communications

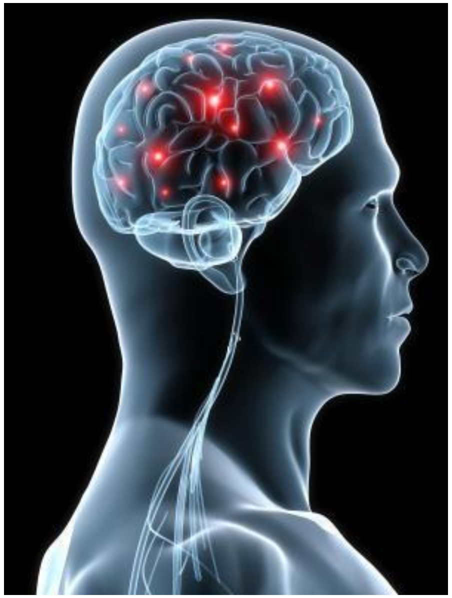


- Can be developed for both macro (>cm) and micro (<mm) scale communications
- Greenfield area of research:
  - Need new modulation schemes, channel impairment mitigation, multiple acces, etc.

Applications in Health, Biomedicine and Neuroscience



Body-Area Networks



Neuroscience

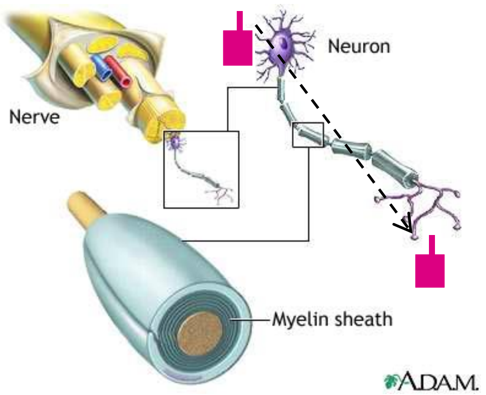
-Nerve network (re)configuration

-EEG/ECoG signal processing

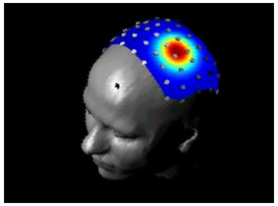
- Signal processing/control for deep brain stimulation

- SP/Comm applied to bioscience

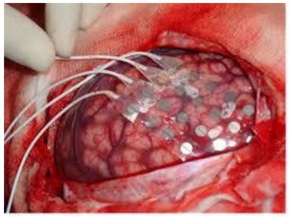
Recovery from Nerve Damage



EEG



ECoG



ECoG Epileptic Seizure Localization