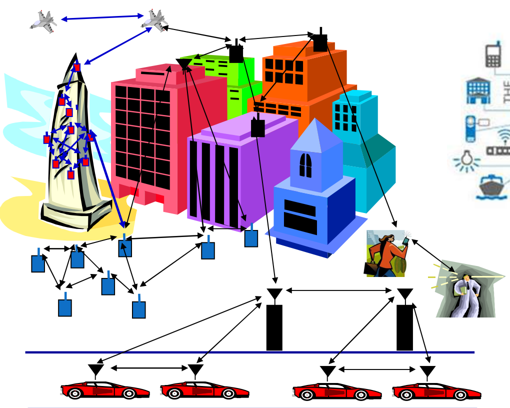
EE 359: Wireless Communications

Professor Andrea Goldsmith



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

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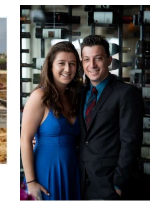
About me



- Engineering prof dad, cartoonist mom
- Undergrad at UC Berkeley 1982-1986
- Worked in Silicon Valley 1986-1989
- Fell in love with wireless.
- Ph.D. from UCB: 1989-1994
  - Summers at AT&T Bell Labs
- Taught at Caltech 1994-1999
- Moved to Stanford in 1999
  - Lots of stuff in addition to research, teaching
- Founded 2 wireless companies: Quantenna (QTNA'06) and Plume WiFi'10 Much work around diversity in STEM (in academia, industry, and IEEE)
- Best Results: Daniel (22) and Nicole (20)

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Outline

- Course Basics
- Course Syllabus
- Wireless History
- The Wireless Vision
- Technical Challenges
- Current/Next-Gen Wireless Systems
- Spectrum Regulation and Standards
- Emerging Wireless Systems (Optional Lecture)

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Course Information*
People

- Instructor: Andrea Goldsmith, Pack 371, andrea@ee, OHs: TTh immediately after class and by appt.
- TA: Tom Dean (trdean@stanford.edu)
  - Discussion section: Wed 4-5 pm (hopefully taped)
  - OHs: Wed 5-6pm, Th 4-5pm, Fri 11-12pm (tentative). Emails received during OHs will be responded to during or just after. Email questions are ideally via Piazza.
  - Piazza: https://piazza.com/stanford/win2020/ee359/home. All are registered, will use to poll on OH/discussion times
- Class Administrator: Dash Corbett, email: dashiellcorbett@stanford.edu, 365 Packard, 723-2681. Homework dropoff: Fri by 4 pm.

*See web or handout for more details

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Course Information
Nuts and Bolts

- Prerequisites: EE279 or equivalent (Digital Communications)
- Textbook: *Wireless Communications* (by me), draft 2nd Ed.
  - Available as reader at bookstore or on website
  - Raffle for $100 Amazon gift card for typos/mistakes/suggestions
  - Supplemental texts at Engineering Library.
- Class Homepage: www.stanford.edu/class/ee359
  - All announcements, handouts, homeworks, etc. posted to website
  - "Lectures" link continuously updates topics, handouts, and reading
  - Calendar will show any changes to class/OH/discussion times
- Class Mailing List: ee359-win1920-students@lists (automatic for on-campus registered students).
  - Guest list ee359-win1920-guest@lists for SCPD and auditors: send Tom email to sign up.
  - Sending mail to ee359-win1920-staff@lists reaches me and Tom.

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Course Information
Policies

- Grading: Two Options
  - No Project (3 units): HW – 25%, 2 Exams – 35%, 40%
  - Project (4 units): HWs- 20%, Exams - 25%, 30%, Project - 25%
- HWs: assigned Thu, due following Fri 4pm (starts next week)
  - Homeworks lose 33% credit after 4pm Fri, lowest HW dropped
  - Up to 3 students can collaborate and turn in one HW writeup
  - Collaboration means all collaborators work out all problems together
  - Unpermitted collaboration or aid (e.g. solns for the book or from prior years) is an honor code violation and will be dealt with strictly.
  - Extra credit: up to 2 "design your own" HW problems; course eval
- Exams:
  - Midterm week of 2/17 (It will be scheduled outside class time; the duration is 2 hours.) Final on 3/17 from 3:30-6:30pm (pizza after)
  - Exams must be taken at scheduled time (with very few exceptions)

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Course Information
Projects

- The term project (for students electing to do a project) is a research project related to any topic in wireless
- Two people may collaborate if you convince me the sum of the parts is greater than each individually
- A 1 page proposal is due 2/7 at midnight.
  - 5-10 hours of work typical for proposal
  - Must create project website and post proposal there (submit web link)
  - Preliminary proposals can be submitted for early feedback
- The project is due by midnight on 3/14 (on website)
  - 20-40 hours of work after proposal is typical for a project
- Suggested topics in project handout
  - Anything related to wireless or application of wireless techniques ok.

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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 Systems: OFDM and other waveforms
- Multiuser and Cellular Systems

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Tentative Detailed Syllabus

Lecture #	Date	Topic	Required Reading
		Introduction	
1	1/7	Overview of Wireless Communications	Chapter 1
		Wireless Channel Models	
2-3	1/9, 1/14	Path Loss and Shadowing Models, Millimeter wave propagation	Chapter 2
4-5	1/17, 1/21	Statistical Fading Models, Narrowband Fading	Section 3.1-3.2.3
6	1/23	Wideband Fading Models	Section 3.3
		Impact of Fading and ISI on Wireless Performance	
7	1/28	Capacity of Wireless Channels	Chapter 4
8,9,10	1/30, 2/5, 2/6	Digital Modulation and its Performance	Lec 8: Chapter 5 Lec 9-10: Chapter 6
		Flat-Fading Countermeasures	
11	2/11	Diversity	Chapter 7
MT	**Week of 2/17**	**Midterm (outside class time)**	**Chapters 2 to 7**
12-13	2/13-2/18	Adaptive Modulation	Chapter 9.1-9.3
14-15	2/21-2/25	Multiple Input/Output Systems (MIMO)	Chapter 10, Appendix C
		ISI Countermeasures	
16-17	2/27, 3/3	Multicarrier Systems, OFDM, and other multicarrier waveforms	Chapter 12
18-19	3/4-3/10	Multiuser and Cellular Systems	Topics in Chapters 13-15
		Course Summary	
20	3/12	Course summary/final review (and optional advanced topics lecture over lunch)	
Final	**3/17**	**3:30-6:30pm**	*Pizza party to follow*

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Class Rescheduling

- No lectures Thu 1/16, Tue 2/4, Thu 2/20 and Thu 3/5.
- These lectures are tentatively rescheduled as:
  - Lecture on Thu 1/16 is rescheduled to Fri 1/17 at lunch
  - Lecture on Tue 2/4 is rescheduled to Wed 2/5 at lunch
  - Lecture on Thu 2/20 is rescheduled to Fri 2/21 at lunch
  - Lecture on Thu 3/5 is rescheduled to Wed 3/4 at lunch
- Last lecture on 3/12 has an optional component 11:50-12:30 on advanced topics with lunch.

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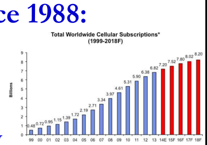
Wireless History

- Ancient Systems: Smoke Signals, Carrier Pigeons, …
- Radio invented in the 1880s by Marconi
- Many sophisticated military radio systems were developed during and after WW2
- Exponential growth in cellular use since 1988: approx. 8B worldwide users today
  - Ignited the wireless revolution
  - Voice, data, and multimedia ubiquitous
  - Use in 3rd world countries growing rapidly



- Wifi also enjoying tremendous success and growth
- Bluetooth pervasive, satellites also widespread

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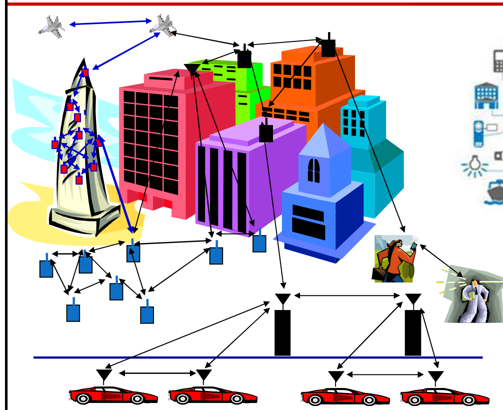
Future Wireless Networks

Ubiquitous Communication Among People and Devices



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

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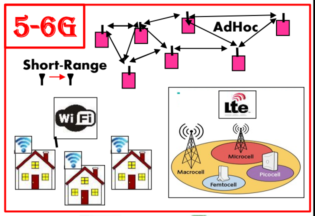
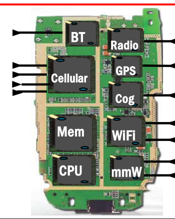
Challenges

- **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, Energy
  - High frequencies/mmWave
  - Multiple Antennas
  - Multiradio Integration
  - Coexistance



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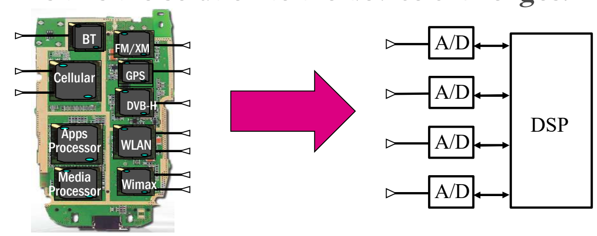
Software-Defined (SD) Radio:

Is this the solution to the device challenges?



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

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

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

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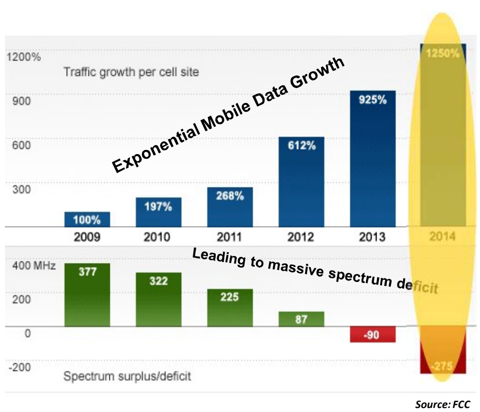
"Sorry America, your airwaves are full*"



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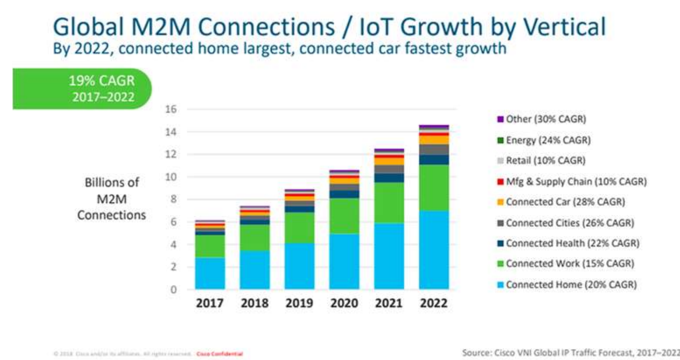
On the Horizon, the Internet of Things



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What is the Internet of Things:

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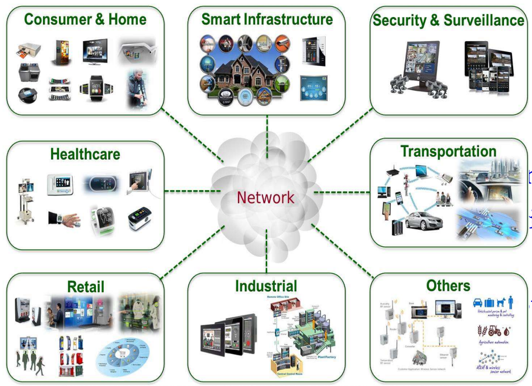

Different requirements than smartphones: low rates/energy consumption

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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.*

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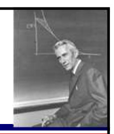
What would Shannon say?



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

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Current/Next-Gen Wireless Systems

- Current:
  - 4G Cellular Systems (LTE-Advanced)
  - 6G Wireless LANs/WiFi (802.11ax)
  - mmWave massive MIMO systems
  - Satellite Systems
  - Bluetooth
  - Zigbee
  - WiGig
- Emerging
  - 5G Cellular and 7G WiFi Systems
  - Ad/hoc and Cognitive Radio Networks
  - Energy-Harvesting Systems
  - Chemical/Molecular

Much room For innovation

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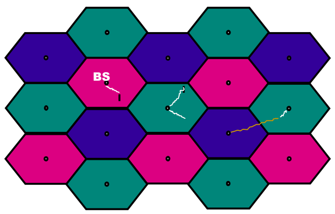
Spectral Reuse

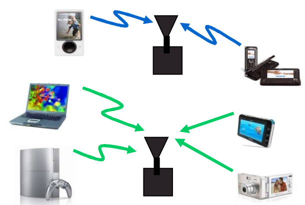
Due to its scarcity, spectrum is *reused*

In licensed bands



Cellular

and unlicensed bands

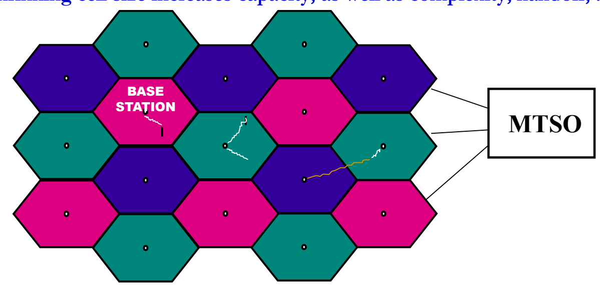


Wifi, BT, UWB,…

Reuse introduces interference

Cellular Systems: Reuse channels to maximize capacity

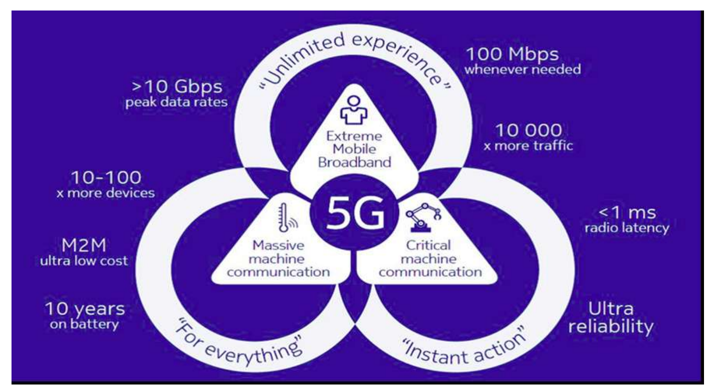
- Geographic region divided into cells
- Freq./timeslots/codes/space reused in different cells (reuse 1 common).
- Interference between cells using same channel: interference mitigation key
- Base stations/MTSOs coordinate handoff and control functions
- Shrinking cell size increases capacity, as well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



4G/LTE Cellular

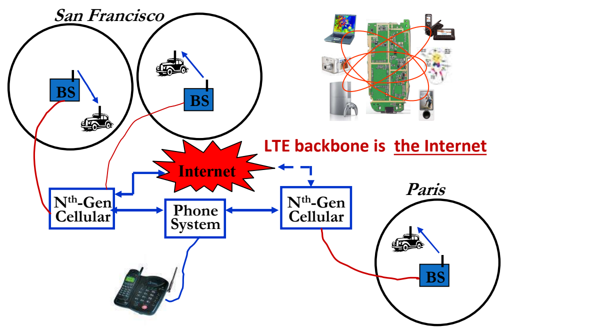
- Much higher data rates than 3G (50-100 Mbps)
  - 3G systems has 384 Kbps peak rates
- Greater spectral efficiency (bits/s/Hz)
  - More bandwidth, adaptive OFDM-MIMO, reduced interference
- Flexible use of up to 100 MHz of spectrum
  - 10-20 MHz spectrum allocation common
- Low packet latency (<5ms).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

5G Upgrades from 4G



Future Cellular Phones

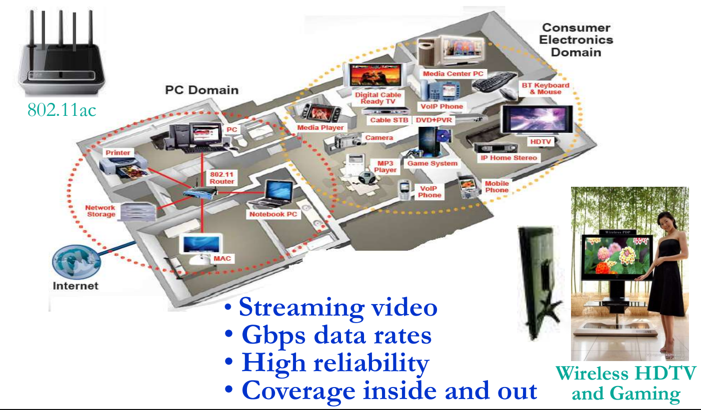
Burden for this performance is on the backbone network



Much better performance and reliability than today

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

Wifi Networks
Multimedia Everywhere, Without Wires



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

Wireless LAN Standards

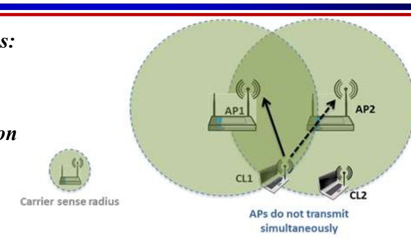
- 802.11b (Old – 1990s)
  - Standard for 2.4GHz ISM band (80 MHz)
  - Direct sequence spread spectrum (DSSS)
  - Speeds of 11 Mbps, approx. 500 ft range
- 802.11a/g (Middle Age– mid-late 1990s)
  - Standard for 5GHz band (300 MHz)/also 2.4GHz
  - OFDM in 20 MHz with adaptive rate/codes
  - Speeds of 54 Mbps, approx. 100-200 ft range
- 802.11n/ac/ax or Wi-Fi 6 (current 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 many generations

Why does WiFi performance suck?

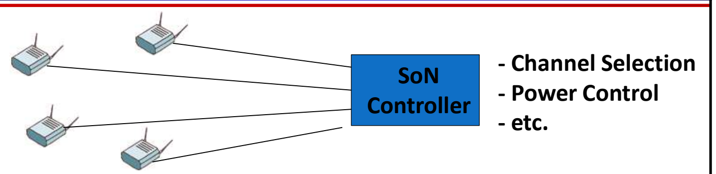
Carrier Sense Multiple Access: if another WiFi signal detected, random backoff

Collision Detection: if collision detected, resend



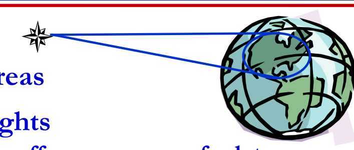
- The WiFi standard lacks good mechanisms to mitigate interference, especially in dense AP deployments
  - Multiple access protocol (CSMA/CD) from 1970s
  - Static channel assignment, power levels, and sensing thresholds
  - In such deployments WiFi systems exhibit poor spectrum reuse and significant contention among APs and clients
    - Result is low throughput and a poor user experience
  - Multiuser MIMO will help each AP, but not interfering APs

Self-Organizing Networks for WiFi



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

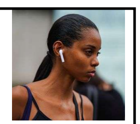
Satellite Systems



- Cover very large areas
- Different orbit heights
  - Orbit height trades off coverage area for latency
  - GEO (39000 Km) vs MEO (9000 km) vs LEO (2000 Km)
- Optimized for one-way transmission
  - Radio (XM, Sirius) and movie (SatTV, DVB/S) broadcasts
  - Most two-way LEO systems went bankrupt in 1990s-2000s
  - LEOs have resurfaced with 4G to bridge digital divide
- Global Positioning System (GPS) ubiquitous
  - Satellite signals used to pinpoint location
  - Popular in cell phones, PDAs, and navigation devices

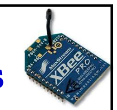
Bluetooth®

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.

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

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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 summarized in text Appendix D.

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Advanced Topics Lecture: See Backup Slides

Emerging Systems

- New cellular system architectures
- mmWave/massive MIMO communications
- Software-defined network architectures
- Ad hoc/mesh wireless networks
- Cognitive radio networks
- Wireless sensor networks
- Energy-constrained radios
- Distributed control networks
- Chemical Communications
- Applications of Communications in Health, Bio-medicine, and Neuroscience

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Main Points

- The wireless vision encompasses many exciting applications
- Technical challenges transcend all system design layers
- 5G networks must support higher performance for some users, extreme energy efficiency and/or low latency for others
- Cloud-based software to dynamically control and optimize wireless networks needed (SDWN)
- Innovative wireless design needed for 5G cellular/WiFi, mmWave systems, massive MIMO, and IoT connectivity
- Standards and spectral allocation heavily impact the evolution of wireless technology

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Backup Slides: Emerging Systems

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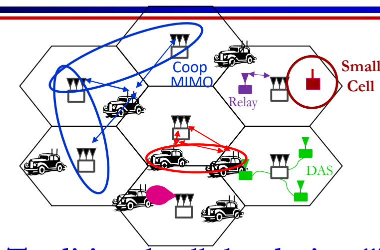
Rethinking "Cells" in Cellular



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

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

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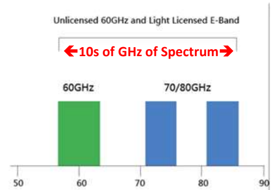
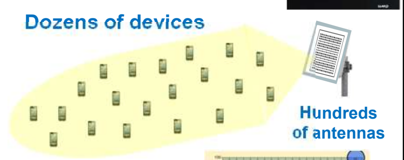
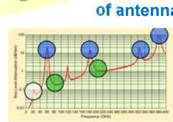
mmWave Massive MIMO







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

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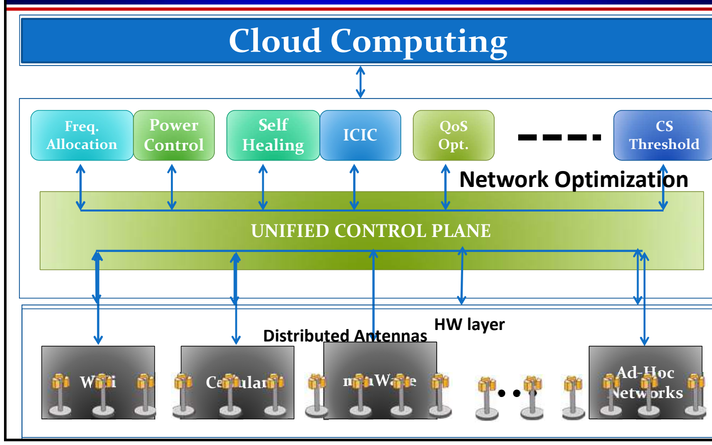
Software-Defined Network Architectures



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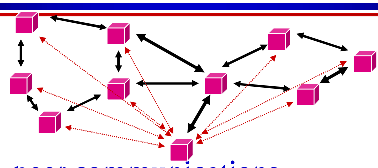
Ad-Hoc Networks



- 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

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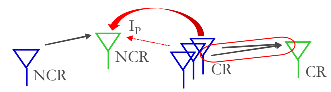
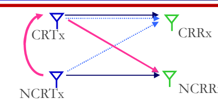
Cognitive Radios



MIMO Cognitive Underlay



Cognitive Overlay

- Cognitive radios support new users in existing crowded spectrum <u>without degrading licensed users</u>
  - Utilize advanced communication and DSP techniques
  - Coupled with novel spectrum allocation policies
- Multiple paradigms
  - (MIMO) Underlay (interference below a threshold)
  - Interweave finds/uses unused time/freq/space slots
  - Overlay (overhears/relays primary message while cancelling interference it causes to cognitive receiver)

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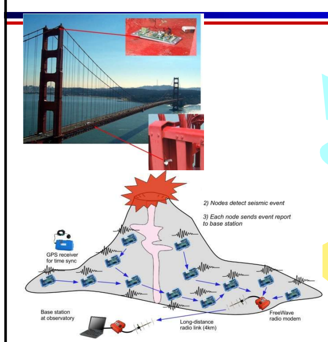
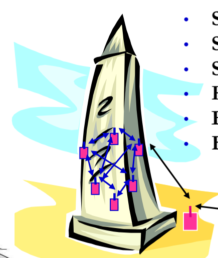
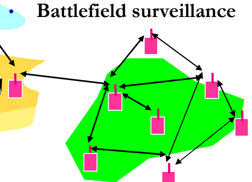
Wireless Sensor Networks
Data Collection and Distributed Control





- 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

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Energy-Constrained Radios

- Transmit energy minimized by sending bits slowly
  - Leads to increased circuit energy consumption
- Short-range networks must consider both transmit and processing/circuit energy.
  - Sophisticated encoding/decoding not always energy-efficient.
  - MIMO techniques not necessarily energy-efficient
  - Long transmission times not necessarily optimal
  - Multihop routing not necessarily optimal
  - Sub-Nyquist sampling can decrease energy and is sometimes optimal!

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Where should energy come from?

- Batteries and traditional charging mechanisms
  - Well-understood devices and systems
- Wireless-power transfer
  - Poorly understood, especially at large distances and with high efficiency
- Communication with Energy Harvesting Radios
  - Intermittent and random energy arrivals
  - Communication becomes energy-dependent
  - Can combine information and energy transmission
  - New principles for radio and network design needed.

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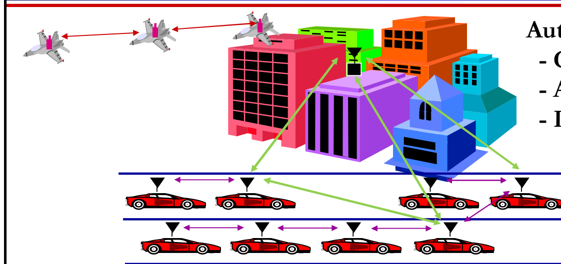
Distributed Control over Wireless



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*

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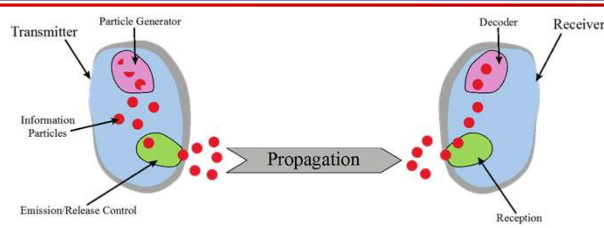
Chemical Communications



- 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.

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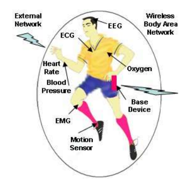
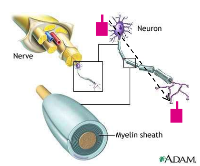
Applications in Health, Biomedicine and Neuroscience



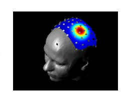
Body-Area Networks

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

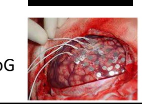
Recovery from Nerve Damage



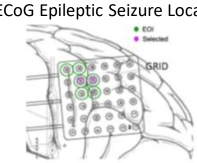
EEG



ECoG



ECoG Epileptic Seizure Localization



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