The future of wireless and what it will enable

Andrea Goldsmith

Stanford University

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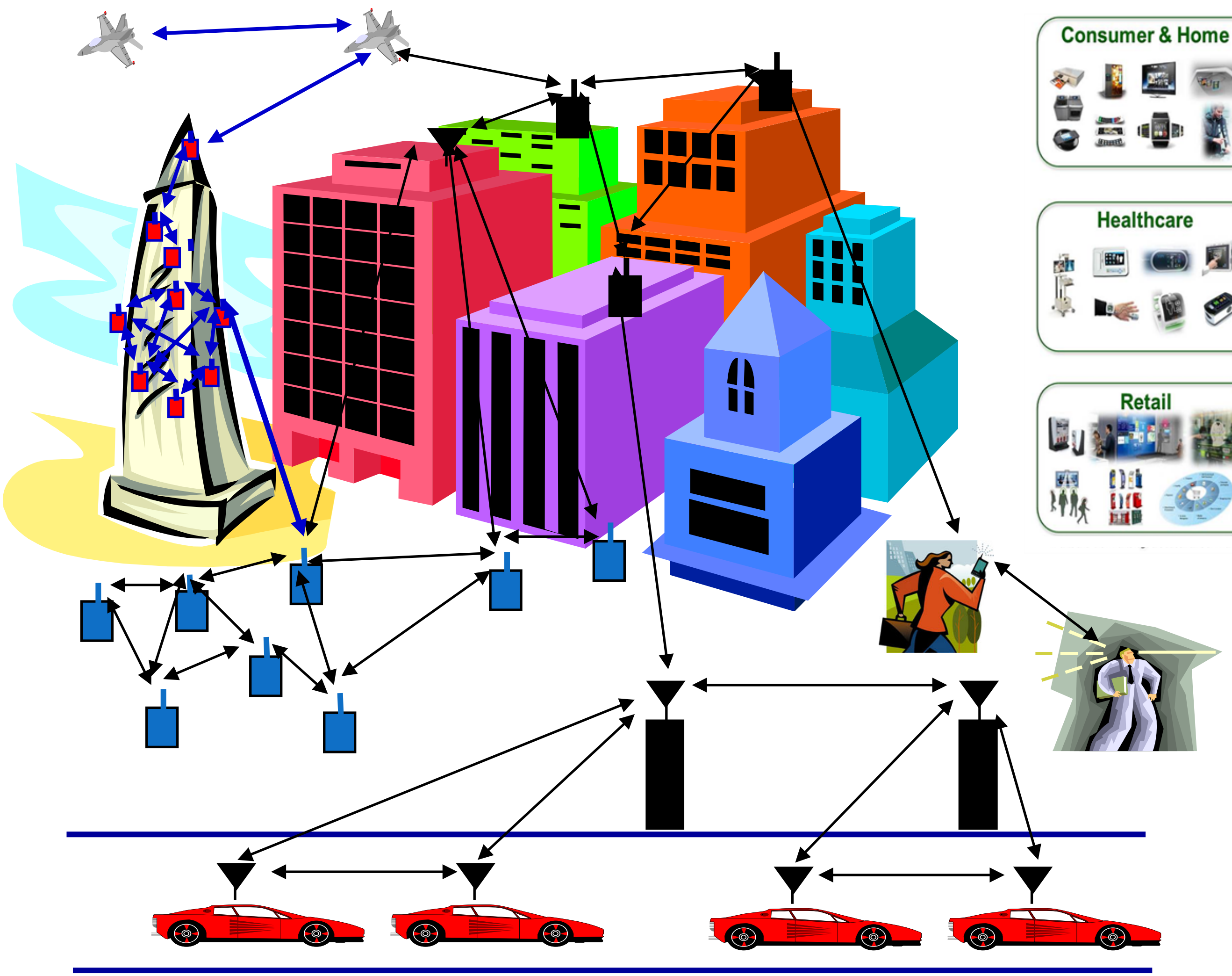
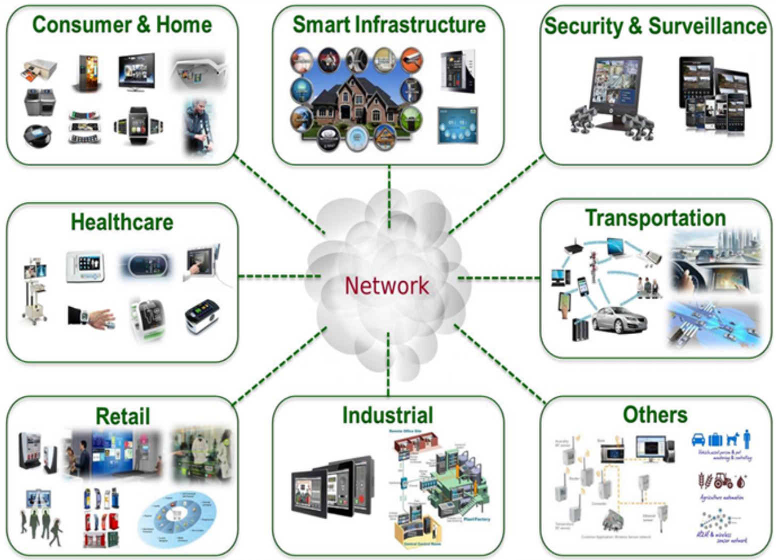
Future Wireless Networks

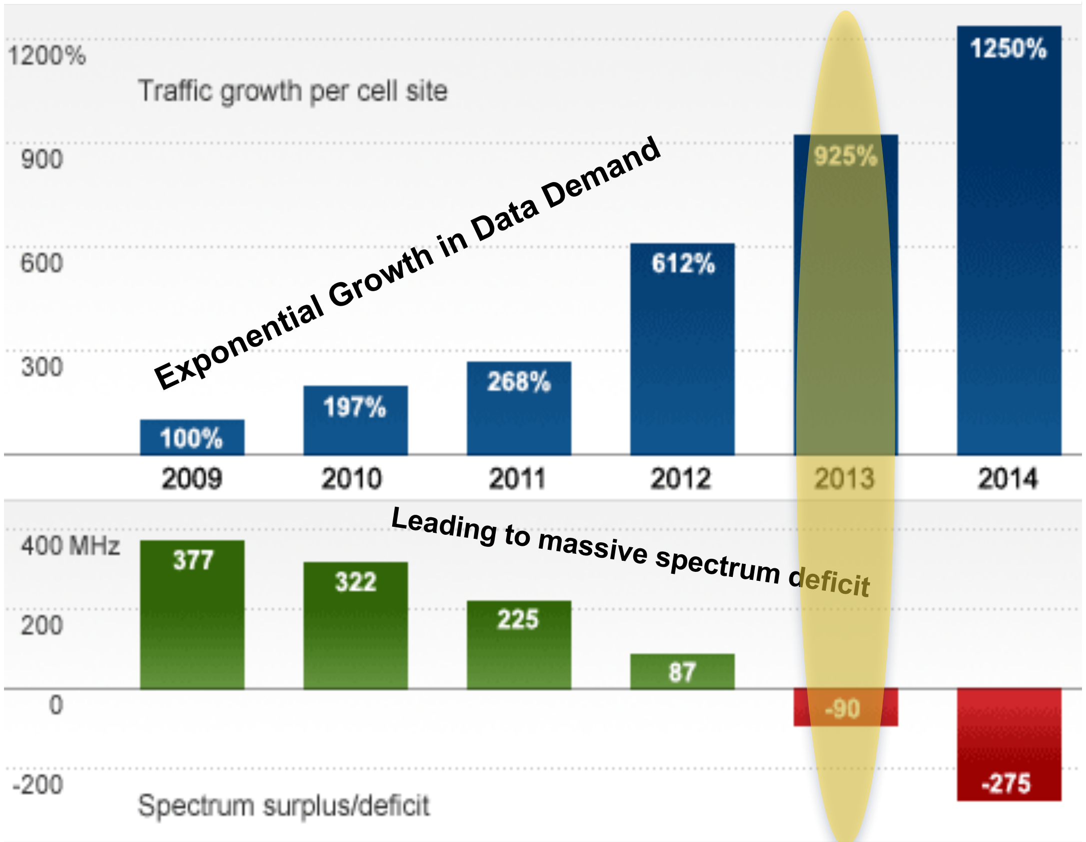
Ubiquitous Communication Among People and Devices





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

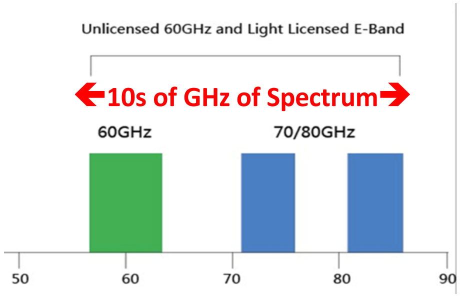
The Licensed Airwaves are “Full”



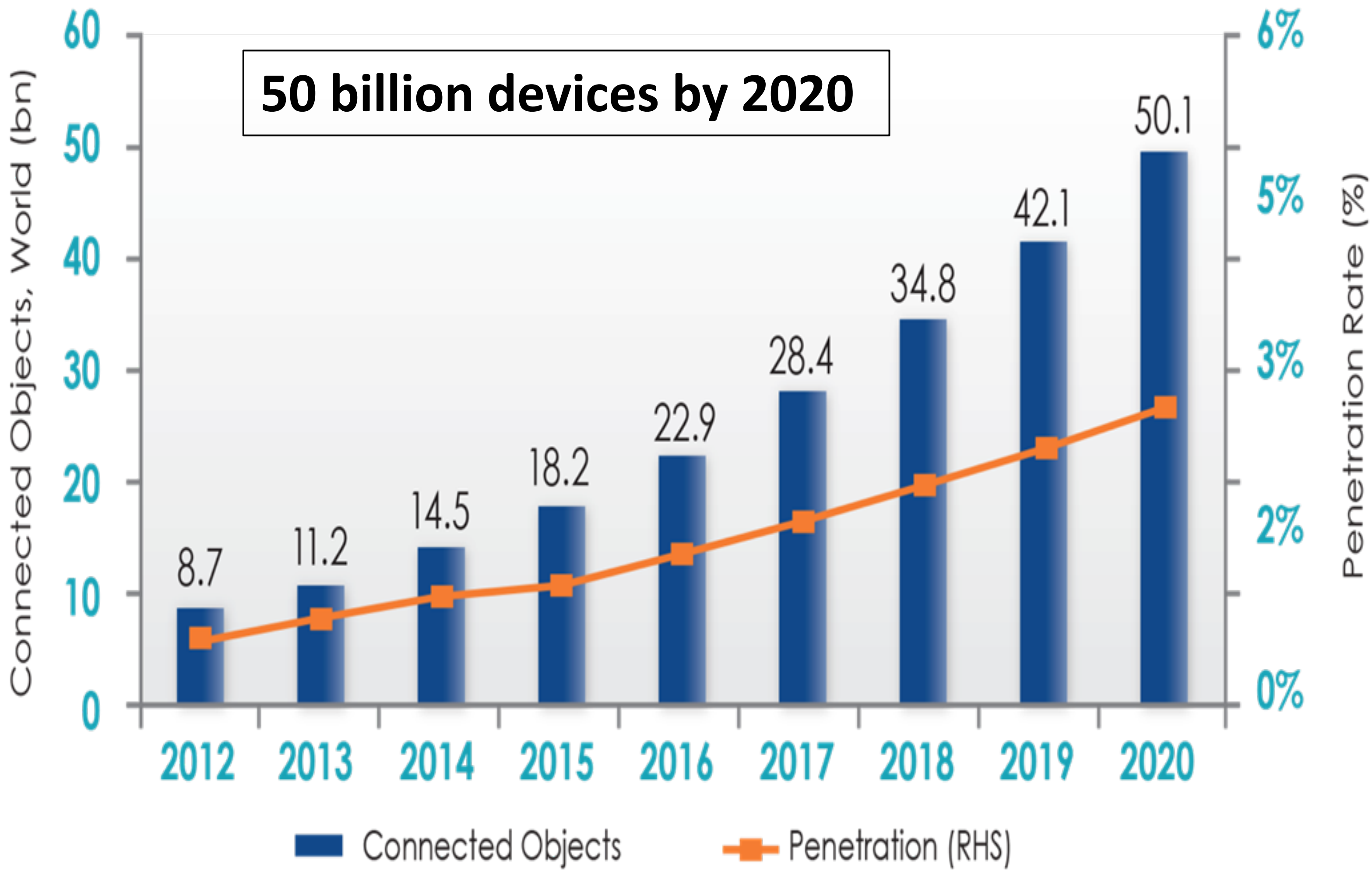
Source: FCC

Also have Wifi

And mmWave



On the horizon, the Internet of Things



What is the Internet of Things:

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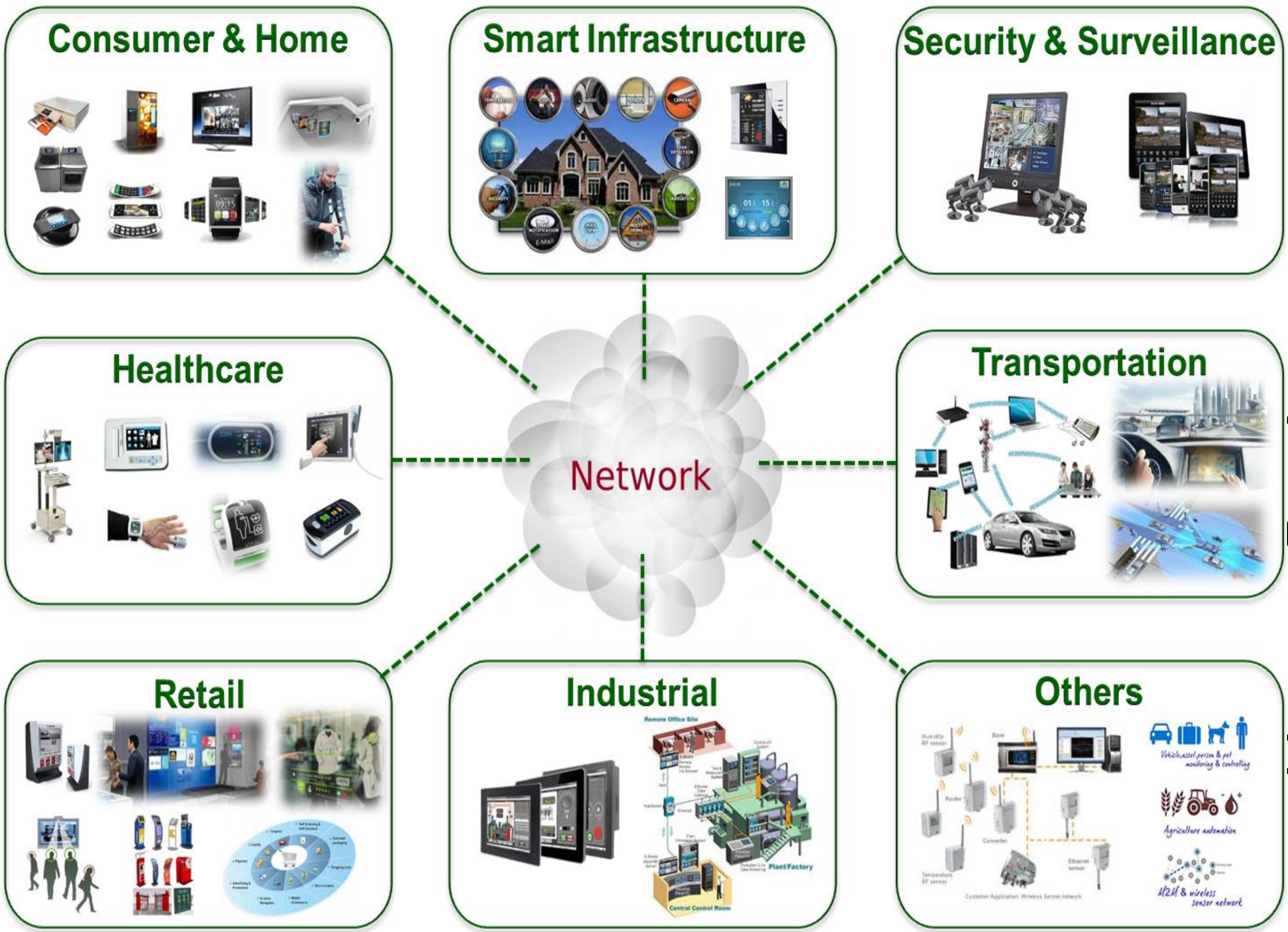
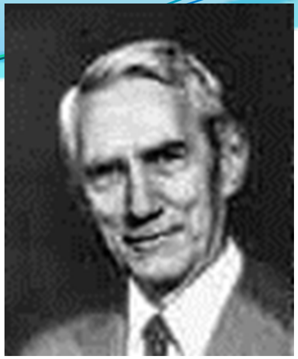


Different requirements than smartphones: low rates/energy consumption

Are we at the Shannon capacity of wireless systems?



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

- Channels without models: molecular, mmW, THz
- Time-varying channels.
- Channels with interference or relays.
- Cellular systems
- Ad-hoc and sensor networks
- Channels with delay/energy/$$$ constraints.

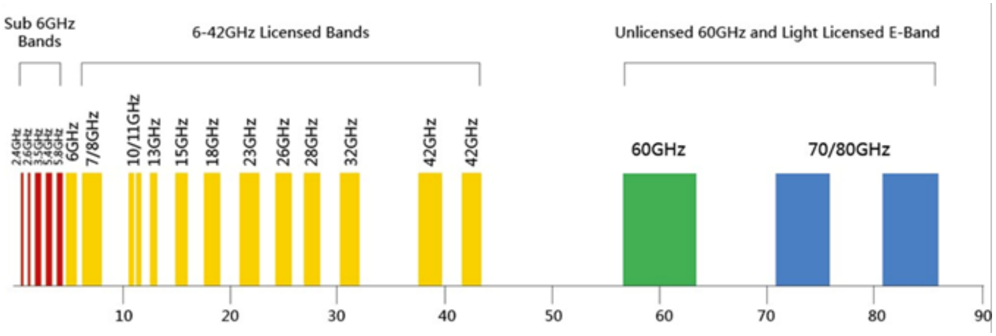
Shannon theory provides design insights and system performance upper bounds

Enablers for Increasing Wireless Data Rates

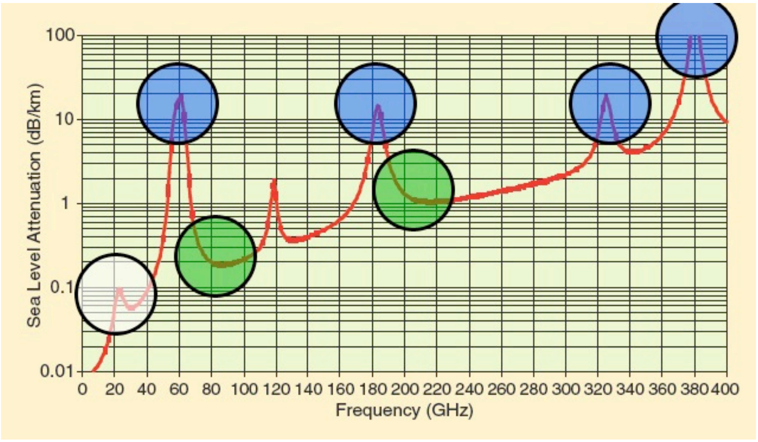
- Utilizing more spectrum (mmWave)
- (Massive) MIMO
- Rethinking cellular system design
- Software-defined wireless networking
- “Smarter” and more agile (cognitive) radios

mmWave enables high data rtes

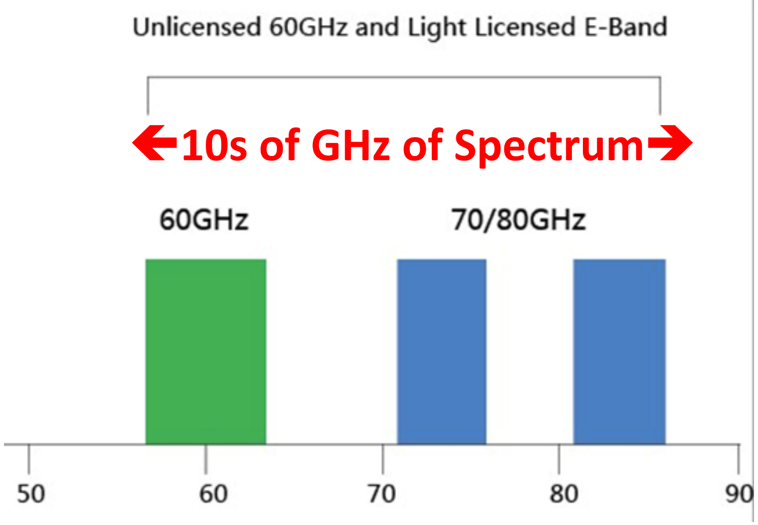
- Large BW allocations
  - 10s of GHz
  - In the 60-120 GHz bands

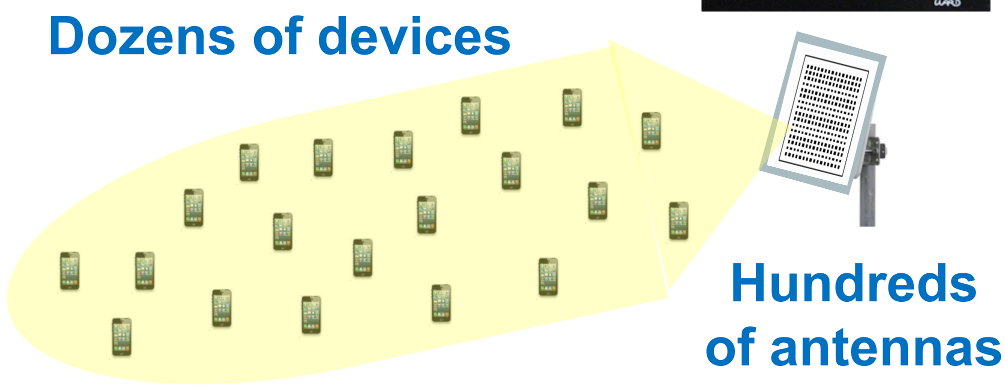


- Small form factor
  - Small signal wavelengths
  - Inter-antenna spacing small $\Rightarrow$ smaller arrays
- Challenges:
  - Attenuation (not monotonic in f)
  - Propagation poorly understood
    - Path loss, shadowing, multipath
  - Channel estimation



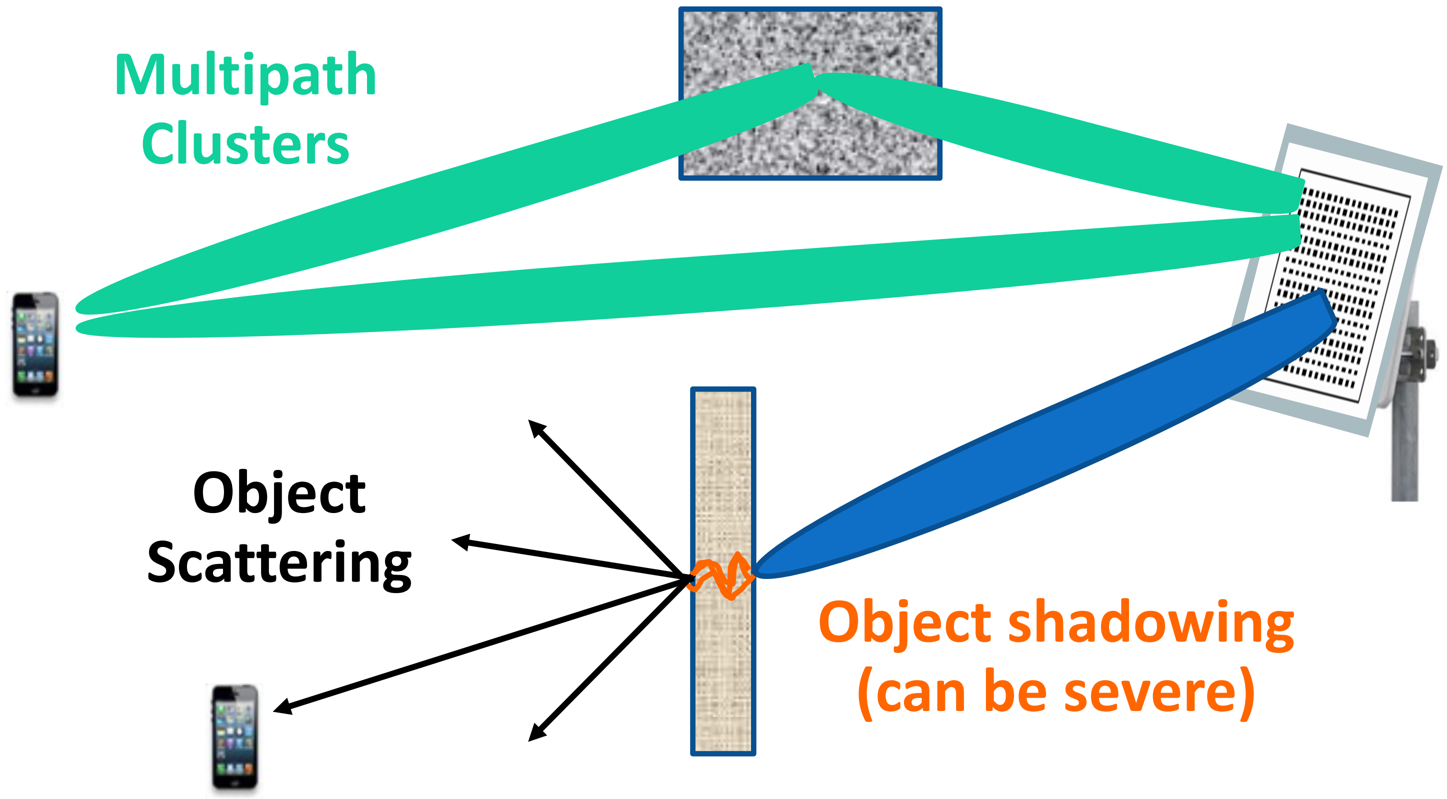
mmWave Massive MIMO





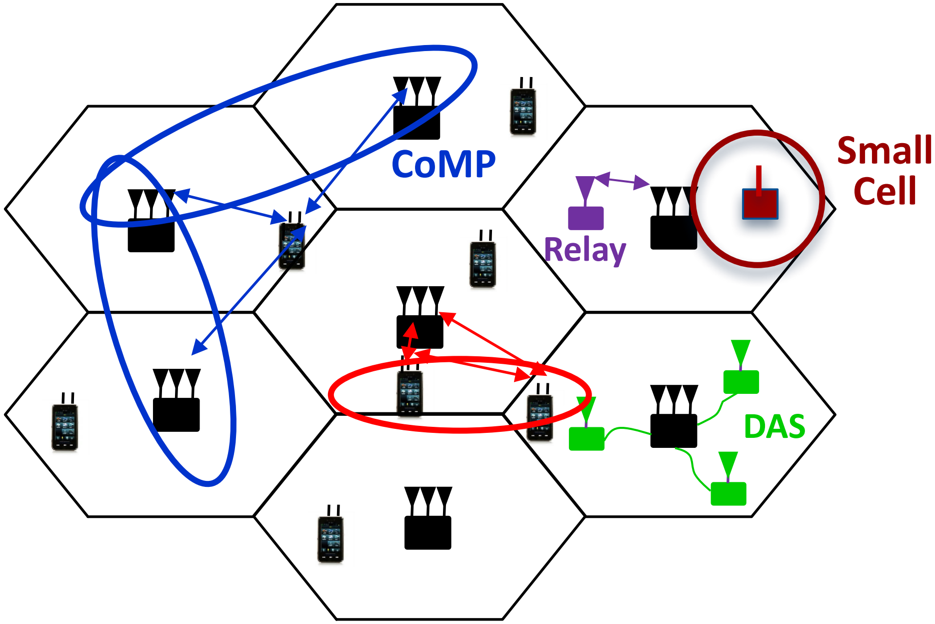
- mmWaves have large attenuation and path loss
- For asymptotically large arrays with channel state information, no attenuation, fading, interference or noise
- mmWave antennas are small: perfect for massive MIMO
- Bottlenecks: channel estimation, complexity, propagation
- Non-coherent design holds significant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

Multipath and Shadowing under Beamsteering



- Propagation different than in current systems; not well understood
- New beamsteering techniques that incorporate propagation needed

Rethinking Cellular System Design



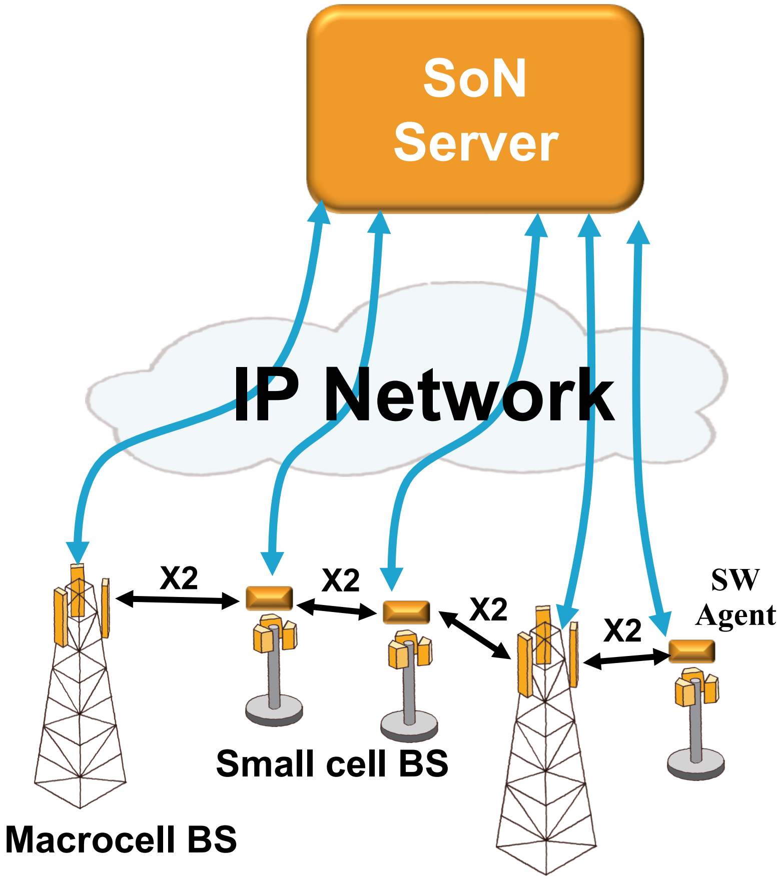
How should cellular systems be designed?

Will gains be big or incremental; in capacity, coverage or energy?

- Cellular systems reuse channels/timeslots in different cells
  - Traditional design assumes system is "interference-limited"
  - Capacity unknown; upper bound based on BC/MAC with pooled antennas
- No longer the case with recent technology advances:
  - MIMO, multiuser detection, cooperating BSs (CoMP) and relays
  - Raises interesting questions such as "what is a cell?"
- Dynamic self-organization (SoN) needed for deployment and optimization

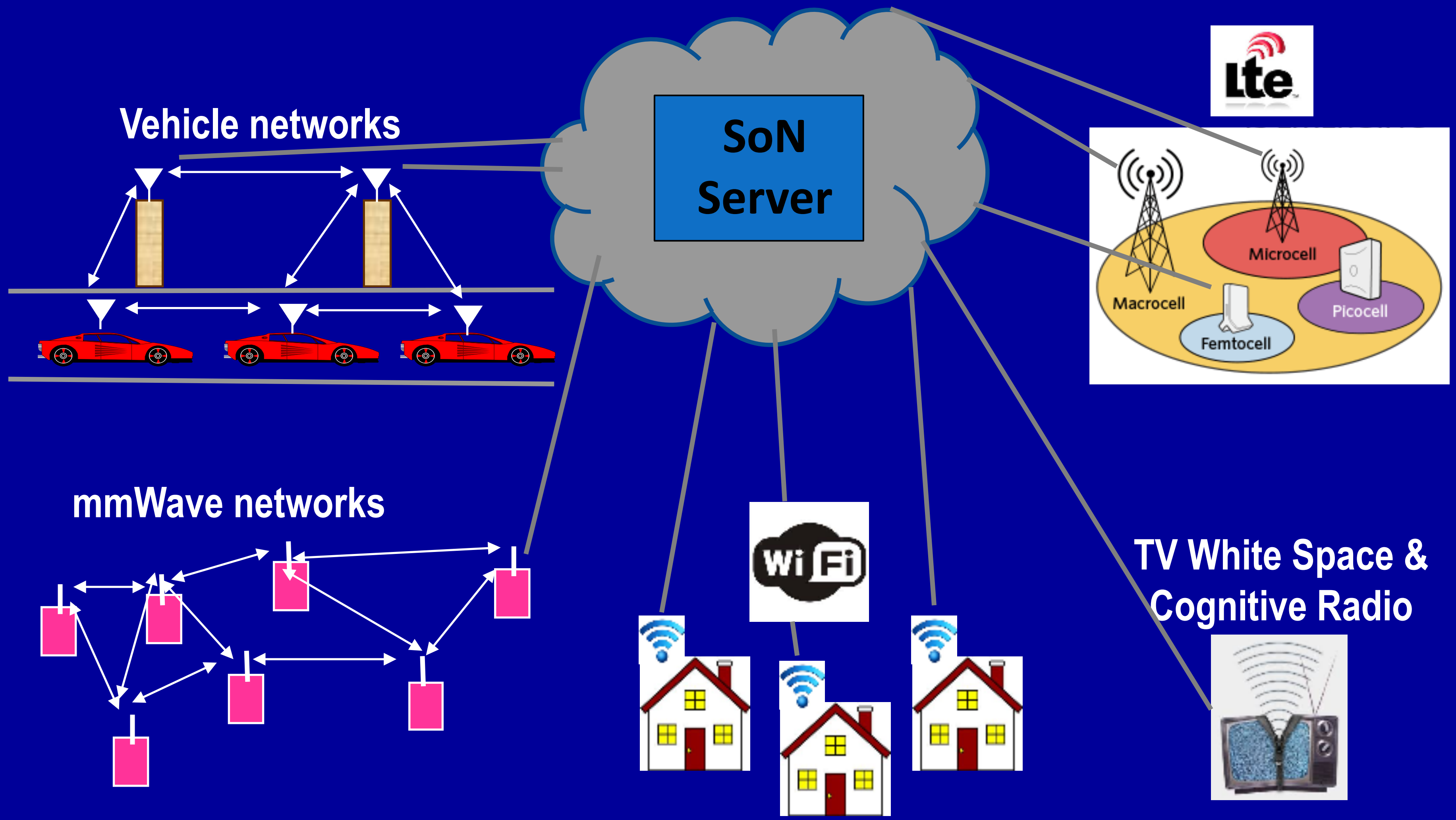
Small cells are the solution to increasing cellular system capacity

In theory, provide exponential capacity gain

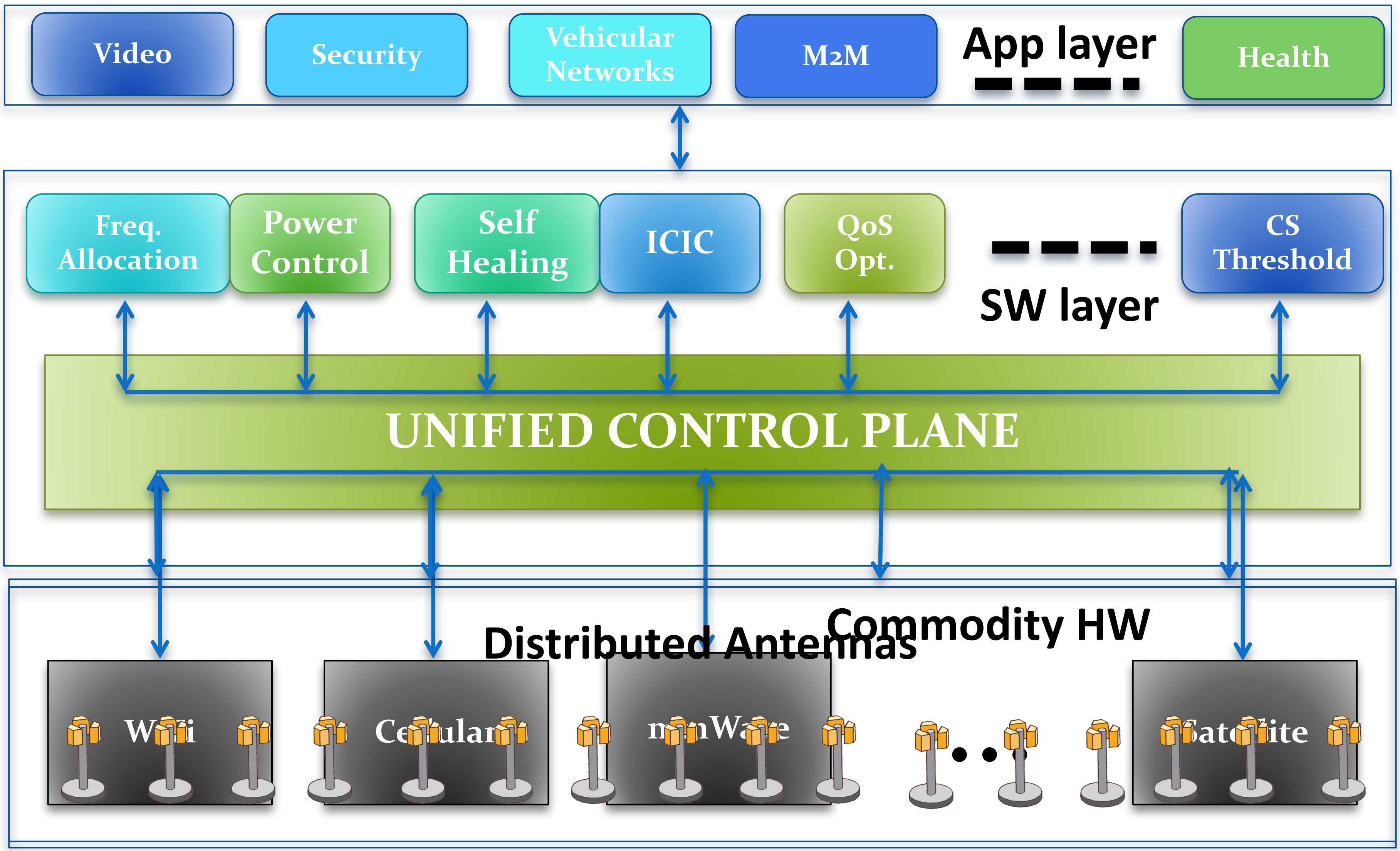


- Future cellular networks will be hierarchical
- Large cells for coverage
- Small cells for capacity and power efficiency
- Small cells require self-optimization in the cloud

Why not use SoN for all wireless networks

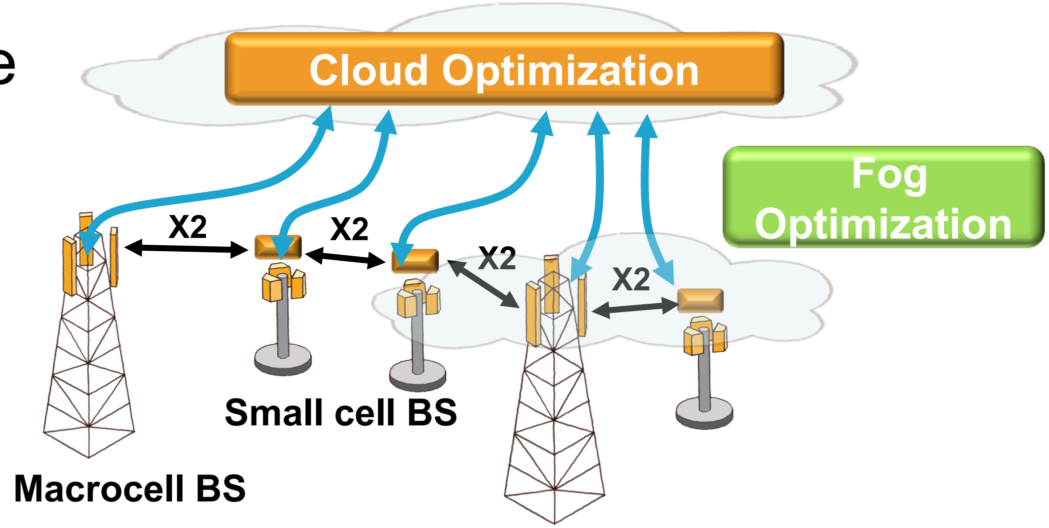


Software-Defined Network Architecture

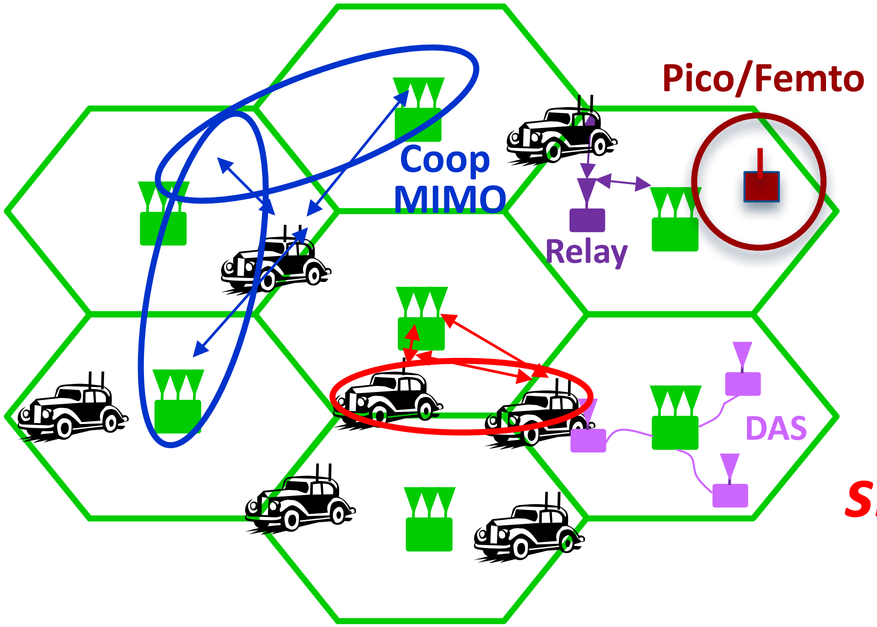


SDWN Challenges

- Algorithmic complexity
  - Frequency allocation alone is NP hard
  - Also have MIMO, power control, CST, hierarchical networks: *NP-really-hard*
  - Advanced optimization tools needed, including a combination of centralized (cloud) distributed, and locally centralized (fog) control
  - ML can also play a role
- Hardware Interfaces
- Seamless handoff
- Resource pooling



"Green" Cellular Networks for the IoT



How should cellular systems be redesigned for minimum energy?

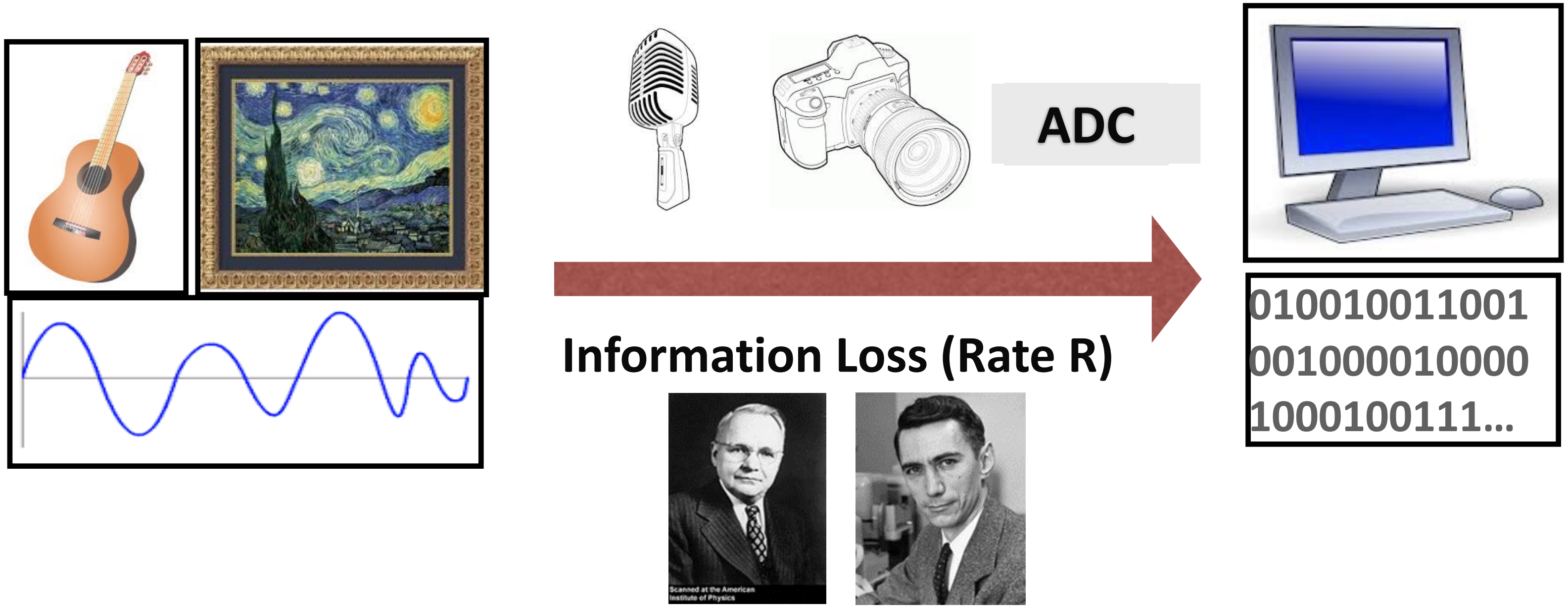
Research indicates that significant savings is possible

- Drastic energy reduction needed for IoT devices
  - New Infrastuctures: 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

Energy-Constrained Radios

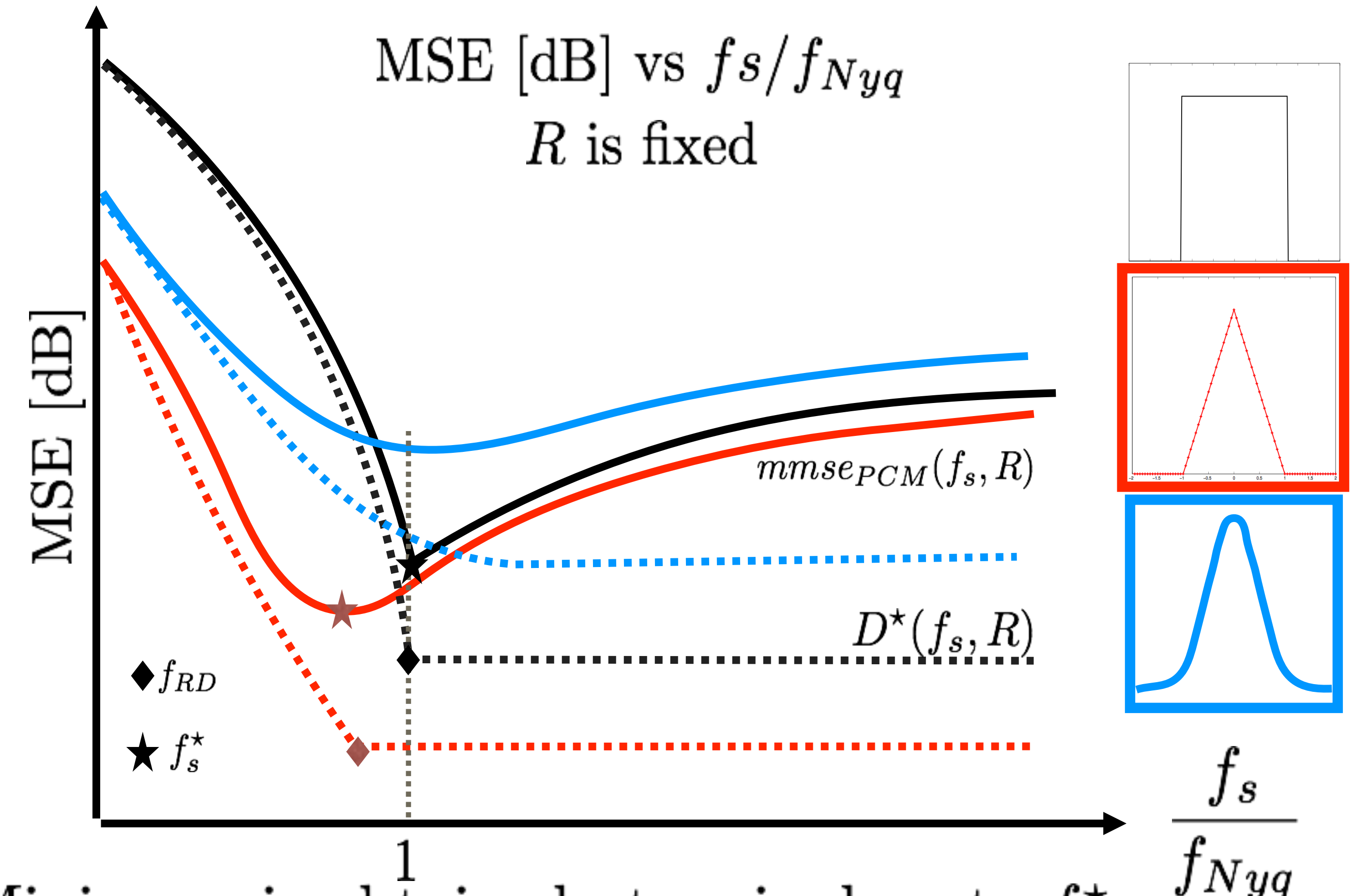
- Transmit energy minimized by sending bits very slowly
  - Leads to increased circuit energy consumption
- Short-range networks must consider both transmit and processing/circuit energy.
  - Sophisticated encoding/decoding not always energy-efficient.
  - MIMO techniques not necessarily energy-efficient
  - Long transmission times not necessarily optimal
  - Multihop routing not necessarily optimal
- Recent work to minimize energy consumption in radios
  - Sub-Nyquist sampling
  - Codes to minimize total energy consumption

Rate-Distortion Limits of Analog-to Digital-Compression



We investigate distortion due to sampling and converting those samples to bits under a bit rate constraint

MSE Depends on Input Signal



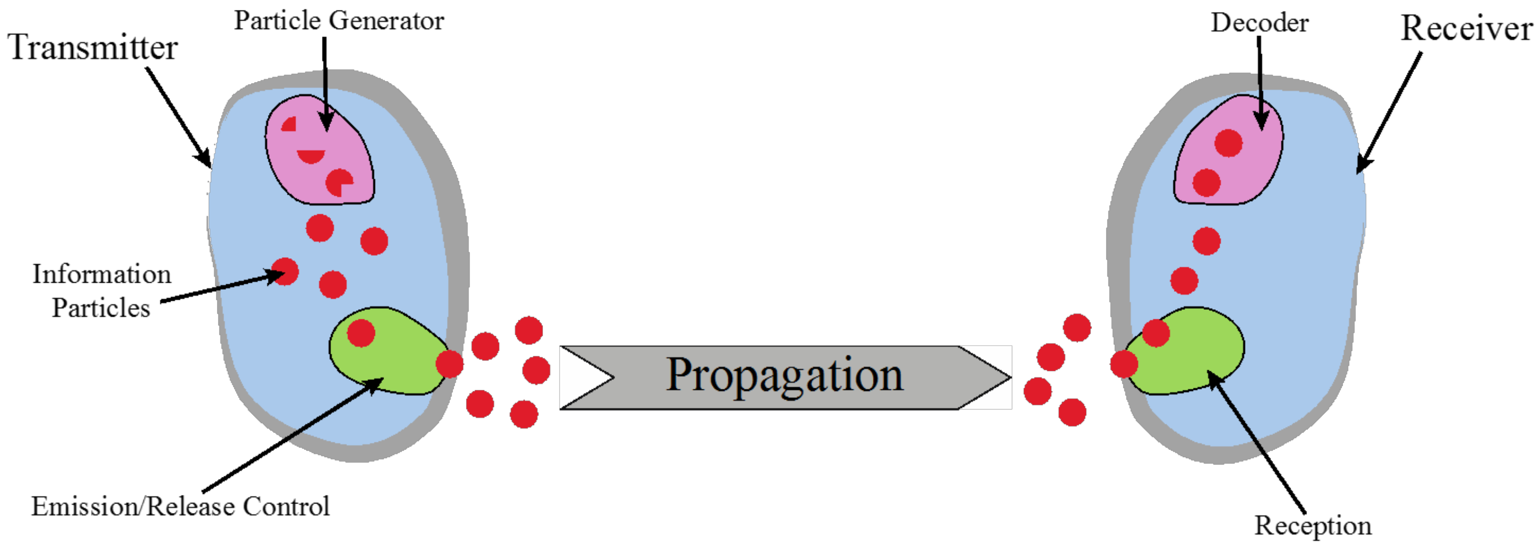
- Minimum is obtained at a single rate $f_s^\star$
- $f_s^\star \leq f_{Nyq}$ depending on $S_X(f)$

Joint with A. Kipnis and Y. Eldar

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 Devices
  - Intermittent and random energy arrivals
  - Communication becomes energy-dependent
  - Can combine information and energy transmission
  - New principles for communication system design needed.

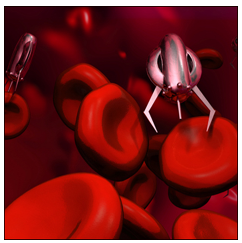
Chemical Communications

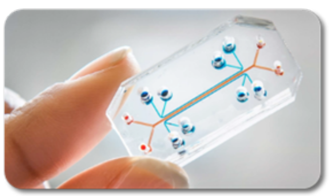


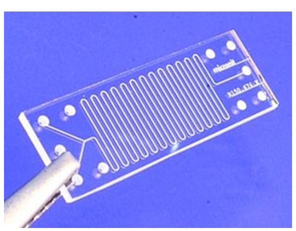
- Can be developed for both macro (>cm) and micro (<mm) scale communications
- Greenfield area of research:
  - Need new channel models, modulation schemes, channel impairment mitigation, multiple acces, etc.
  - Fundamental capacity limits also unknown

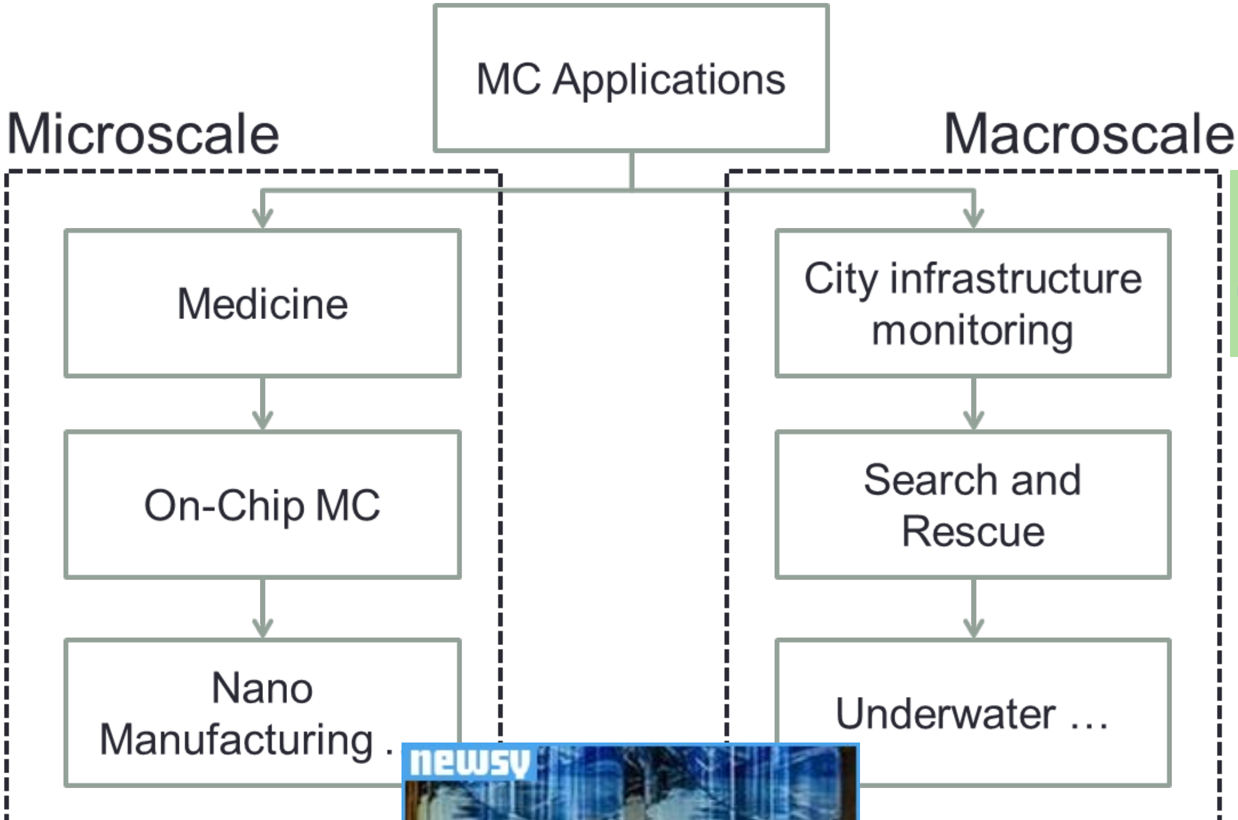
Joint with N. Farsad and C.B. Chae

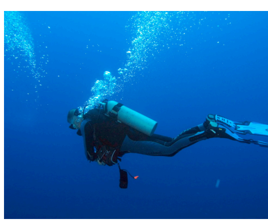
Applications







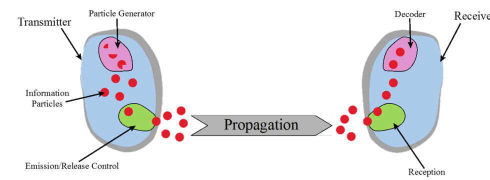


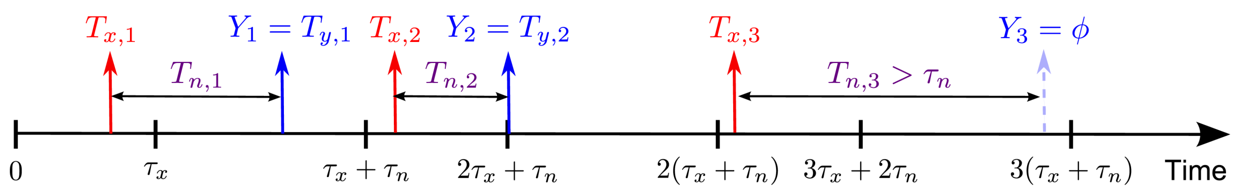


Data rate: .5 bps

“fan-enhanced” channel

Chemical Channel Capacity





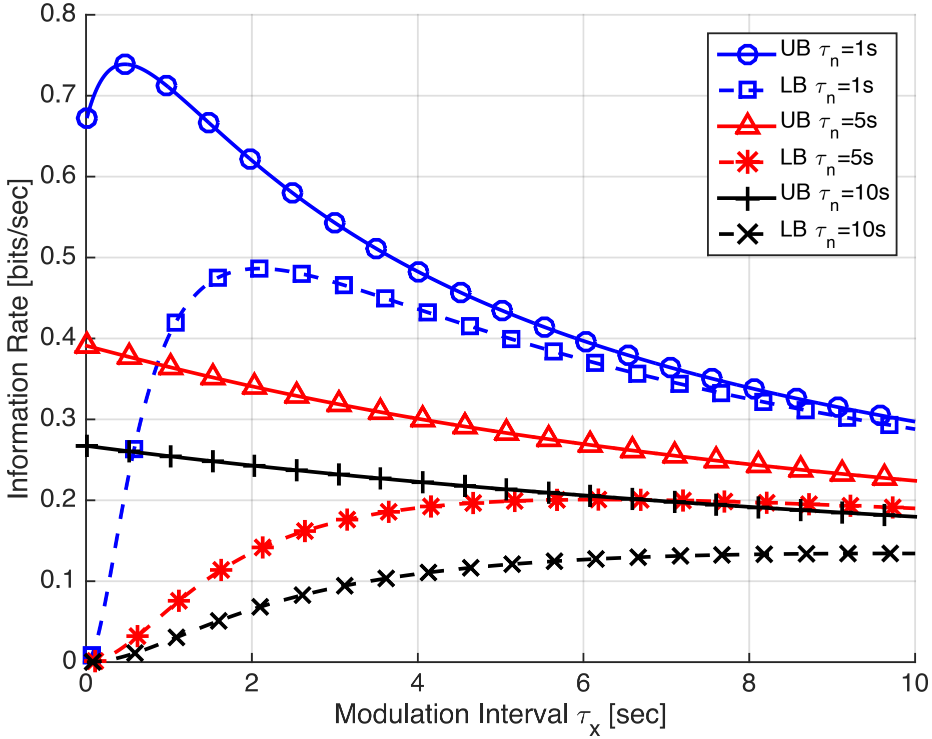
- Diffusion-Based Propagation
  - Information encoded in TX release time of a molecule over symbol interval τ_x
  - Particle dissipates after duration τ_n (channel dependent)
  - Diffusion propagation introduces a random time-of-arrival "noise" T_n
  - Distribution of T_n modeled as additive Levy noise

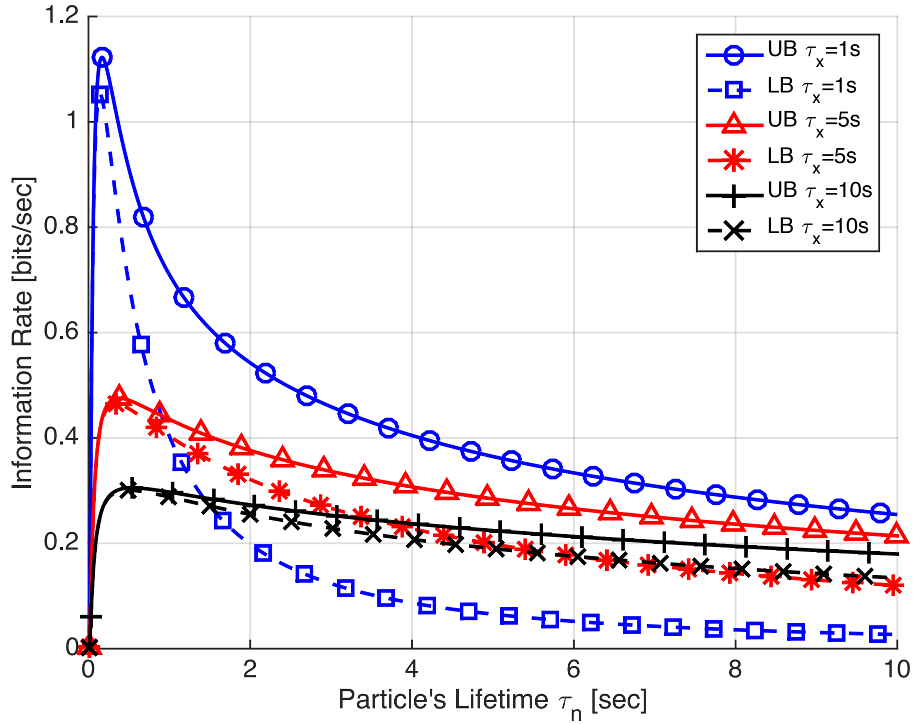
- Capacity obtained by optimizing symbol interval

$$C(\tau_n) = \max_{\tau_x, \mathcal{F}(\tau_x)} \frac{I(T_x; T_y | T_n < \tau_n) F_{T_n}(\tau_n)}{\tau_x + \tau_n} = \max_{\tau_x, \mathcal{F}(\tau_x)} \frac{I(T_x; Y)}{\tau_x + \tau_n}$$

  - Y has no closed form pdf
  - Can obtain upper and lower capacity bounds

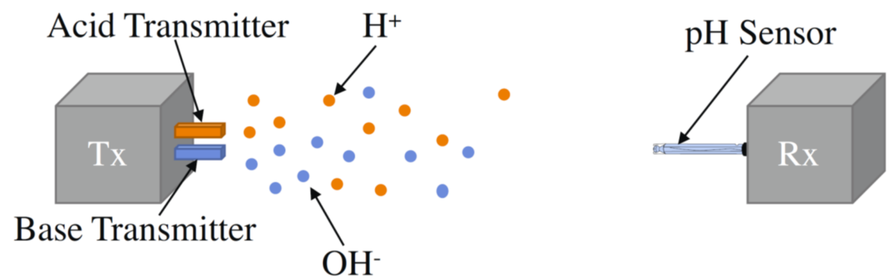
Capacity Bounds



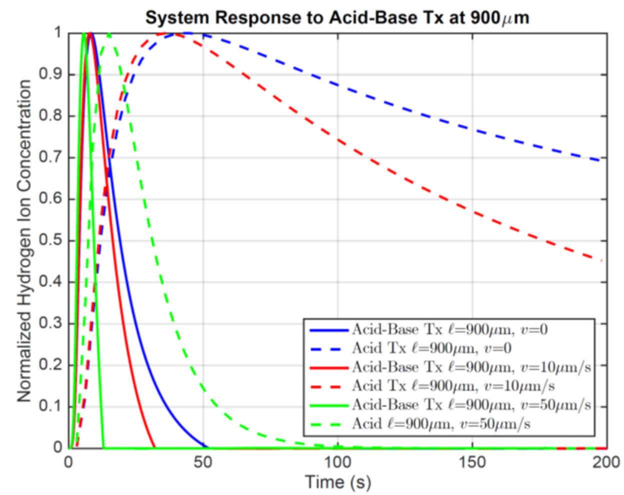


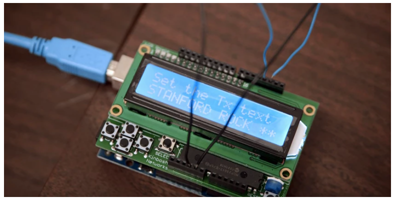
Multiple particle release (diversity) leads to a log linear increase in capacity

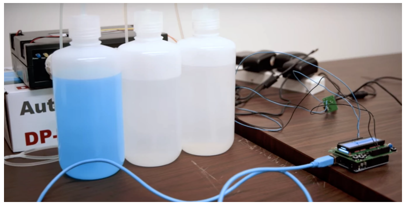
Current Work



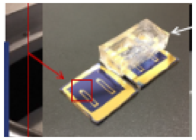
- Slow dissipation of chemicals leads to ISI
- Can use acid/base transmission to decrease ISI
- Similar ideas can be applied for multilevel modulation and multiuser
- Equalization requires machine learning
  - Applied to both SISO and MIMO
  - Leads to a 10x data rate increase
- Currently reducing to nanoscale







Sending text messages with windex and vinegar

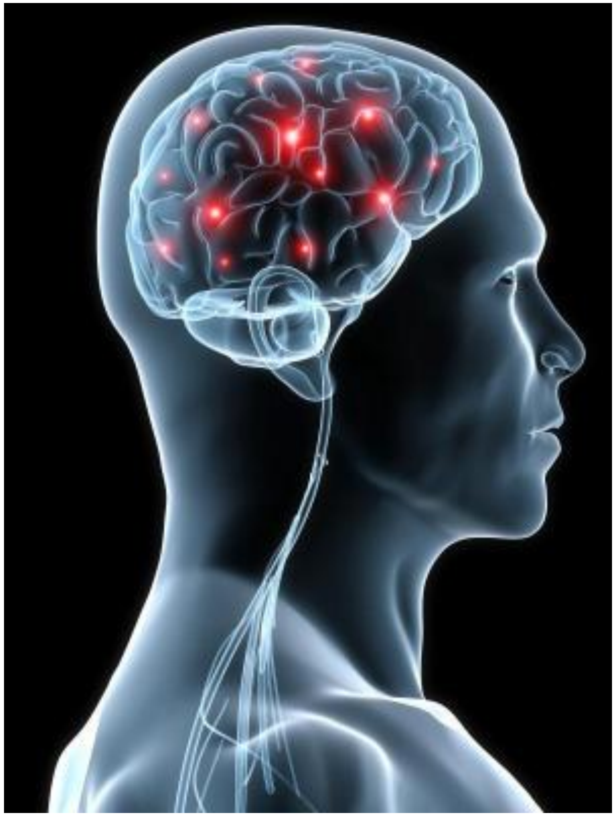


Stanford Report: November 15, 2016

Machine Learning in Communications

- ML has excellent performance in equalization for molecular communications
- Application of ML to communication systems with unknown channel model/parameters
  - Channels include molecular, mmWave, THz, …
  - Modulation and detection
  - Encoding and decoding
  - Joint source and channel decoding
  - ML algorithm and training optimization needed
    - That is where Communication Theory comes in

The brain as a communications network

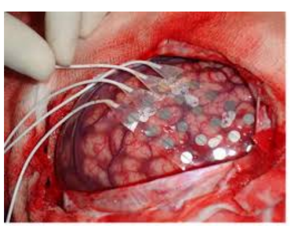


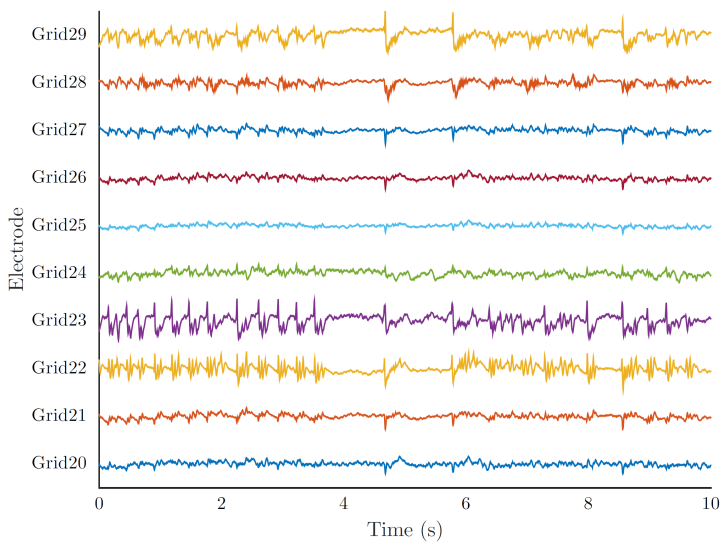
Joint with N. Soltani, T. Coleman, R. Ma, J. Kim, Y. Morin and J. Parvizi

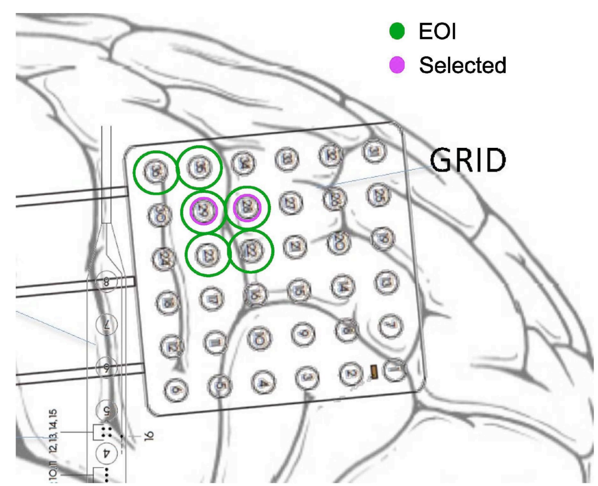
Epileptic Seizure Focal Points

- Seizure caused by an oscillating signal moving across neurons
  - When enough neurons oscillate, a seizure occurs
  - Treatment “cuts out” signal origin: errors have serious implications
- Directed mutual information spanning tree algorithm applied to ECoG measurements estimates the focal point of the seizure
- Application of our algorithm to existing data sets on 3 patients matched well with their medical records

ECoG Data







Summary

- The next wave in wireless technology is upon us
  - This technology will enable new applications that will change people's lives worldwide
- Future wireless networks must support high rates for some users and extreme energy efficiency for others
  - Small cells, mmWave massive MIMO, Software-Defined Wireless Networks, and energy-efficient design key enablers.
  - Machine learning is a promising new tool to use in receiver design, multiple access, and resource optimization
- Communication tools and modeling techniques may provide breakthroughs in other areas of science