2014 Distinguished University Professor Lecture

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The Wireless 21st Century

Pervasive Broadband Wireless and the Wireless Internet of Things

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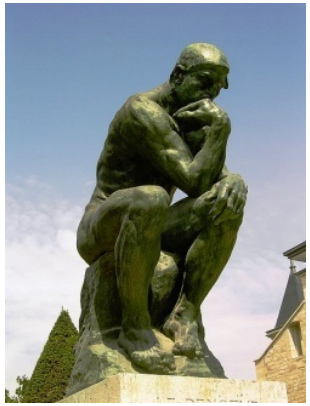


"*It is dangerous to put limits on wireless*" Guglielmo Marconi (1932)

USF UNIVERSITY OF SOUTH FLORIDA

Wireless 21st Century --- Outline

- **Vision**: Second Information Age altering information access and networking.
- **Expectation**: Demand increases by orders of magnitude in the next 10 years.
- **Challenge**: How to fulfill this expectation?
- **Enabling Technologies** ☺
- **Transformative applications**
  - Integrating the physical world with the Internet → ***Wireless Internet of Things***
  - Biomedical applications (*in vivo* wireless communications and networking)*

*My research focus at USF

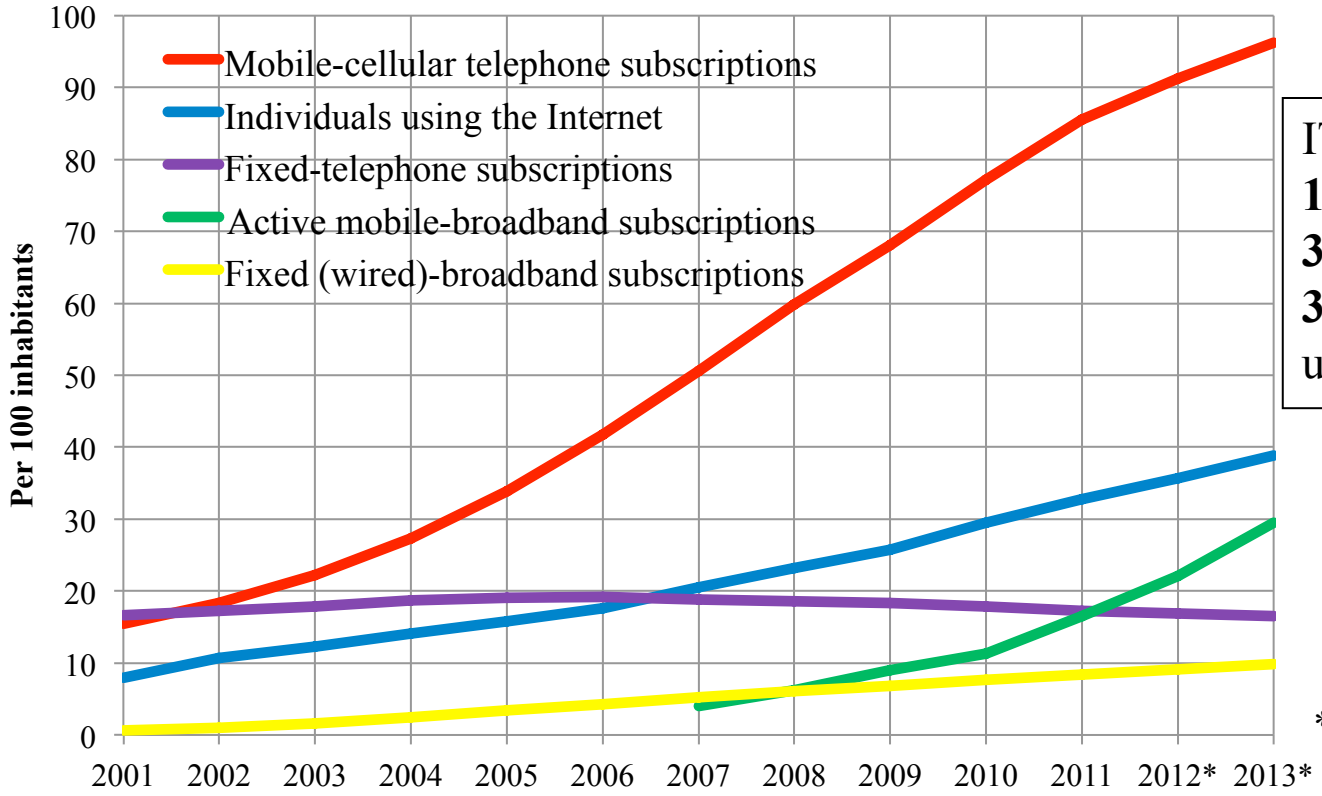
The Wireless 21st Century: Evolution or Revolution?

- 19th century: the telegraph and the telephone forever changed telecommunications.
- 20th century: radio, TV, computers and the Internet revolutionized *instantaneous* processing and transmission of data --- the dawn of the wireless era.
- 21st century:
  - ***Heterogeneous wireless networks*** --- [***HetNets***] consists of devices using different underlying radio access technologies.
  - ***Wireless (Cyber-Physical) Internet of Things*** **[*IoT*]** --- *Integration of the physical world with the Internet.*

First Mobile Radio Telephone (1924) ⟶ The Wireless 21stCentury

Wireless --- Most Rapidly Adopted Technology in History

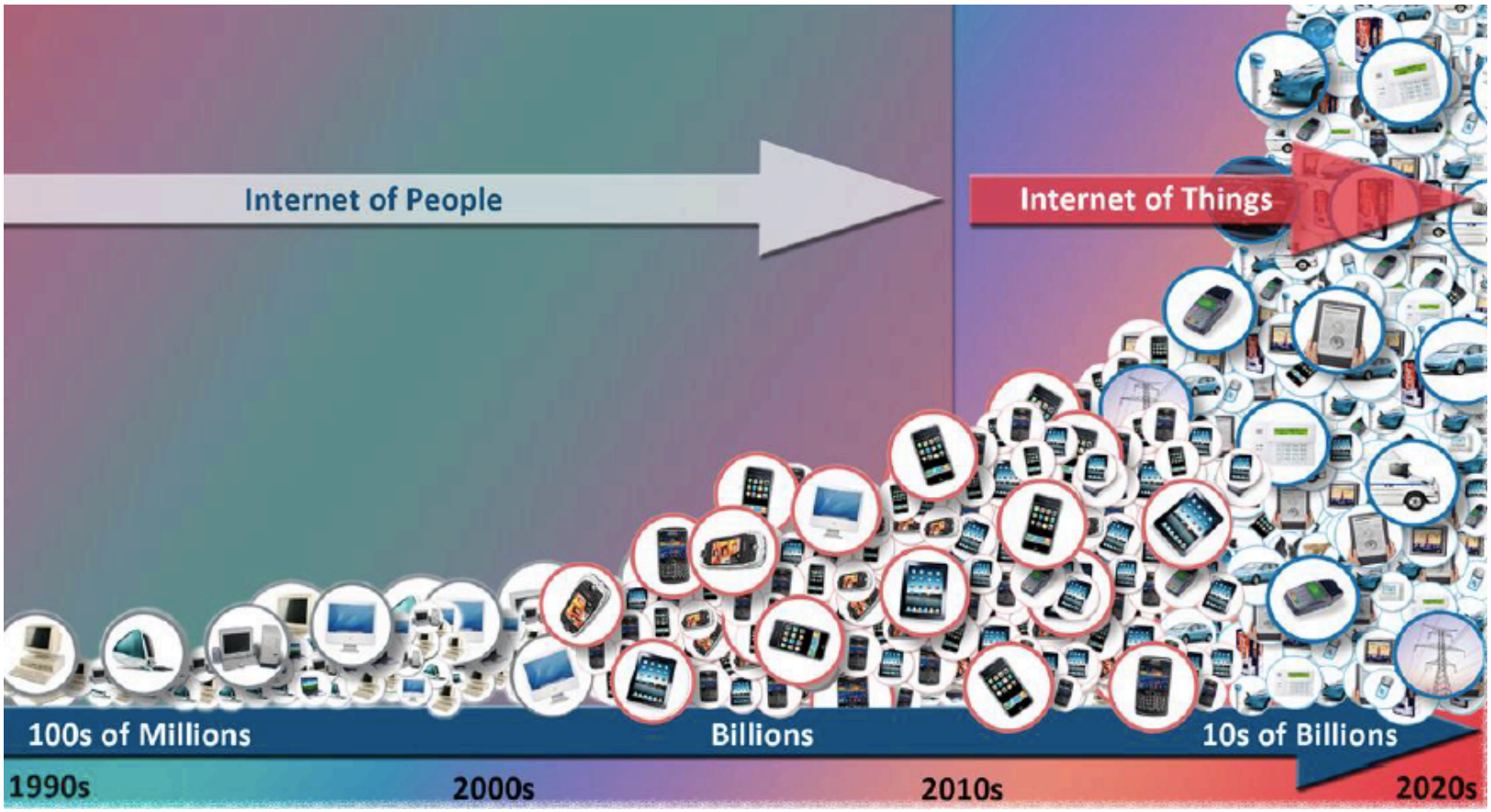
- Cellular is *the most rapidly adopted technology in history*. According to the ITU, 6.8B mobiles in 2013 (more than 96% of the world's population.)
- By 2002 the *number of mobiles exceeded the number of land lines* globally.
- **Mobile data traffic overtook voice traffic in 2011, placing extremely high capacity requirements on mobile networks today and in the future.**
- By 2017, **7 trillion wireless devices will serve 7B people → *Internet of Things*.**



ITU Predictions 2011 to 2017:
18x more smartphone devices
30x more wireless data traffic
32x greater smartphone usage/km^2

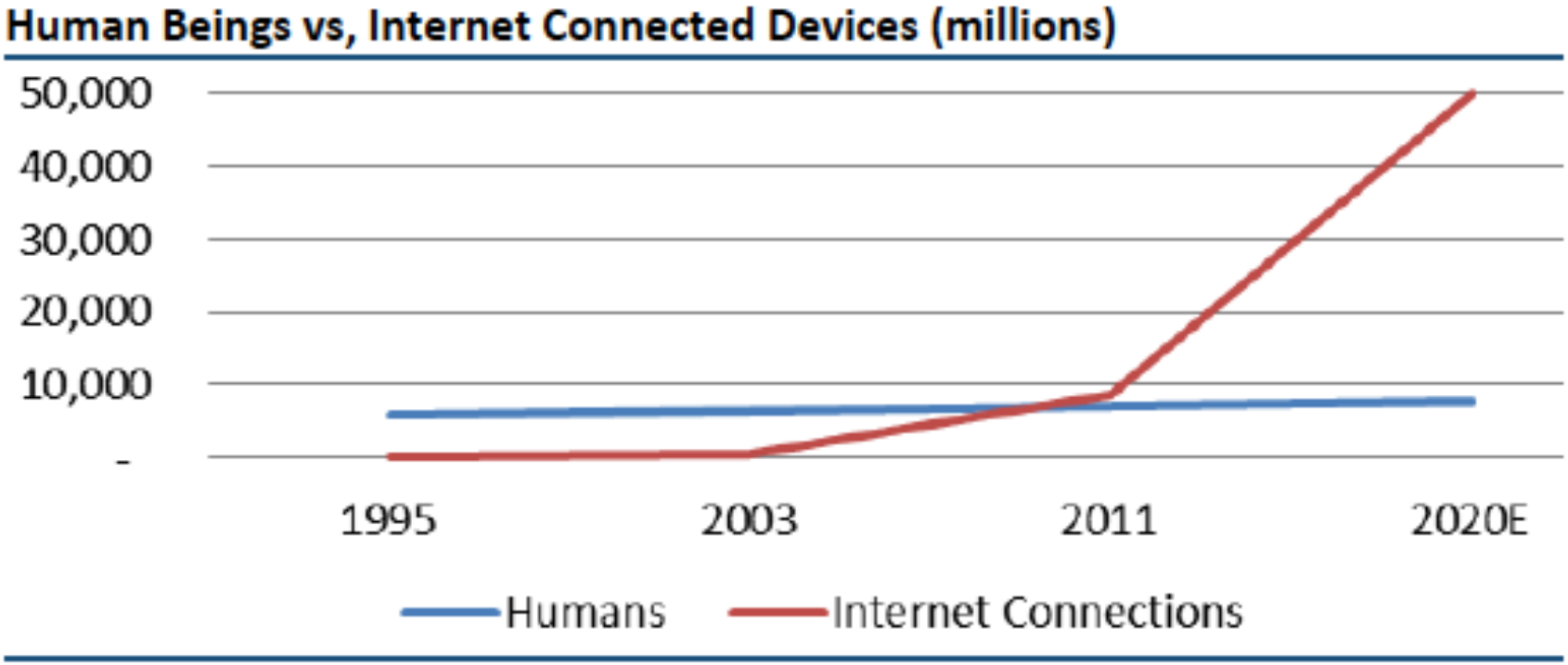
* Estimate

The (Wireless) Internet of Things



The confluence of efficient wireless protocols, improved sensors, cheaper processors, and development of the necessary management and application software has finally made the concept of the (Wireless) *Internet of Things* (*IoT*) mainstream.

Wireless Internet of Things-2



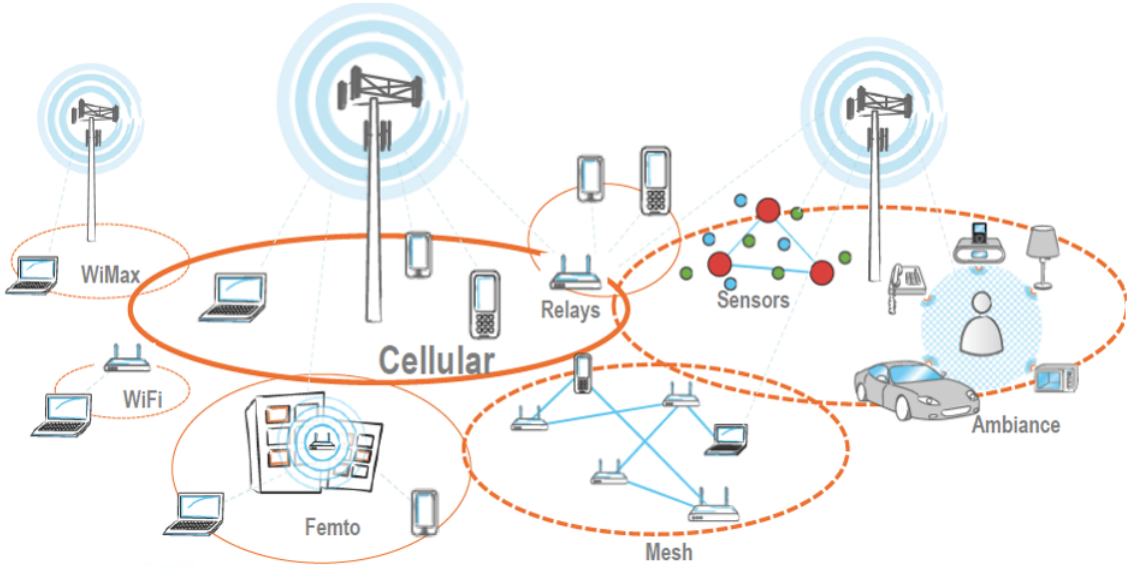
Source: Cisco Systems, LM Ericsson, Raymond James research.

- The number of Internet-connected devices surpassed the number of human beings on the planet in 2011, and by 2020, Internet-connected devices are expected to approach 50 billion.
- For every Internet-connected PC or handset there will be 5-10 other types of devices sold with native wireless Internet connectivity --- cars, tools, appliances, consumer electronics, medical devices, …

Wireless (R)Evolution

Today

People Connecting to People via Smartphones



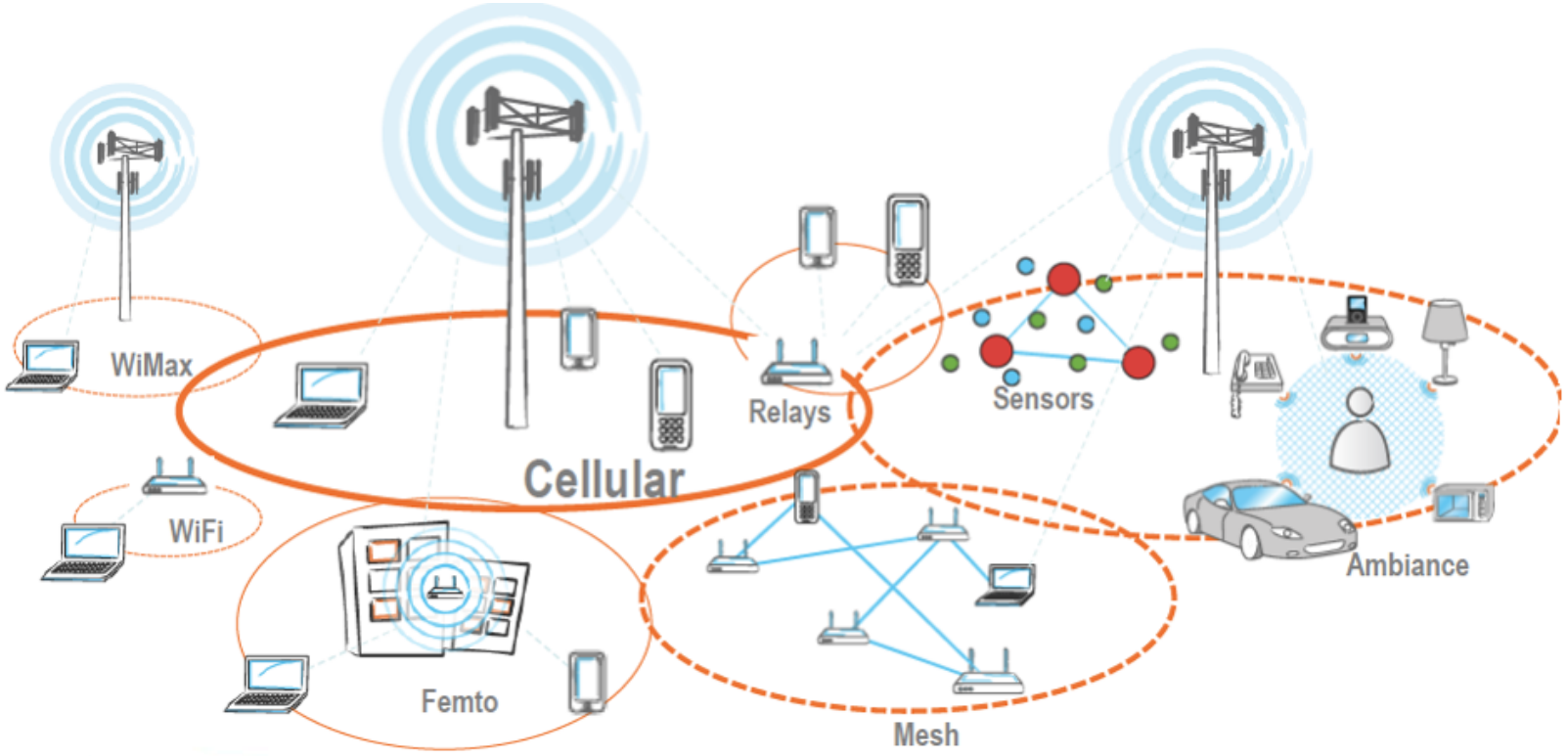
(Near) Future

Network of Networks

- Billions of subscribers
- Trillions of connections
- Seamlessly connected
- Self organizing
- Device-to-device capabilities

Wireless (R)Evolution: "5G" HetNet

People Connecting to Things and Things Connecting to Things (IoT)

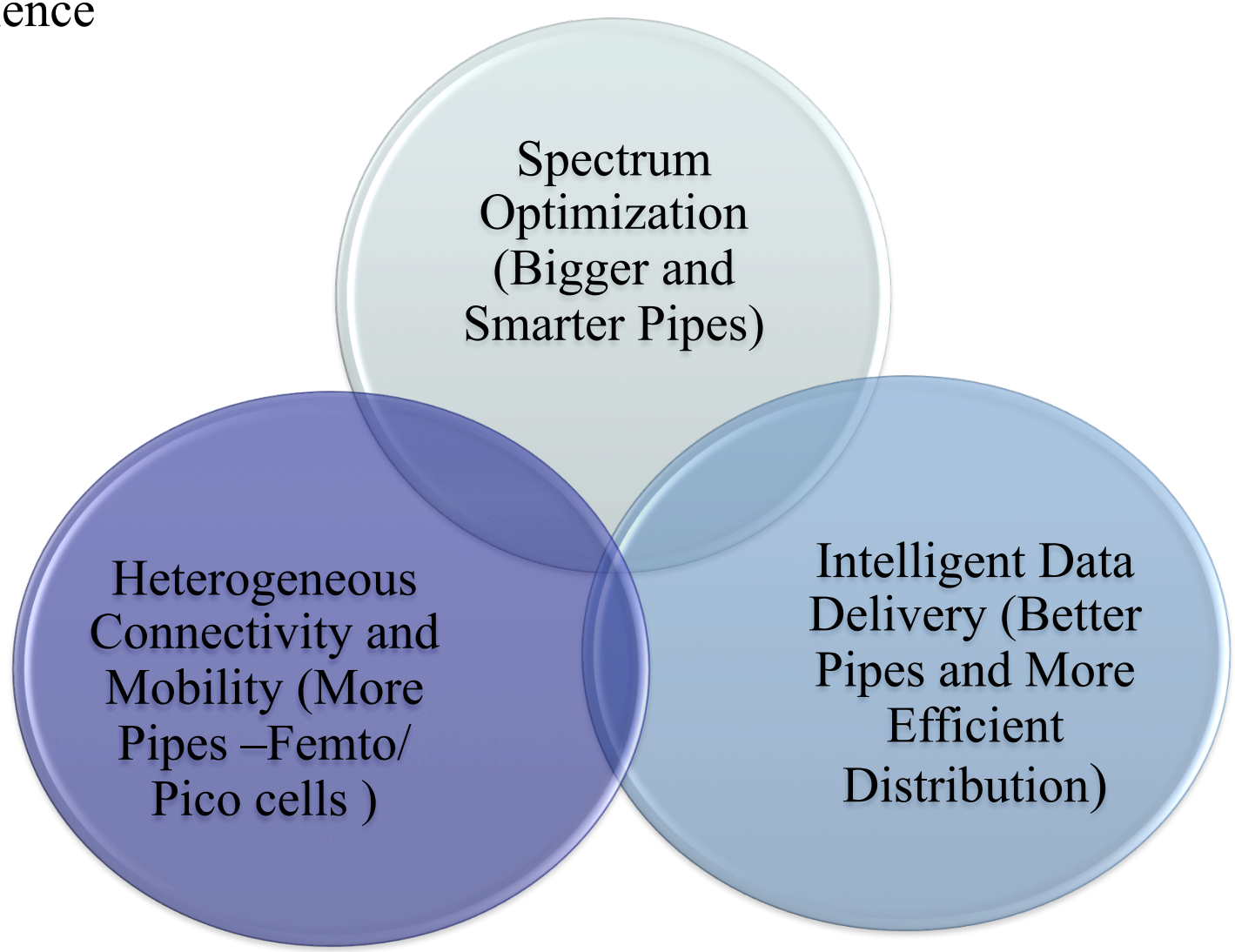


"5G" Network characteristics and (some) research challenges

- Ubiquitous seamless connectivity for billions of subscribers with trillions of connections.
- Broadband, low latency, high capacity, and reliable coverage (scaling).
- Quality of Service flexibility: balancing high throughput with low power and low cost.
- Security and privacy, preventing misuse, tampering, malware, other unauthorized access.
- Self organizing networks and device-to-device discovery and communications.

Holistic Approach to Solving the Wireless Bandwidth Crunch

Core innovations and advanced technologies will support increased data usage, heterogeneous and pervasive networks, and a richer multimedia experience



Intelligent Data Delivery: Application-Aware Networking

[see *HAMCR* slide later in presentation]

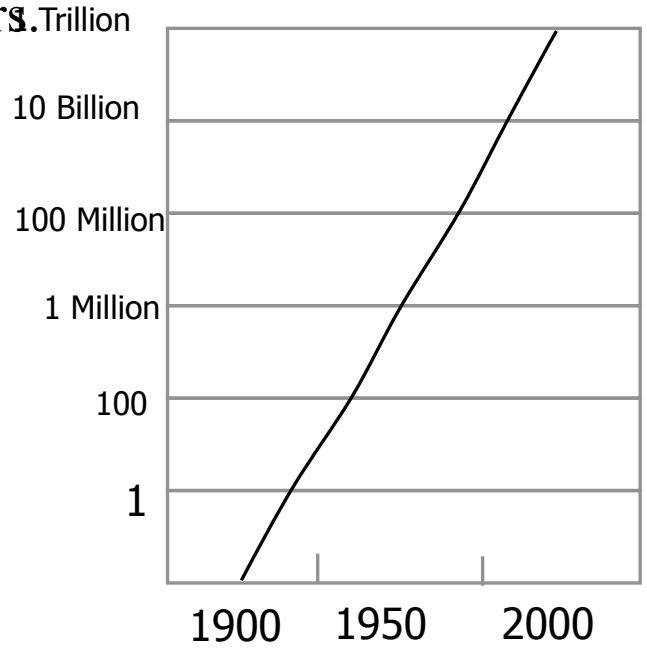
Requirements Vary Widely per Application and User → Opportunity to Increase Capacity

	Smart Energy	Healthcare	Transportation	Retail	Security & Surveillance
Low Power Consumption	●	●		●	
High Data Rate			●	●	●
Mobility		●	●	●	
Delay Sensitivity		●	●		●
Location Tracking	●	●	●	●	●
Long Replacement Cycle	●		●	●	●
Persistent Service	●	●			●

● Critical Importance ● Medium Importance

Capacity Increase in Wireless Networks is Still Possible

"Cooper's law": Every 30 months the information transmitted over the available radio spectrum doubles. This law has held since 1897 when Marconi first patented the wireless telegraph and is expected to prevail for at least 60 years.



Technological Components

- Increased spectrum (25×)
- Source compression (5×)
- Modulation and coding (5×)
- Topology / smaller cells (1600×)
  [**femtocells → 10**]
- Spatial multiplexing: MIMO
  4x4 MIMO (4x) and 8x8 MIMO (8x)
  Network MIMO ~ 5x MIMO?
- **Cognitive radios → >10?**
- Application-aware networking →**?**

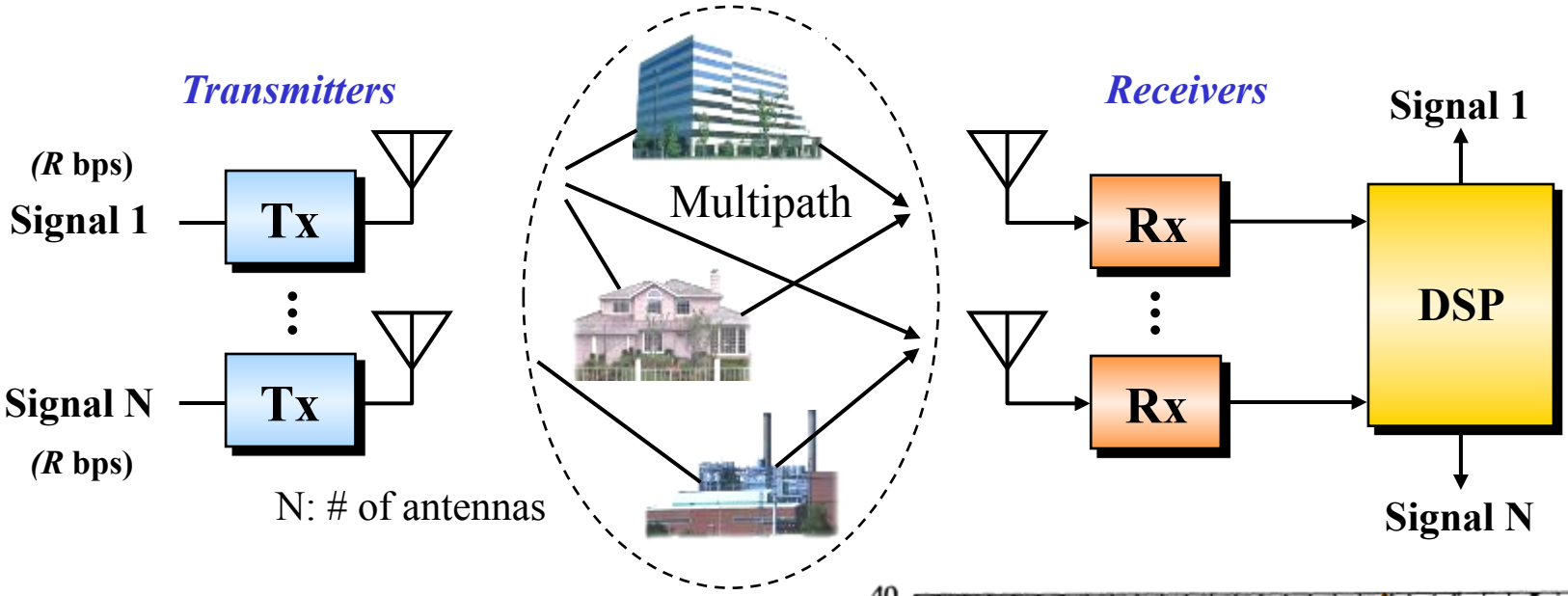
- **From 1954 to 1999: wireless capacity increases by 10^6 (25 × 5 × 5 × 1600)**
- **MIMO, femtocells, and cognitive radios → factor of ~1000 increase in capacity**
- **Protocol improvements: cross layer, application awareness, … → ?**

Advanced Technology: Smart Antennas ("MIMO")

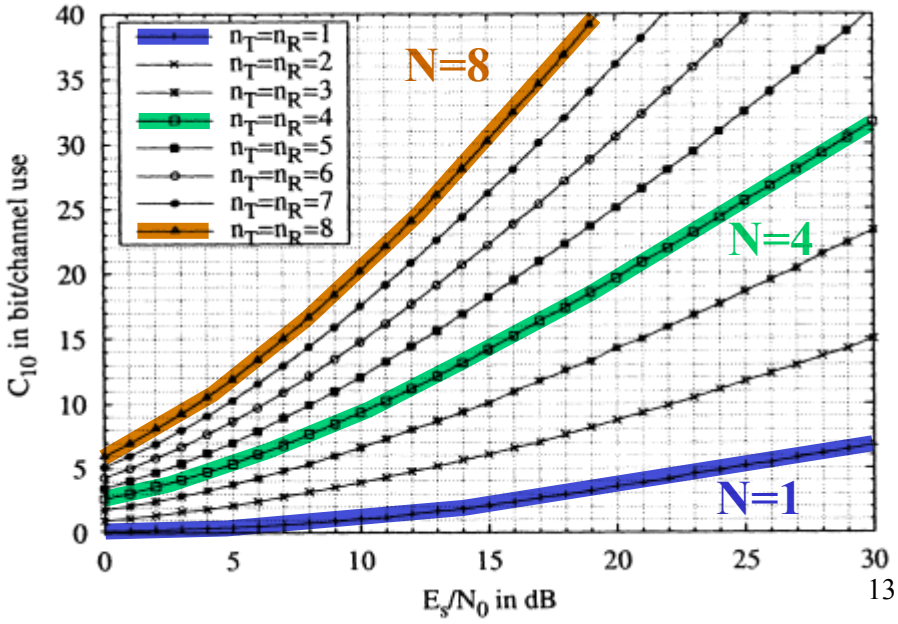
- A MIMO* antenna array uses digital signal processing to focus radio waves on a *personal cell* for each mobile user.
- With MIMO the capacity increases ~ linearly with number of antennas with no increase in total power.
- MIMO technology can also increase the coverage range of wireless networks and allow several users in the same coverage area to simultaneously communicate on the same frequency (**Spatial Division Multiplexing.**)

*MIMO = Multiple Input Multiple Output

Advanced Technology: *MIMO* --- Multiple Transmit and Receive "Smart" Antennas Dramatically Increase Wireless Capacity



- Multipath scattering scrambles the signals such that each receiver has a different combination of signals.
- DSP descrambles the received signal to reproduce original signals at the receiver.
- Capacity increases ~ linearly with number of antennas with no increase in total power.
- Samsung recently used 64 antennas to deliver 256 Mb/s per second in 20 MHz.

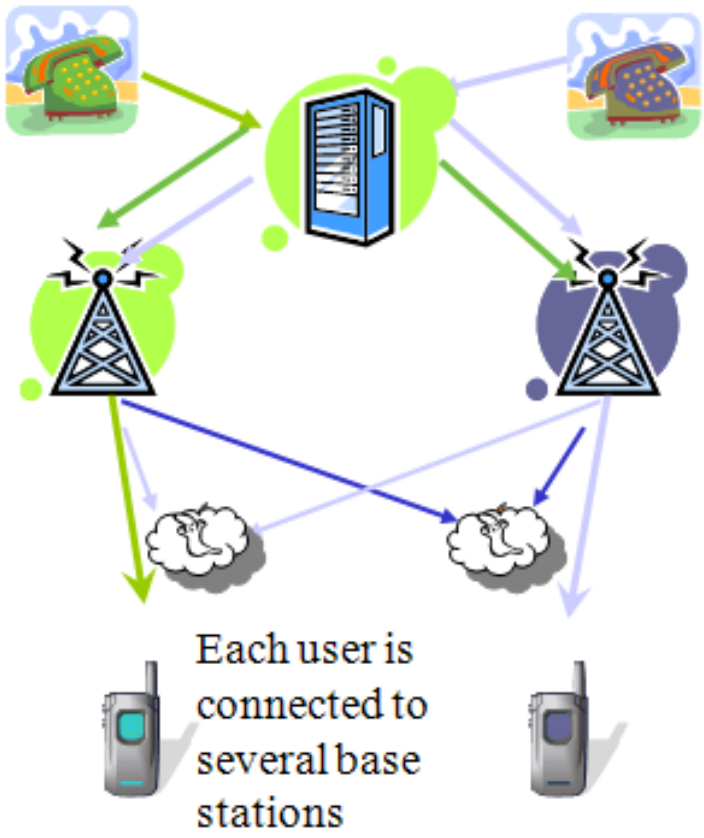


Network MIMO --- Enables Pervasive Wireless Capability

Today: Each user is connected to a single network and data rate limited by interference.

Future **Smart Network MIMO [and Devices]**:

- Overcomes inter-cell interference by coordinating Tx and Rx at several bases [**Network MIMO**] → all signals are potentially useful – no interference and substantial increase in user rates and system capacity.
- Networks and devices that satisfy the requirement for higher average use of video-on-demand with smaller cells and more frequency reuse by use of **cognitive radios** and learning to use the closest device and highest available data rate for transmission and handing off traffic to a variety of heterogeneous radio technologies.

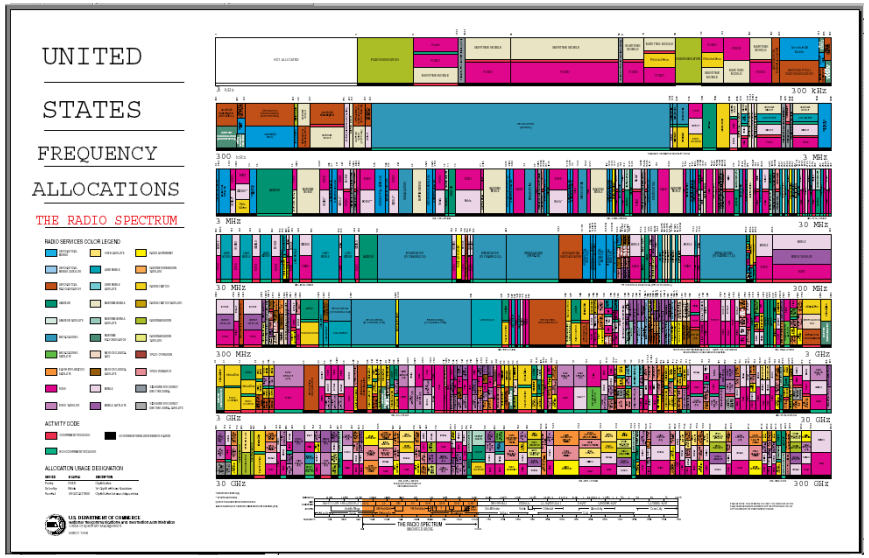


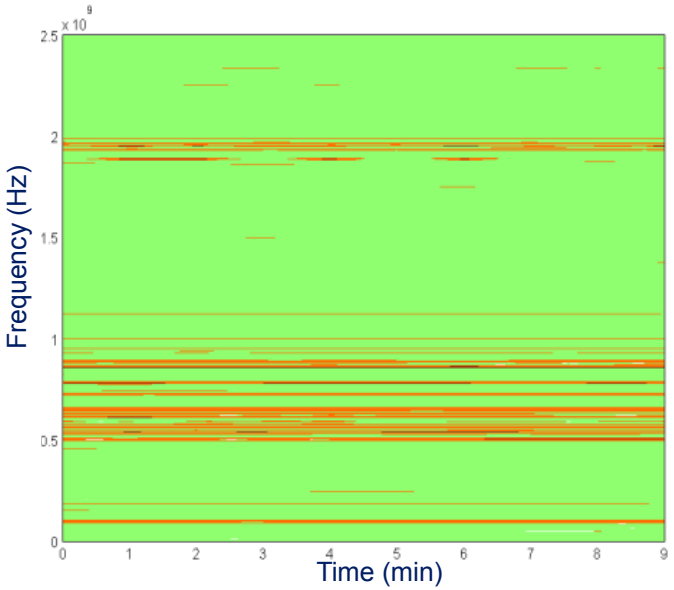
Network MIMO

Advanced Technology: Cognitive Radio

- Existing spectrum policy forces spectrum to behave like a fragmented disk.
- Bandwidth is expensive and good frequencies are taken.
- Unlicensed bands – biggest innovations in spectrum efficiency.

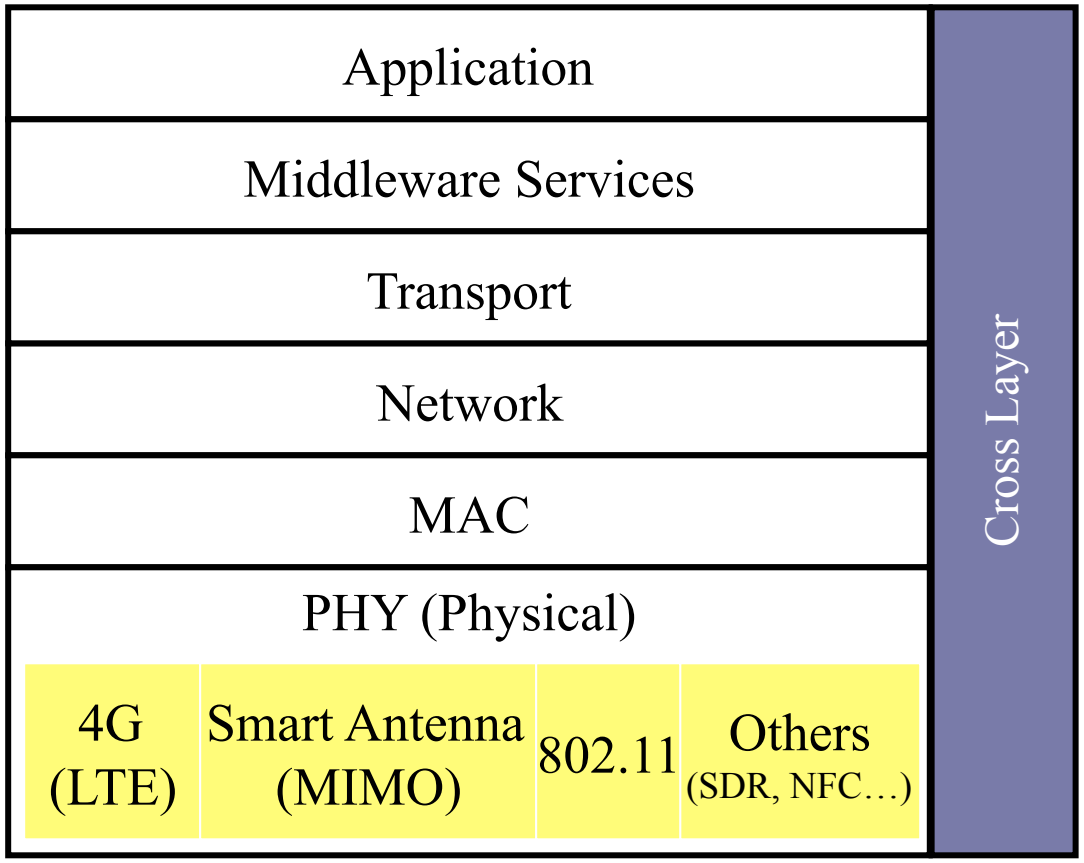
- Recent measurements by the FCC in the US show *70% of the allocated spectrum* is not utilized.
- Time scale of the spectrum occupancy varies from msecs to hours.





Cognitive radio techniques allow sharing of geographically unused licensed spectrum (e.g., for television broadcast service) on a non-interfering basis, to enable broadband wireless access.

Advanced Wireless Technology: Cross Layer Networking
Application-Aware Networking-Intelligent Data Delivery



Application with intermittent connectivity …

Location service …

Wireless aware TCP …

Multi-path routing …

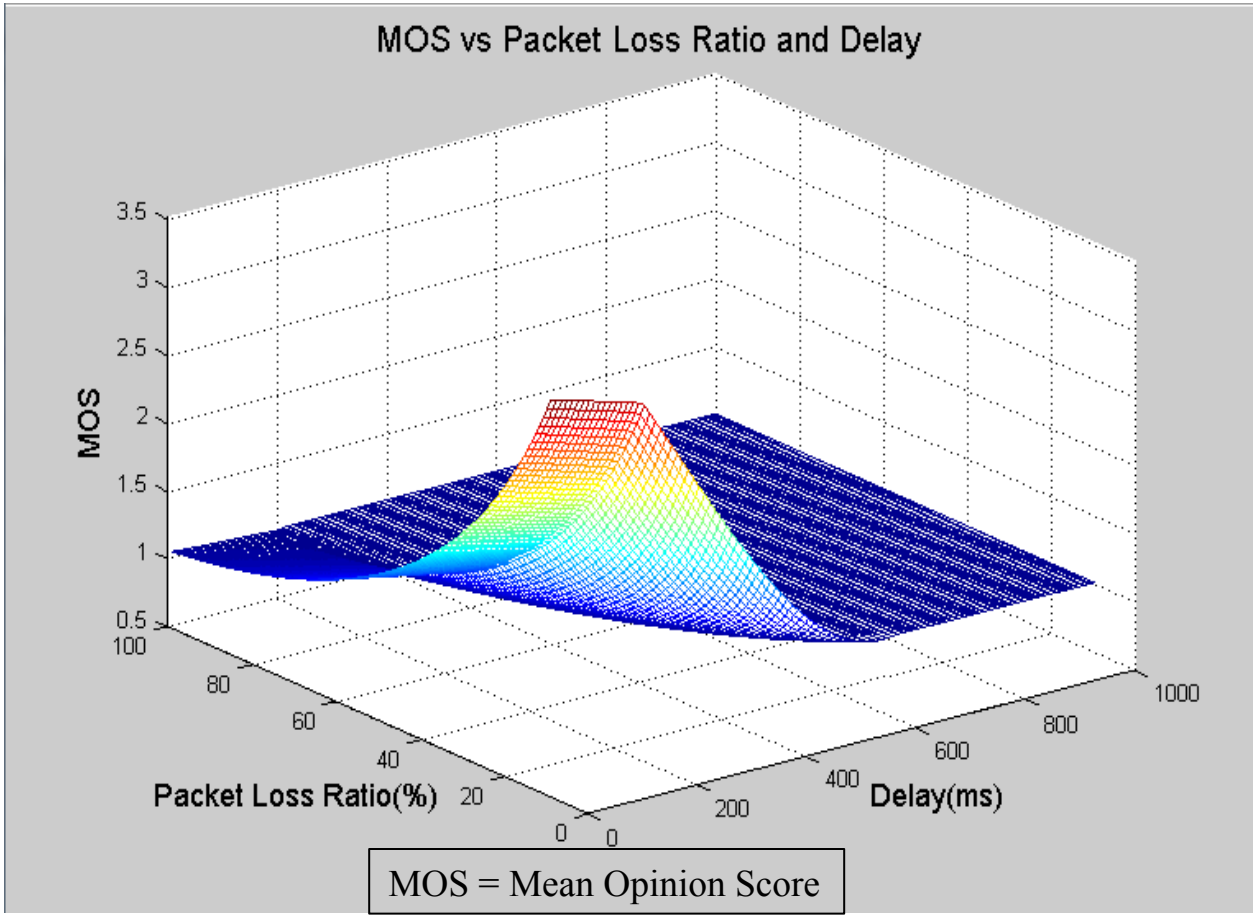
Prioritization, scheduling, power conservation …

Feedback to and from the PHY layer to other (cross) layers [e.g. Application] is a key enablers for advanced wireless networking

Application-Aware Networking-Intelligent Data Delivery

HAMCR--Holistically Application-Aware Multi-Dimensional Cognitive Radio

- In today's LTE 4G wireless networks the spectral allocation of resources is:
  - Independent of the application specific Quality of Service (QoS) requirements.
  - Independent of the user's specific perceived QoS.
  - Relies on a set of pre-defined fixed priorities.
- HAMCR designs a user specific QoS Cross Layer Optimizer (Scheduler) to satisfy specific QoS user requirements or to increase capacity.

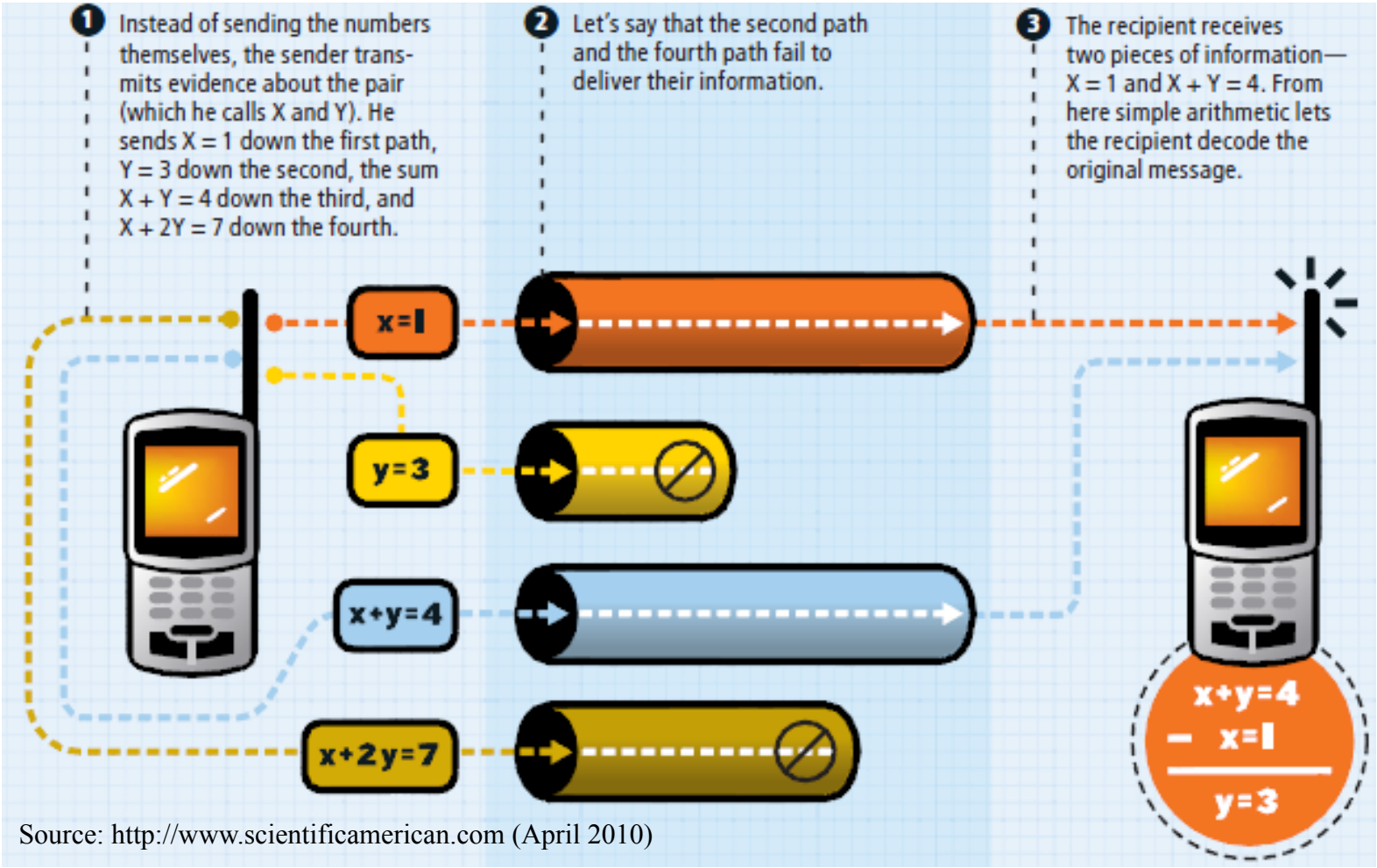


HAMCR: Arslan, Gitlin, and Haas [Cornell and U Texas] --- Chao He [USF PhD student]

Advanced Technology: Network Coding – Smart Redundancy

making reliable networks/systems out of (somewhat) unreliable subsystems

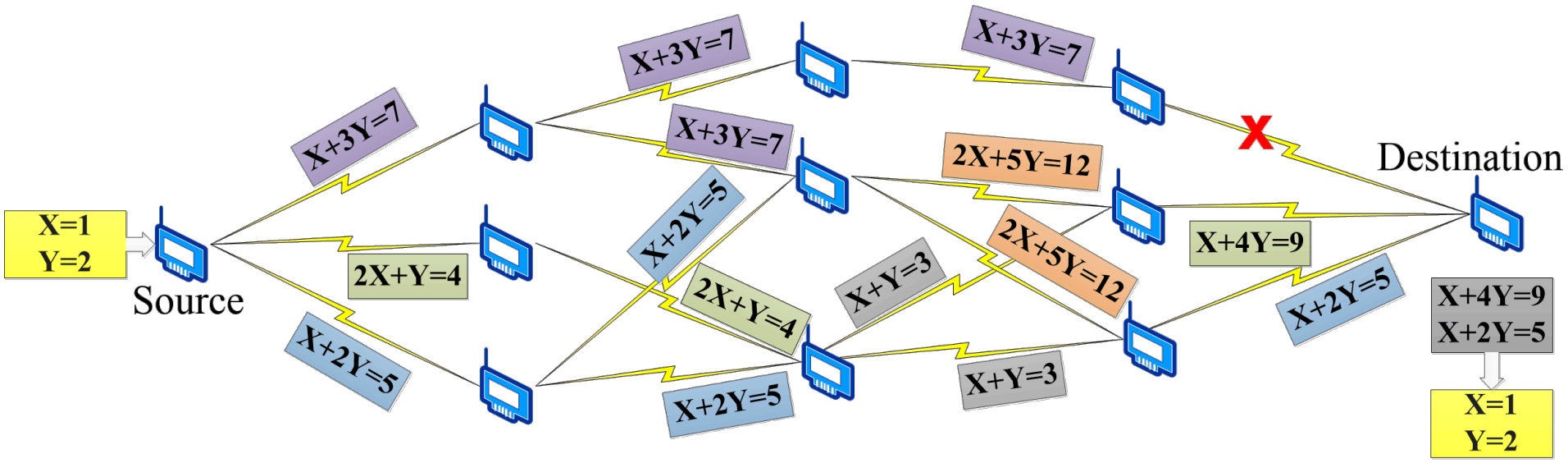
- Network Coding (NC) achieves capacity gain through coding of information.
- Improves network reliability against packet losses and link failures (and coding provides some security against casual or malicious listeners/intruders).



Source: http://www.scientificamerican.com (April 2010)

Emerging Technology: Cooperative Networking
Combining Cooperative Communications and Network Coding

- Benefits
  - Improved probability of successful transmission and improved network reliability.
  - Reduce the number of packet re-transmissions.
  - Reduction in transmission energy requirements.

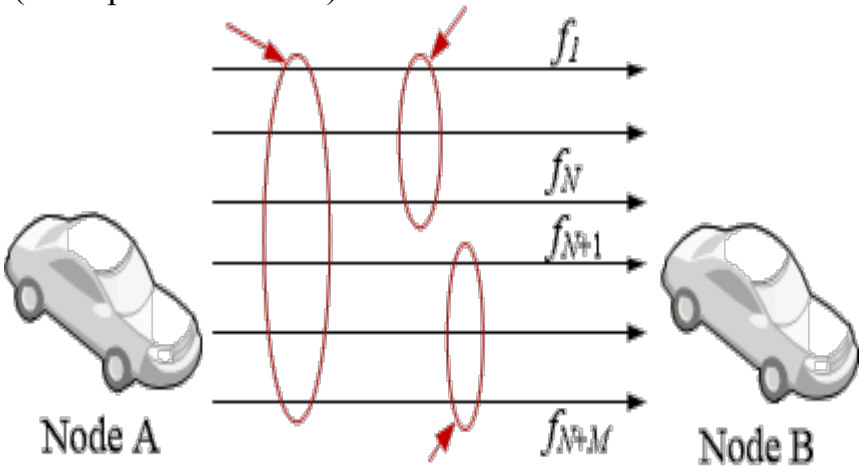


Joint work: Cornell/UT (Haas) and USF (Arrobo and Gitlin)

Emerging Wireless Application: Vehicular Systems Communications for "Farsighted" Driving

On the highway	In city traffic
	
Danger alert	Intersection assistance
Warning beacon Traffic flow	Communication with traffic signals

Diversity Coded OFDM



Vehicle – Vehicle – Communication
(**WLAN + *Ad-hoc* network**)

Arrobo and Gitlin

- IEEE 802.11p – **W**ireless **A**ccess in the **V**ehicular **E**nvironment (WAVE).
- Random group of vehicles creates an *ad-hoc* wireless communication network.
- ***Diversity Coded OFDM*** increases the communication reliability between cars.

Emerging Application: The Pervasive Wireless Internet of Things

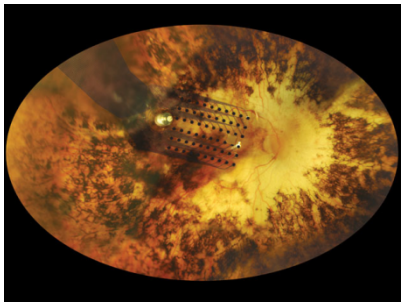
Wireless technology is rapidly migrating from communications to a multitude of embedded real-world applications

Collision avoidance

Tracking farm animals

Wireless dog collar

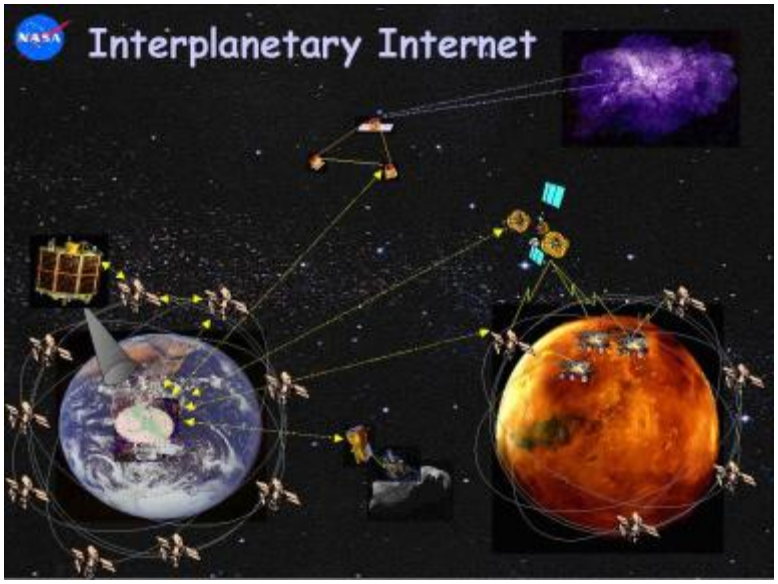
Child finder



Wireless eye implant
IEEE Spectrum January 2012

Implantable RFID devices

Emerging Wireless Application: The Interplanetary Internet: "InterPlaNet"(IPN)



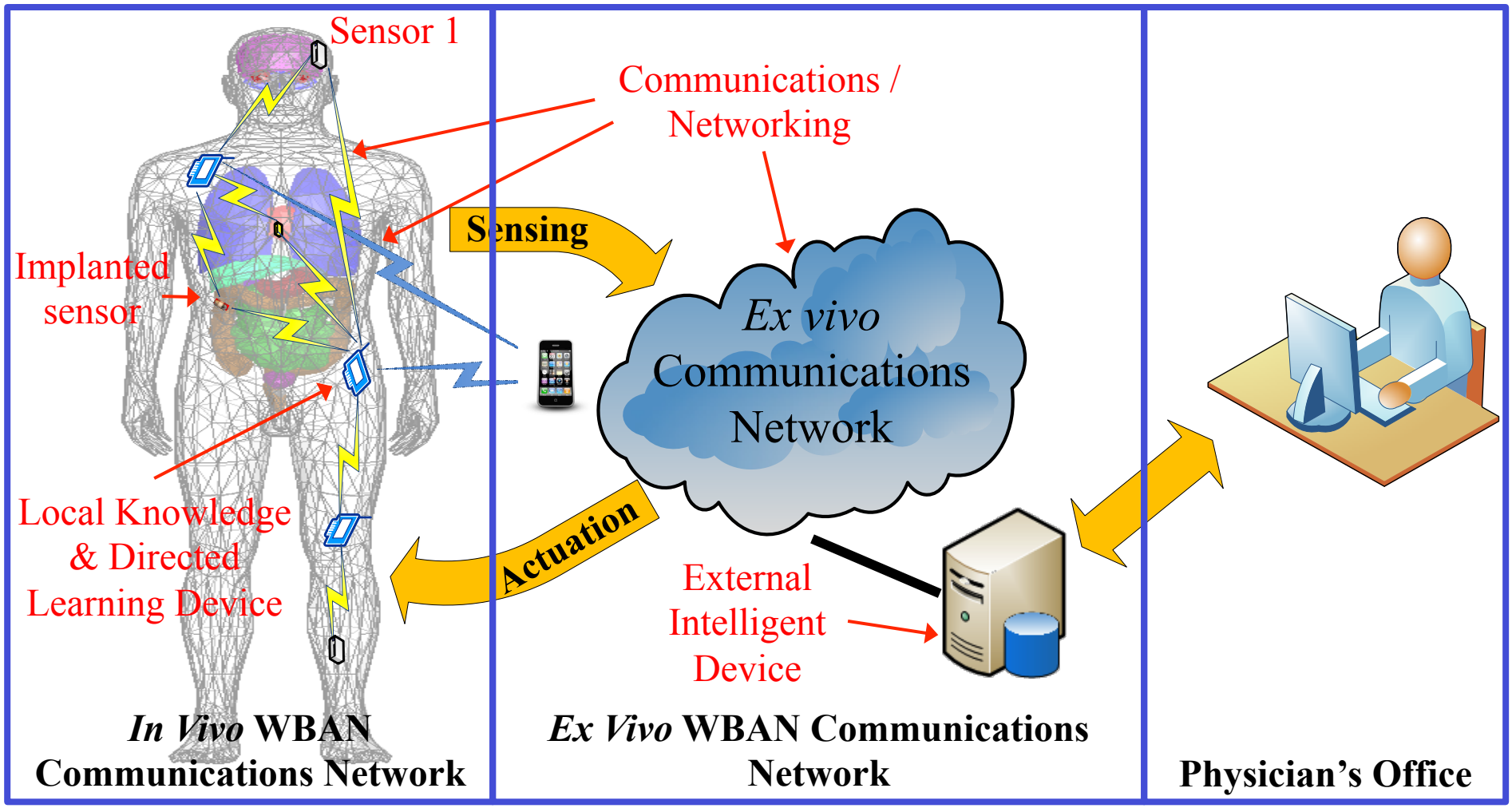
Attenuation: 90dB below GEO satellite (due to differences in orbital characteristics.)
Delay: 10-20 minutes to/from Mars (due to the distance.)
Noise: celestial events, atmospheric conditions, and other spacecraft.

Space --- the last wireless frontier (or is it?)

- Planetary internets, in-space routing, and interplanetary gateways --- interplanetary long-haul protocol with layered architecture.
- **TCP in space – SCPS** (Space Communications Protocol Standard.)
- IP-like protocol suite tailored to operate over long round-trip flight times
- Email-like behavior.
- Delay and disruption tolerant protocols
  - Tactical Mobile applications (DARPA).
  - Cisco announced their "space router" (Jan 2010) which is a hardened router running IOS 14 for satellite deployment.

Our Research Vision: Wirelessly Enabled Healthcare System

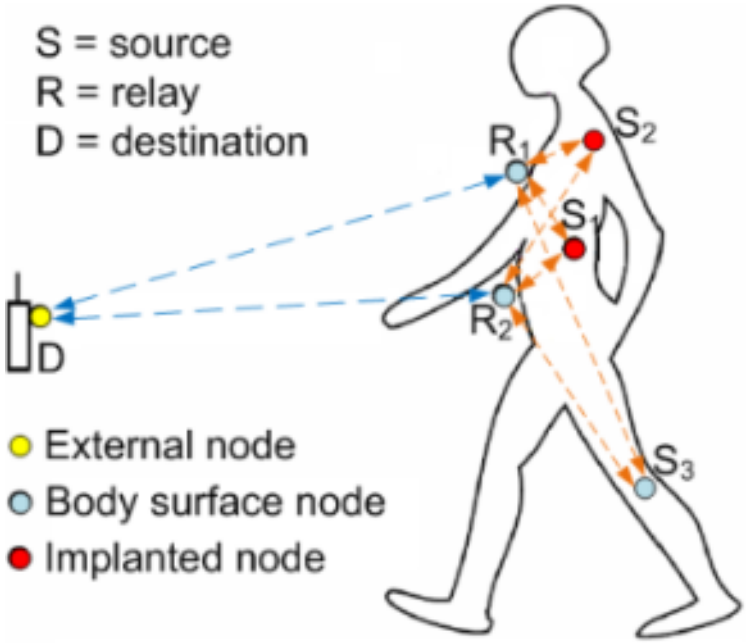
Wireless technology has the potential to advance and transform healthcare delivery by creating new science and technology for *in vivo* wirelessly networked cyber-physical systems of embedded devices that use real-time data to enable rapid, correct, and cost-conscious responses in chronic and emergency circumstances.



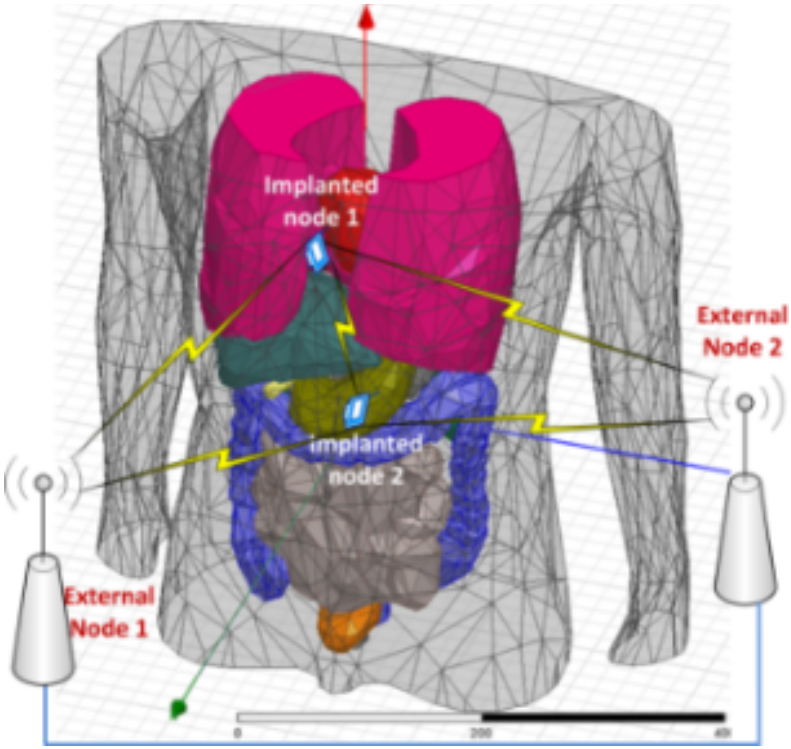
Research opportunities and challenges are abundant

In Vivo [Selected] Wireless System Research Areas

- Sensing and actuation at the micro/nano/molecular level.
- Asymmetric communications and multihop networking paradigms for devices more limited, from a communication and computing standpoint, than any devices that have ever been networked by human-created means.
- Achieving reliable, high-throughput and near zero latency intra-body wireless communications and networking.
- New approaches to privacy and security for devices of limited processing capabilities and developing a scalable architecture for data management.
- Learning systems that distill complex datasets into actionable information.



In vivo wireless networking

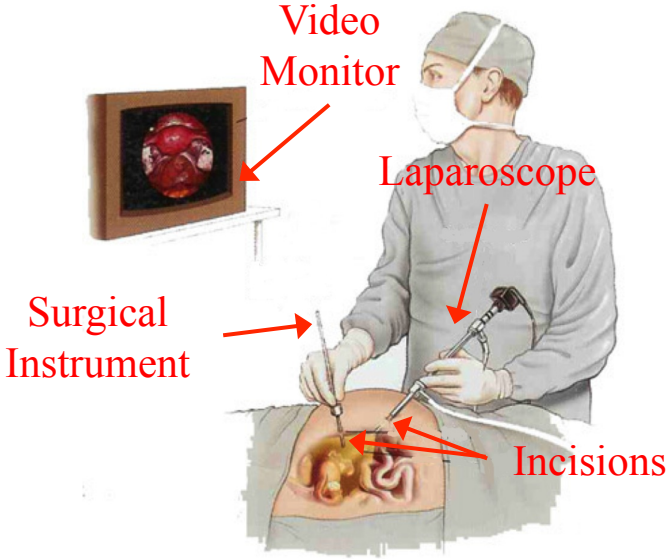


Networked MIMO *In Vivo*

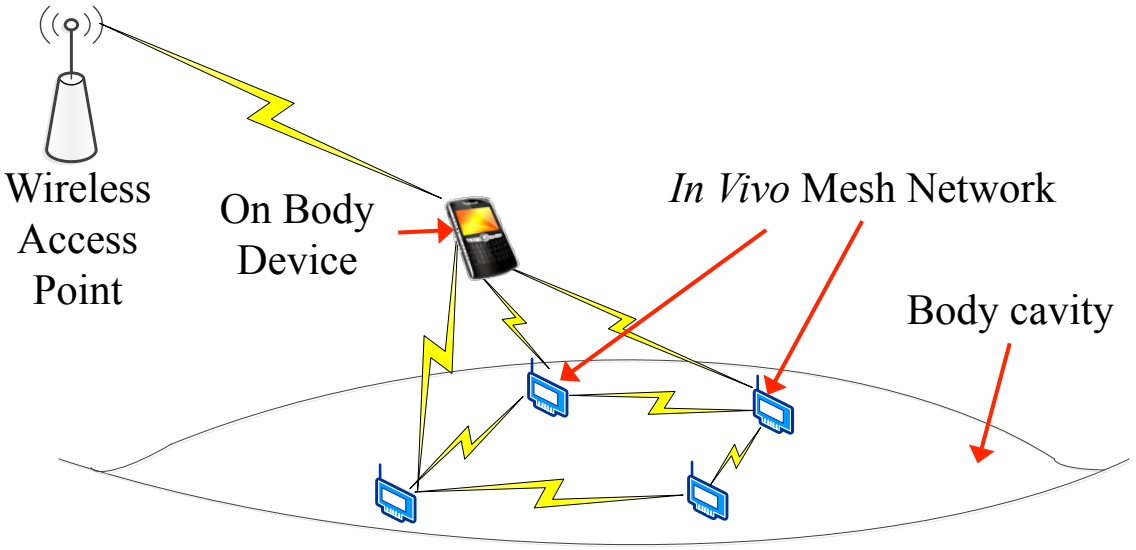
Application: Advancing Minimally Invasive Surgery (MIS) via Wirelessly Networked Devices

- Creation of a wireless mesh network of cyber-physical *in vivo* devices that enhances and enables innovative non-invasive and MIS surgical and other procedures.
  - Network is comprised of a plurality of communicating devices --- such as imaging devices, sensors and actuators, power sources, "cutting" tools.
  - The devices are electronically addressable and controllable and form a distributed network whose capabilities greatly exceed that of any individual device.
- The ***MARVEL*** Camera Module (CM) is the first device in realizing "the vision".

MARVEL = ***M***iniature ***A***nchored ***Robotic*** ***V***ideoscope for ***E***xpedited ***L***aparoscopy



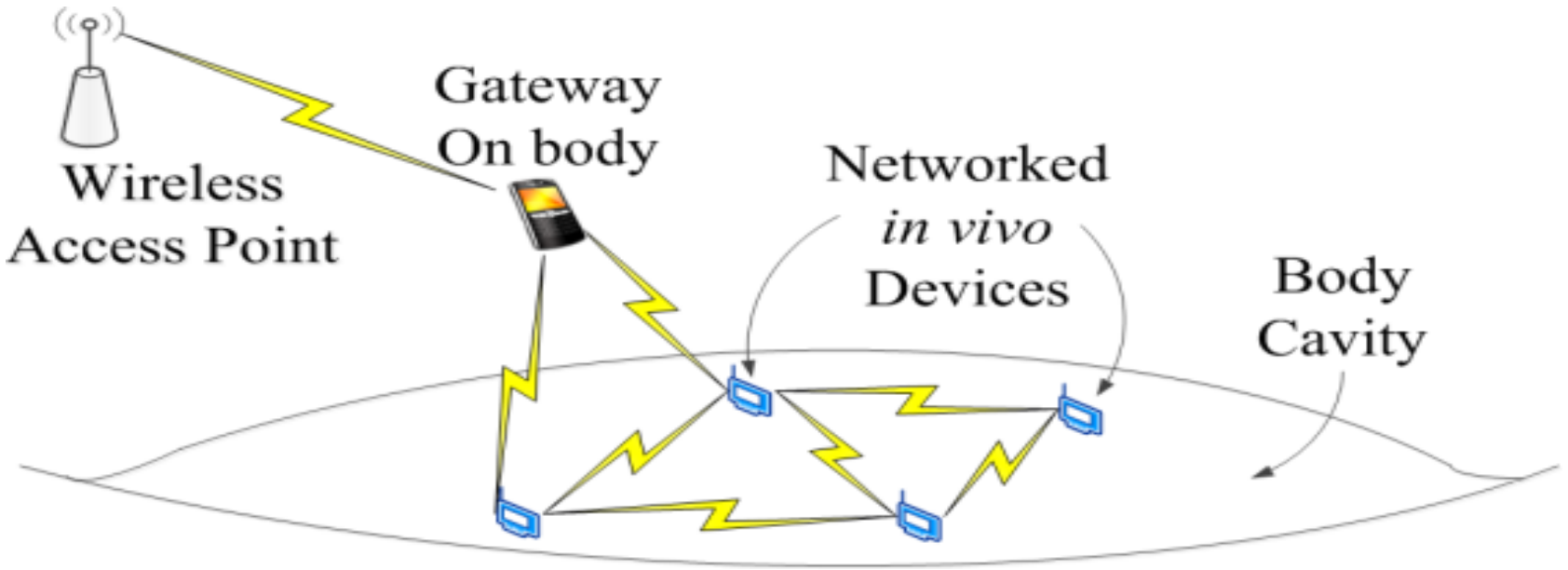
Current laparoscopic technology



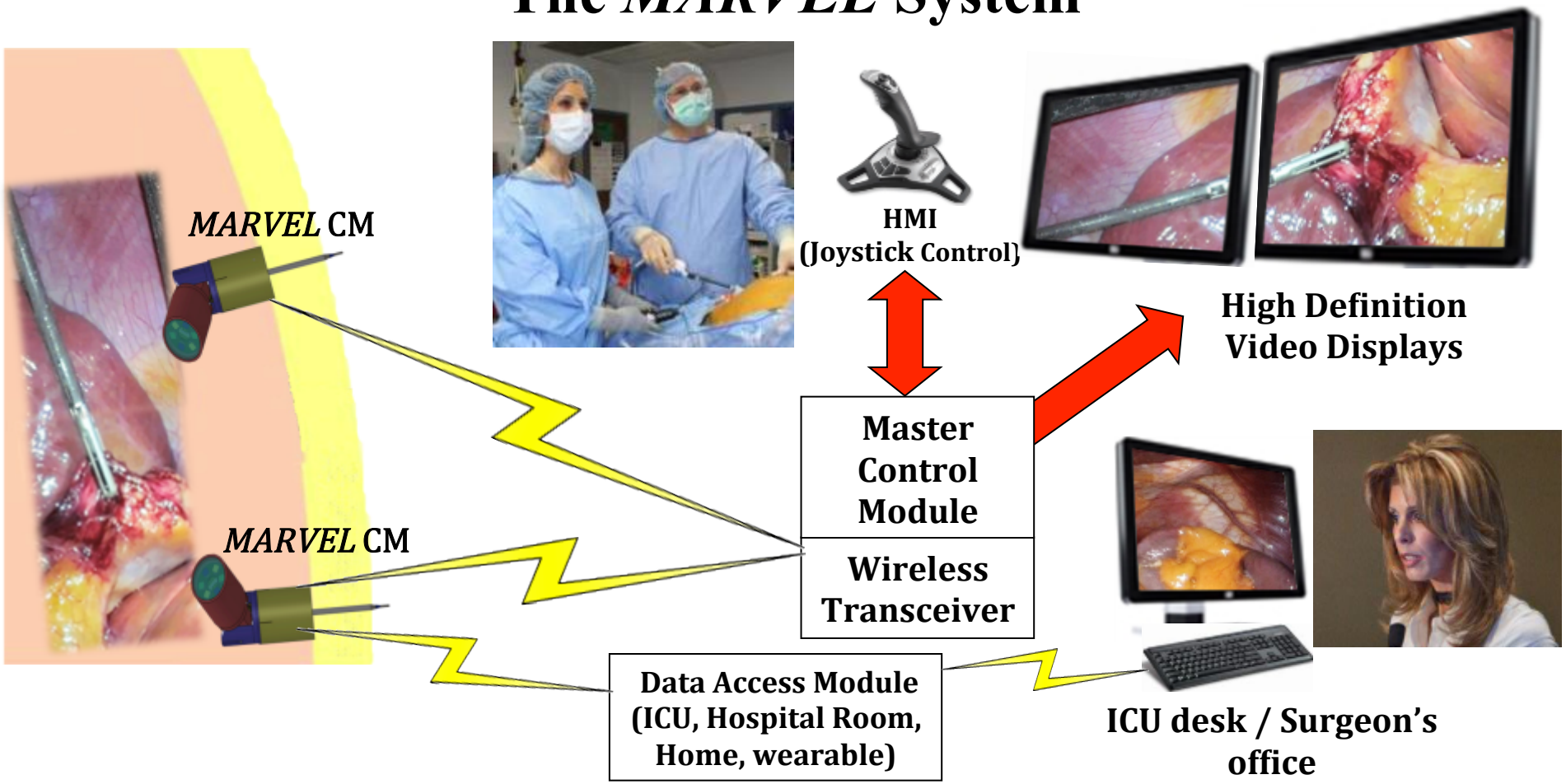
Collaborators: Arrobo, Arslan, Fabri, Hall, Lai-Yuen, Ketterl, Rosemurgy, Ross, Sarkar, and Sun

MARVEL Advantages and Benefits

- Decreases the surgical-tool bottleneck in MIS procedures.
- Eliminates power, video, and light source cabling issues in laparoscope.
- Increase the dexterity and fine motion options for the surgeon.
- Increases visibility and the usable workspace inside the abdominal cavity.
- In process: Wireless high def video, OFDM, reduced physical dimensions, inter-module communications, and 3-D Imaging with Multiple CMs.
- **A paradigm shift in MIS surgery by eliminating the laparoscope!**



The *MARVEL* System



The ***MARVEL*** system includes:

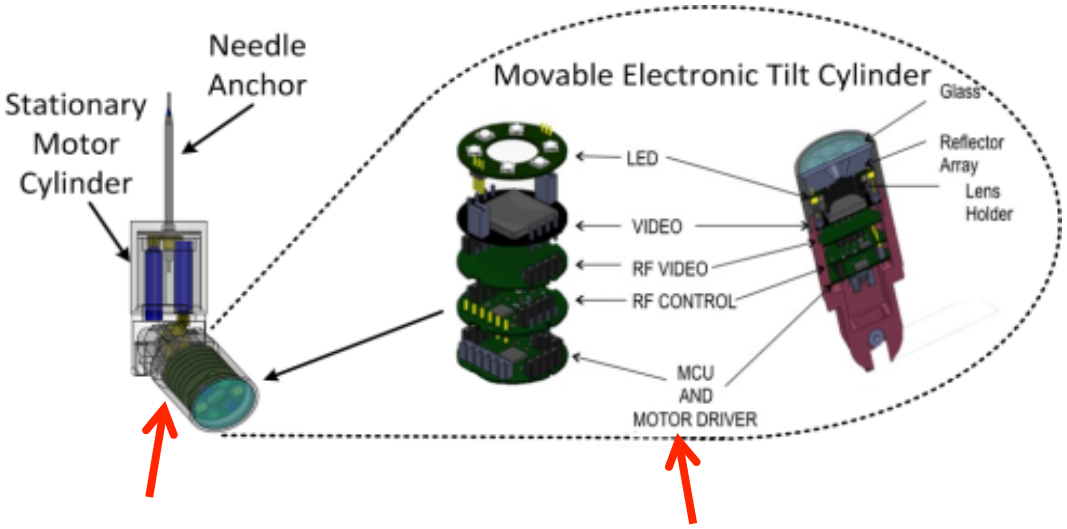
- Multiple CMs with wirelessly controlled pan/tilt enabling a full hemisphere field of view, wirelessly focus/zoom, and a multi-wavelength illumination control.
- Master Control Module (MCM) that provides near-zero latency video wireless communications, and independent wireless control for multiple *MARVEL* CMs.
- Wireless human-machine interface (HMI) that controls the CM functions.

MARVEL: Research Challenges Include

- Reliable, high-throughput and low-latency intra-body wireless communications.
- New networking paradigms for devices which are very limited from a communication and computing standpoint.
- Sensing, actuation, privacy, and security for such devices of limited complexity.
- Electronic, optical and mechanical miniaturization of complex systems.

Experimental Results

- The figures illustrate the ***MARVEL*** design and experimental USF vivarium results.
- Four vivarium experiments with porcine subjects have taught us a lot ☺



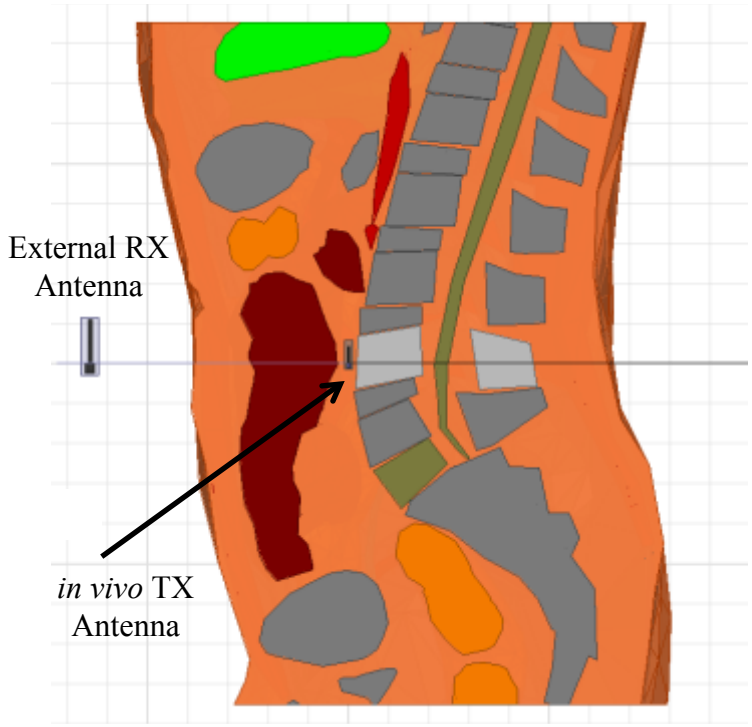
MARVEL CAD model and exploded circuit board stack

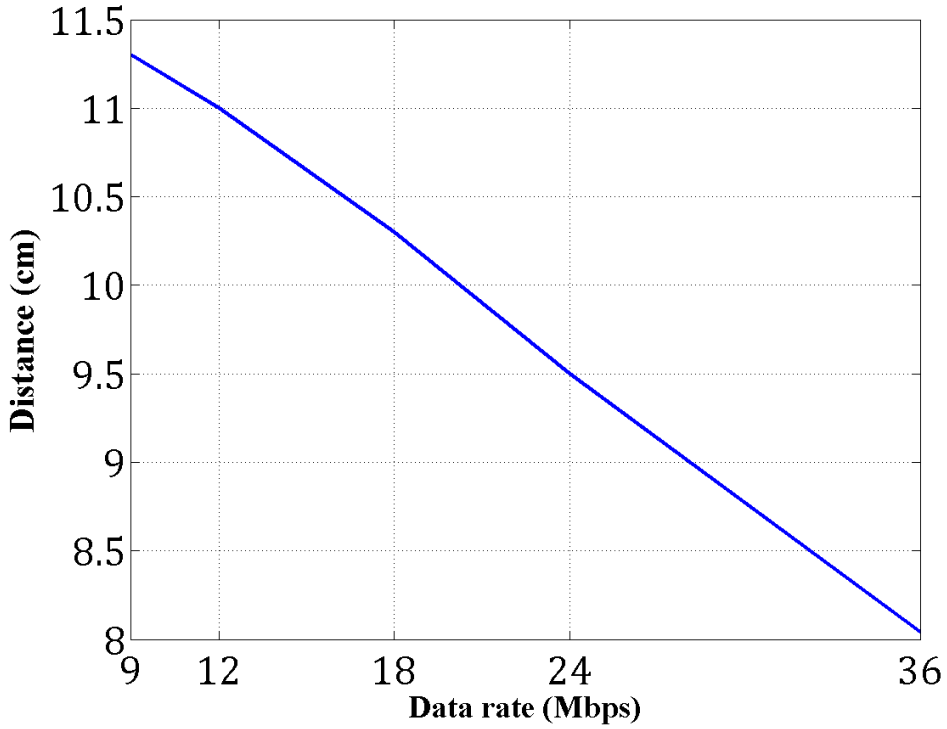
MARVEL units in a porcine abdominal cavity

Image of internal organs captured by ***MARVEL*** unit

SAR Limitations for *In Vivo* Wireless Communications

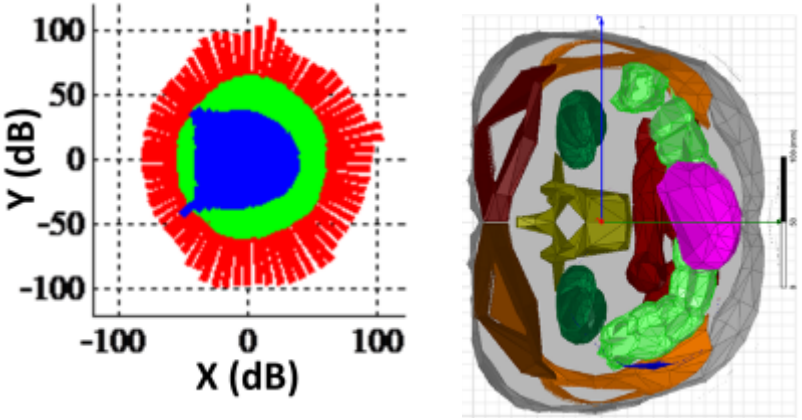
- The specific absorption rate (**SAR**) is the frequency dependent rate at which RF energy is absorbed by a body volume or mass and has units of watts per kilogram (W/Kg).
- Due to this limitation on the specific absorption rate, it is not possible to increase the transmission power beyond a certain level to overcome transmission errors.
- By networking the *in vivo* nodes via relay nodes, it is possible to transmit the *in vivo* sensors' information to external nodes while keeping the SAR within allowed limits.
- The figures below show the location of the *in vivo* and *ex vivo* antennas and our software-based experimental results.



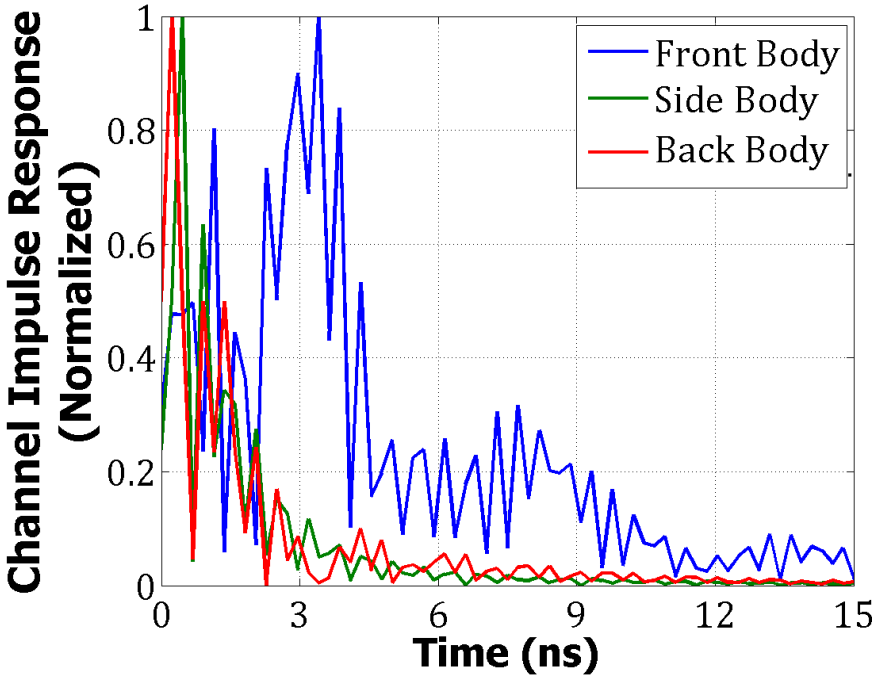


In Vivo Wireless Channel Directional Properties

- One of the many differences between classic RF models and the *in vivo* channel is that the path loss and impulse response is a function of the direction (receiver location.)
- The path loss [lower left] is a function of the frequency and not homogenous around the body. Moreover, the angular dependency is noticeable for 500 MHz as in the left figure (blue curve). The frequencies are 0.5 (blue), 1 (green) and 2 (red) GHz.
- Antenna characteristics (efficiency and radiation patterns) can deviate from the designed values with changes in position and orientation inside the body. This is due to the high likelihood that organs and tissues will be in the antenna's radiating near field.



Path loss as a function of position for the human body without arms (figure on the right) with the transmitter at (0,0) and measured at a height of 1.1m. The attenuation at any point (x,y) is $[(P_x)^2 + (P_y)^2]^{1/2}$

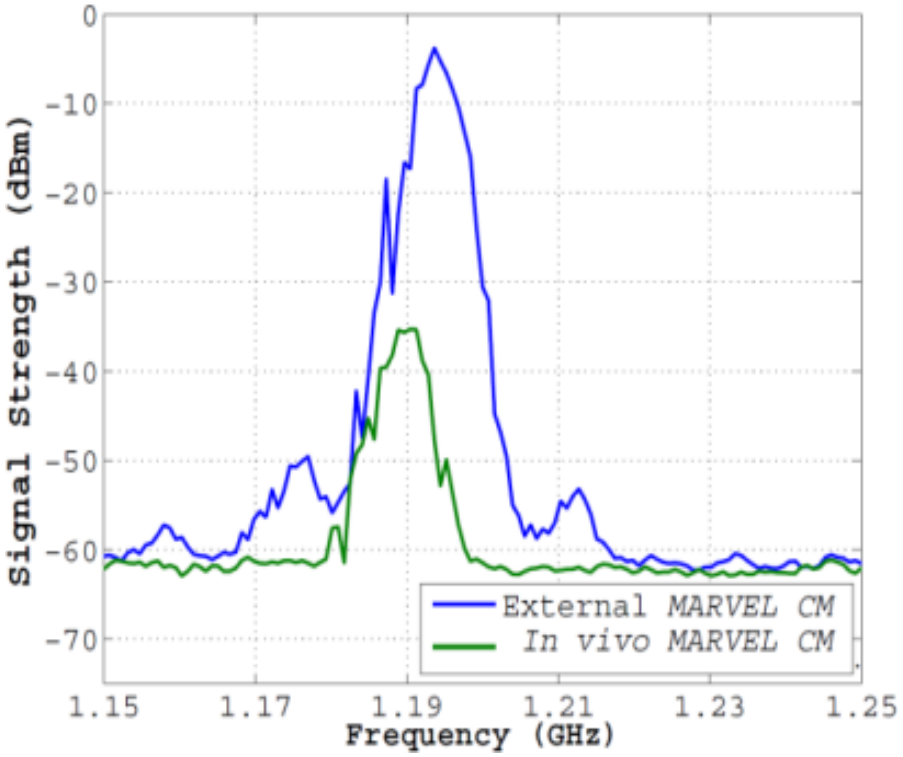


Channel impulse response for the human body for different locations of the receiver

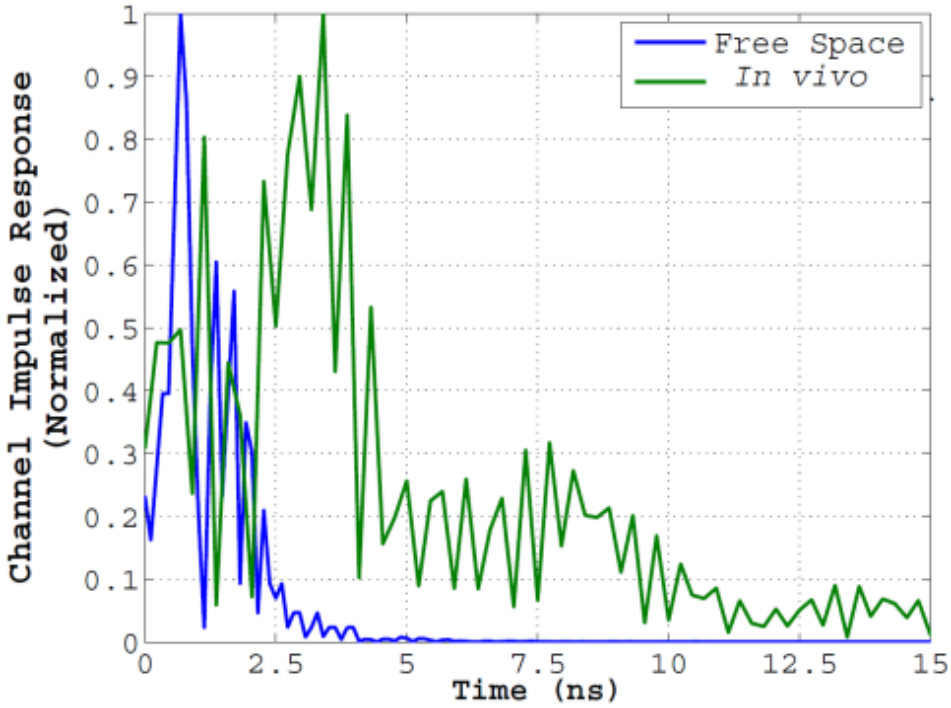
MARVEL In Vivo Attenuation and Multipath: Vivarium Results

- *In vivo* time dispersion [multipath] is much greater than expected based on the physical dimensions.
- The *in vivo* transmitter was located inside the abdominal cavity and the receiver was placed ~ 0.5m from the transmitter in front of the abdomen. There is about a 30 dB loss for the *in vivo* channel.

1.2 GHz band and 11 MHz signal bandwidth



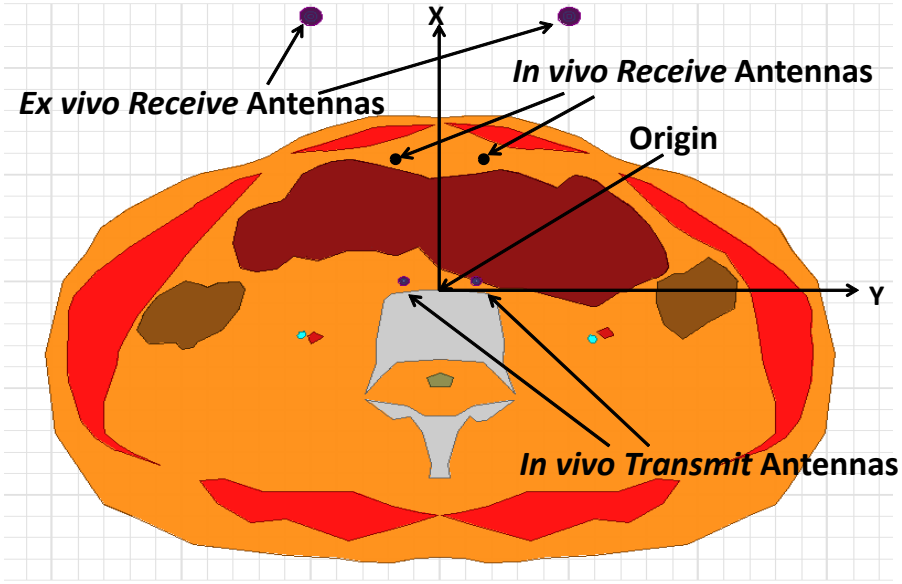
MARVEL Vivarium Experiment - Signal Loss



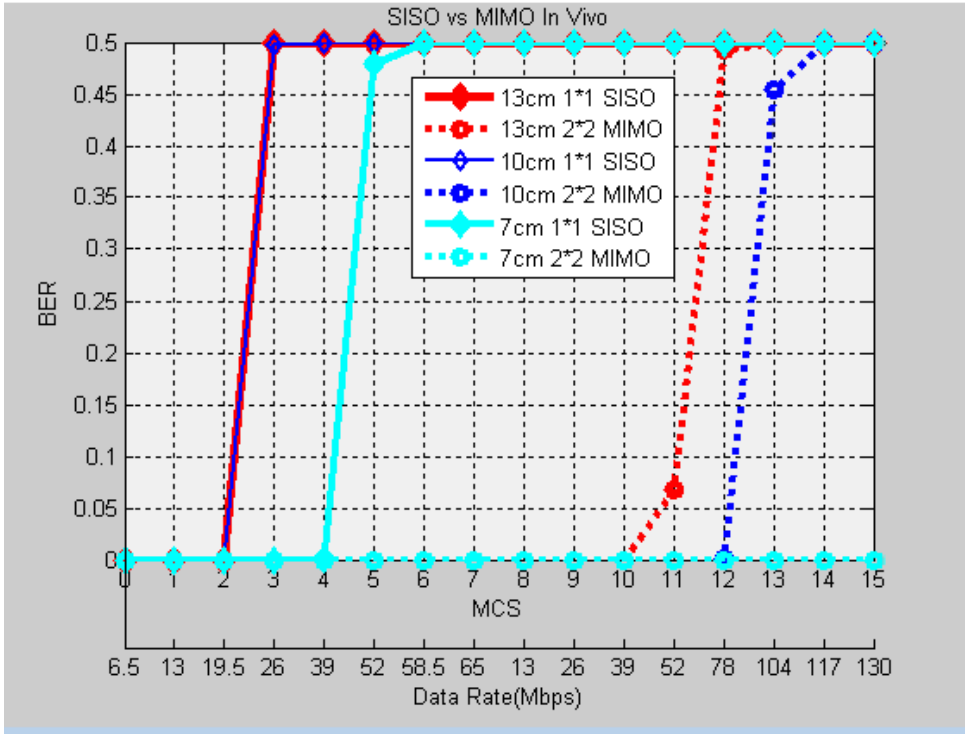
Normalized channel impulse response for the human body for free space and scattered environments

MIMO In Vivo

- Due to the *in vivo* medium, achieving high data rates with reliable performance will be a challenge, especially since the *in vivo* antenna performance is strongly affected by near-field coupling to the lossy medium and the signals levels will be limited by the specific absorption rate (SAR) guidelines.
- 2x2 **MIMO *in vivo*** enables at least two times the 1x1 data rate with SAR limited transmit power levels, making it possible to achieve data rates of ~100Mbps [to support HD video for Minimally Invasive Surgery].



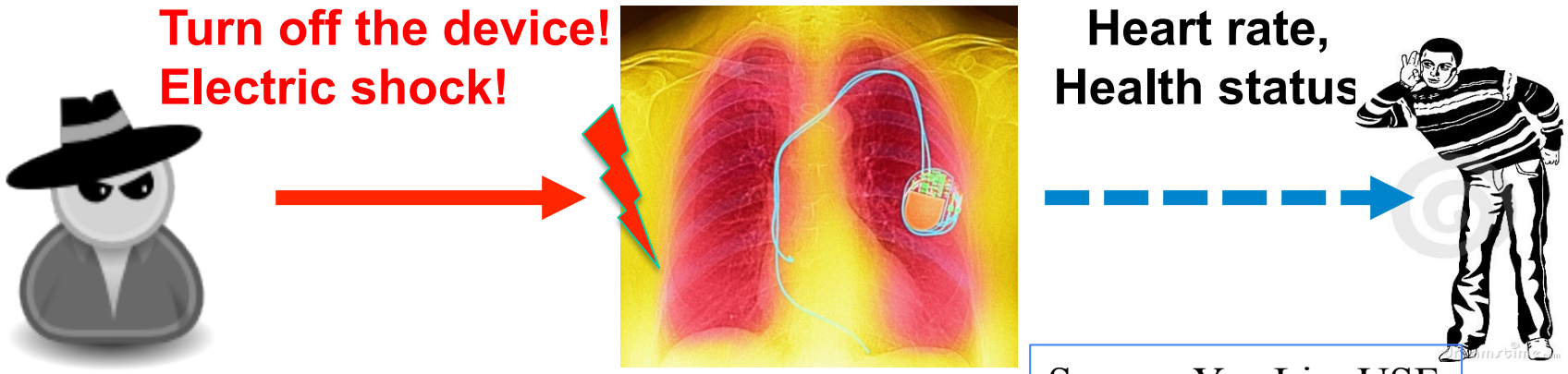
Antenna simulation setup showing locations of the MIMO antennas



SISO and MIMO *in vivo* BER performance comparison as function of the MCS index value (data rate)

Wireless Medical Devices
(Cyber-Physical) Security Threats and Countermeasures

Security Threats	Countermeasures
Eavesdropping: obtain a patient's private data by overhearing the communication of medical devices.	**Data encryption**: encrypt all communication data between medical devices. Data encryption should be energy-efficient .
Unauthorized control to medical devices --- very dangerous to a patient's life.	**Data authentication**: provide authentication information for any control command to make sure the command is sent from a trusted party.

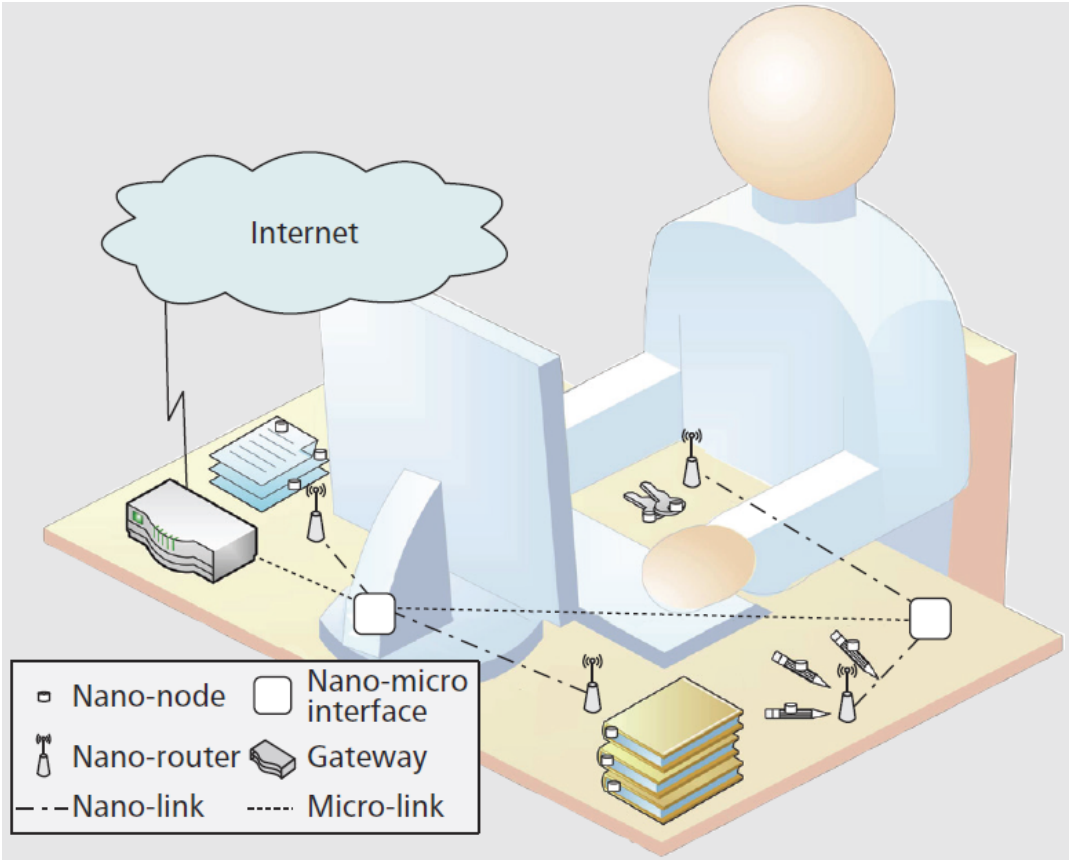


Source: Yao Liu, USF

Future Research Direction: Wireless *Internet of Nano Things*

- The interconnection of nanoscale devices [~ 100 nm] in nano networks creates a new networking paradigm referred to as the *Internet of Nano Things*.
- Major research challenges include channel modeling, information encoding, performance metrics, security, reliability, and protocols for nano-networks and highlighting the fundamental differences from macroscale channels.

- For example, classical communication paradigms need to be revised for the nanoscale, with the two main alternatives based either on electromagnetic communication or on molecular communication.



The Wireless 21st Century --- Concluding Remarks

- The Wireless Century will see the world covered with a wireless broadband "skin."
- Wireless/mobility will be integrated into every device, product, and service that is processor driven and seamlessly connected via heterogeneous internetworks.
- A second Information Age altering information access and networking.
- Advanced technologies will enable Cooper's Law to be satisfied.
- Expect many transformative wireless applications in areas as diverse as biomedical and nano-scale networks.
- The ***Wireless Internet*** will dramatically transform into a ***pervasive broadband cyber-physical network*** with heterogeneous capability, security and privacy, natural interfaces, and software agents for ease of use that extracts desired information via text, voice, images, and video.