WAMI Seminar
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Wireless Directions for the 21st Century

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

Wireless Directions for the 21st Century

Pervasive Broadband Wireless --- more disruptive than the Internet

- Market drivers for 5G and the Wireless Century
- 5G Technology: Advanced materials and devices, communications, and networking technologies will enable new architectures, services, capacity, and reliability paradigms
- What is 5G?

  - Conventional view: Pervasive Broadband Wireless (PBW), IP-based heterogeneous network, scalable, distributed, self organizing, and machine-to-machine networking (*Internet of Things*)
  - Unconventional view: extend PBW to *in vivo* wireless communications and networking ("personal" communications) for healthcare.

- Current research project: ***MARVEL*** an *in vivo* robotic Camera Module (CM) with wireless communications and control.

The Wireless 21st Century

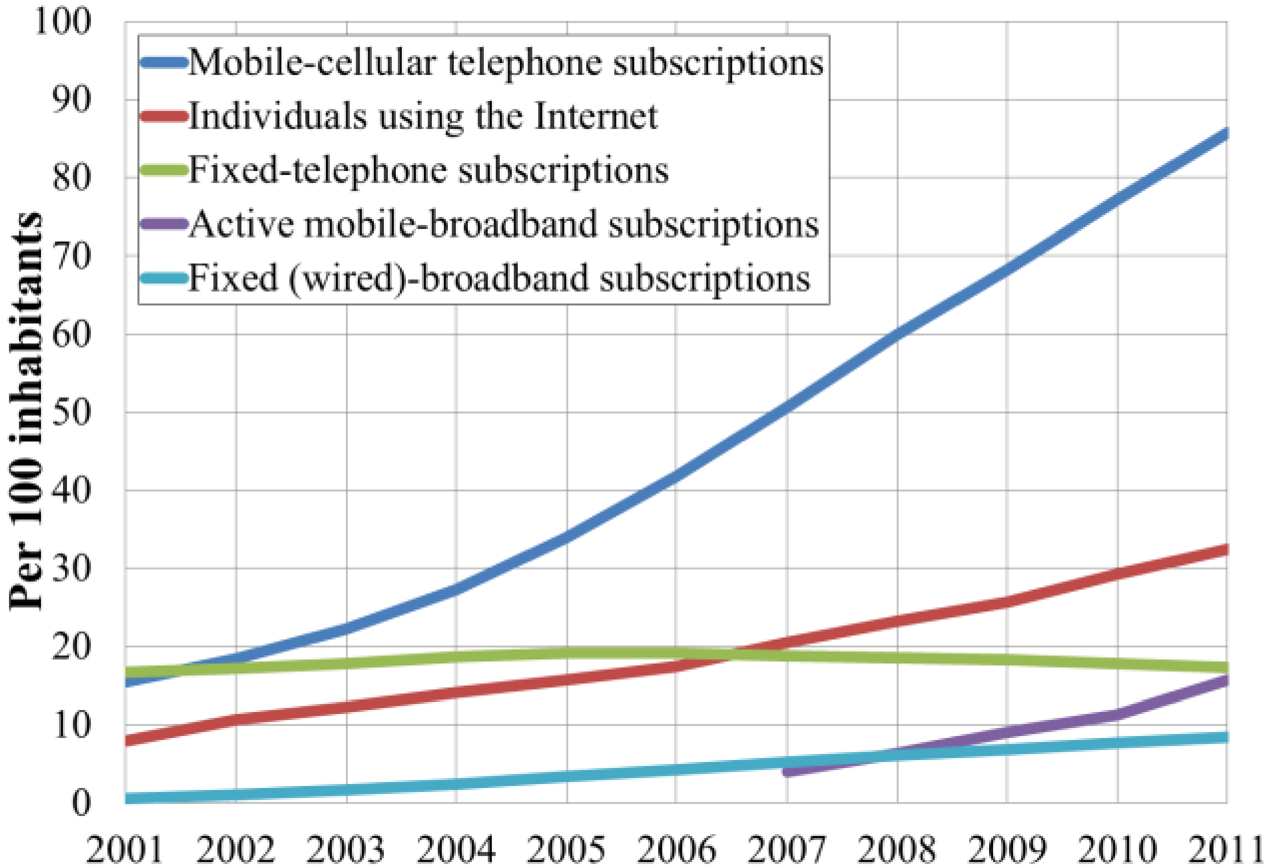
- 19th century: the invention of the telegraph and the telephone forever changed how messages moved around the world.
- 20th century: radio, TV, computers and the Internet revolutionized instantaneous processing and transmission of data. The dawn of the wireless era.
- The 21st century: A second Information Age of *pervasive wireless networking*, in which wireless networks will forever alter how people access information and will facilitate integration of the physical world with the Internet, and will facilitate the ***(Cyber Physical) Internet of Things***.

First Mobile Radio Telephone (1924)

The Wireless Century

Wireless --- Most Rapidly Adopted Technology in History

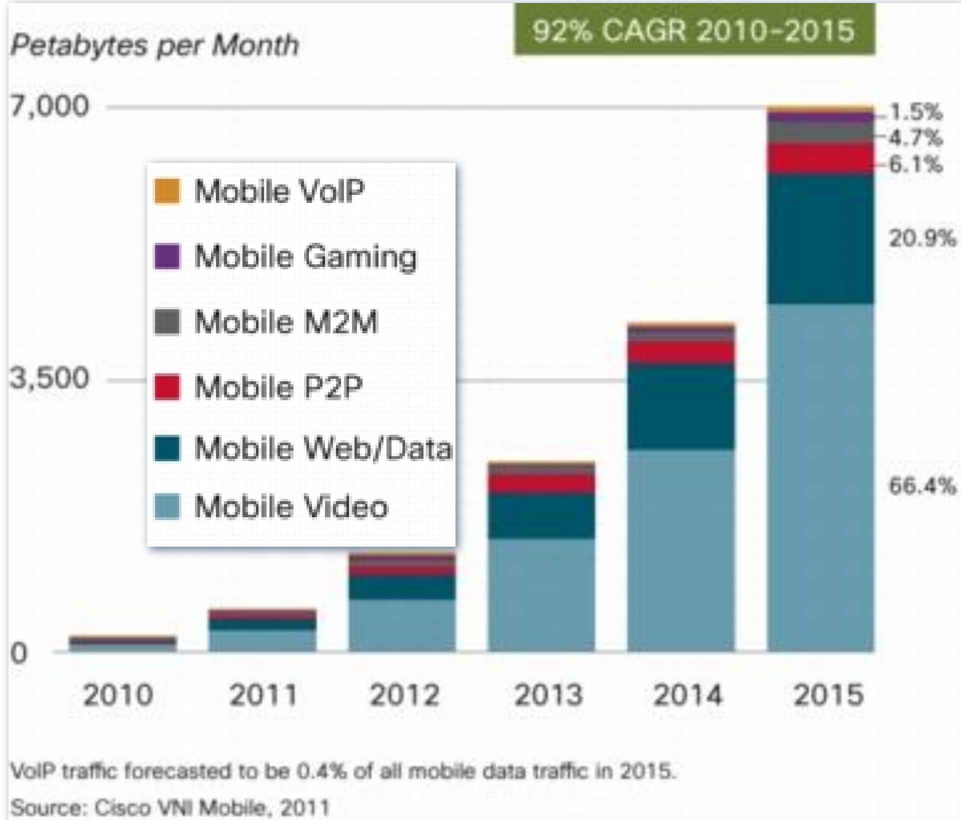
- Cellular: 6B mobiles (2011) (~87% of the world's population). Source: ITU
- In 2001 the number of mobiles exceeded the number of land lines globally.
- Mobile data traffic overtook voice traffic in 2011, which will place extremely high requirements on mobile networks today and in the future
- By 2020, 7 trillion wireless devices will serve 7B people → ***Internet of Things***



Source: ITU World Telecommunication / Information and Communication Technolofy (ICT) Indicators

Wireless Evolution: Today---*People Connecting to People*

Continuing growth since 1990
6B subscribers worldwide

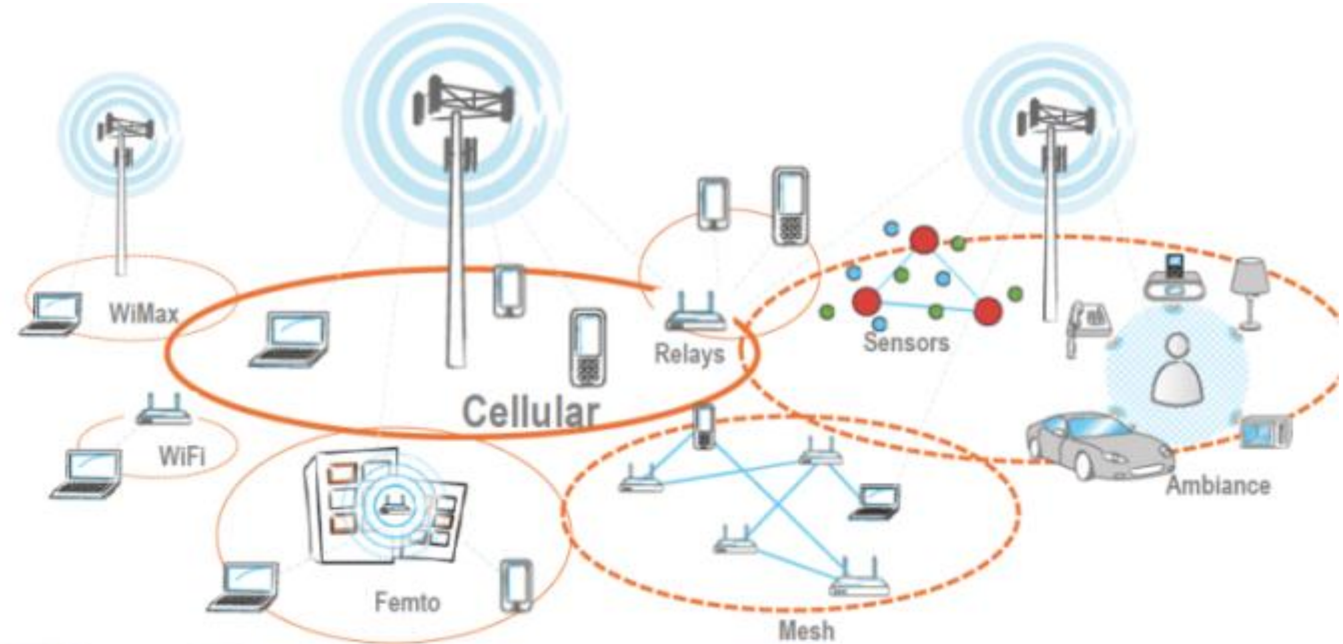


Global Mobile Data Traffic Forecast

- The confluence of user demand and proliferation of devices with advanced media capabilities is stressing the capacity, cost and performance of wireless networks and architectures.
- Growth in wireless devices is exponential in adoption rates and device capabilities.
- As new devices and applications become widely available, developers focus on producing new applications. This increases the value of the wireless network infrastructure, which in turn reinforces the demand cycle.

Wireless Evolution: Future 5G

IP-Based Heterogeneous Networks-- *People Connecting to Things*



- 5G network characteristics
  - Ubiquitous seamless connectivity for billions of subscribers/devices with trillions of connections (massive capacity increase in number of devices and traffic volume)
  - A wide range of applications, each with specific requirements and characteristics.
- 5G network challenges
  - Broadband, low latency, high capacity, and reliable coverage (scaling).
  - Quality of Service (QoS) flexibility: balancing high throughput with low power and low cost.
  - Security and privacy, preventing misuse, tampering, malware, other unauthorized access.

The Promise and Possibility of Pervasive Wireless (Internet of Things)

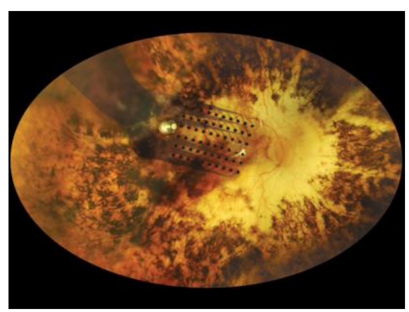
- Wireless technology is rapidly migrating from communications to a multitude of embedded real-world applications

Collision avoidance

Tracking farm animals

Wireless video surveillance

Kid finder

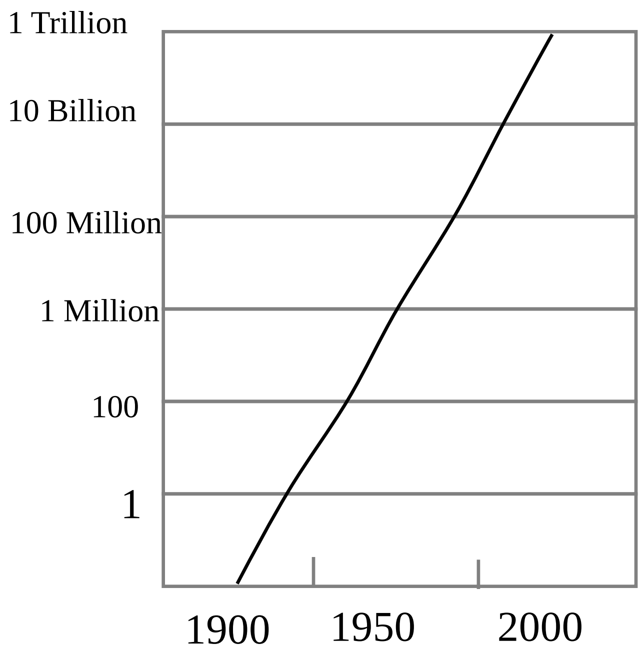


Wireless eye implant
(on market this year)
IEEE Spectrum January 2012

Implantable RFID devices (more later)

Capacity Increase in Wireless Networks is Still Possible ☺

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



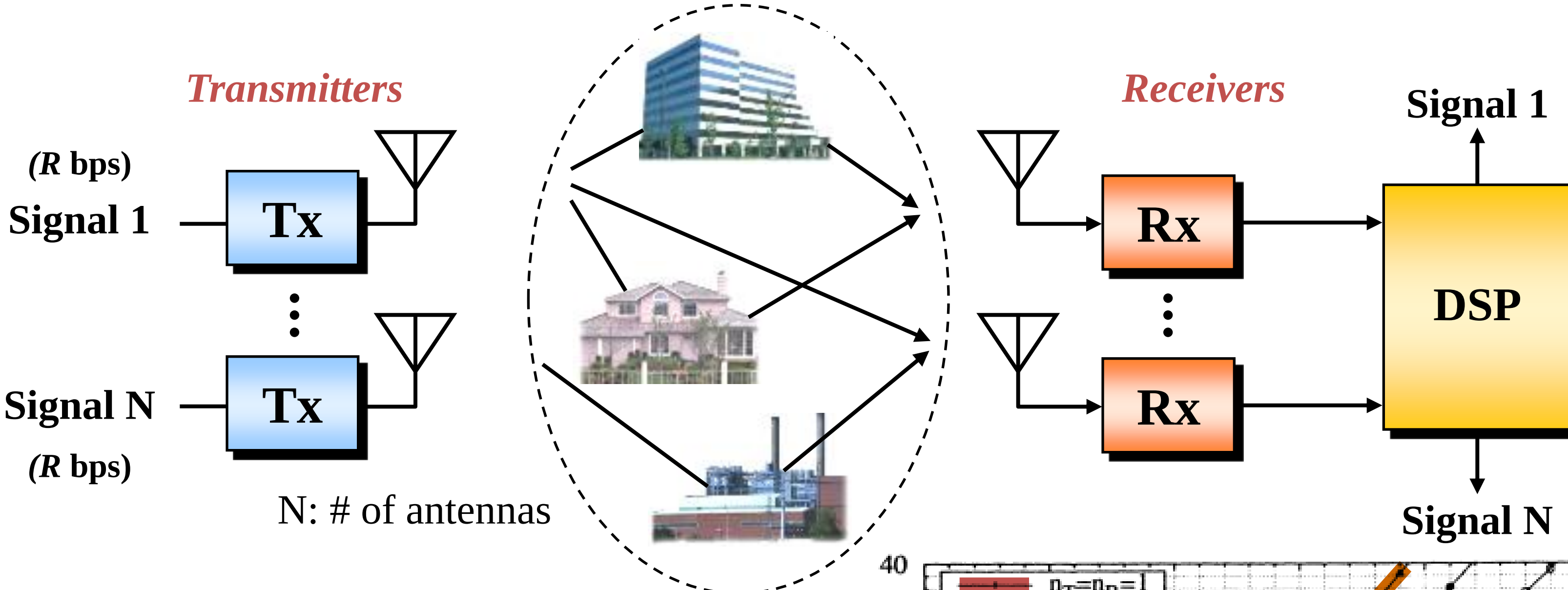
Technology Advances

- Increased spectrum (25×)
- Source compression (5×)
- Modulation and coding (5×)
- Topology: smaller cells (1600×)
  [femtocells →10]
  WiFi and other "offloads" ?
- Smart antennas-MIMO
  Theory: 4x4 MIMO → 4x SISO
  Network MIMO → 5x 4x4 MIMO
- Cognitive Radios ---?
- Self Organizing Networks ---?

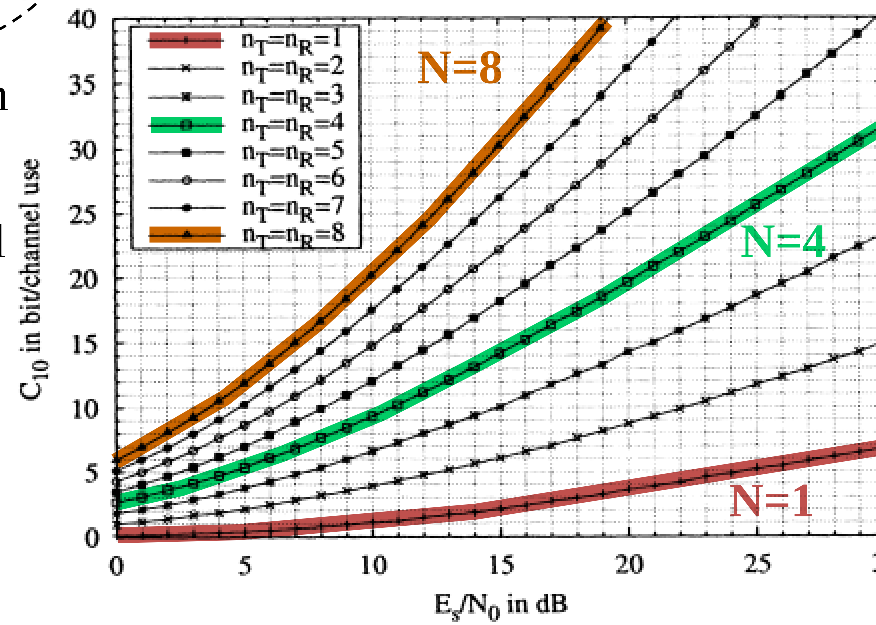
Martin Cooper, while at Motorola, conceived the first handheld mobile phone (distinct from the car phone) and led the team that developed it. He is considered the "father of the cell phone. **Richard Frenkiel** and **Joel Engel**, of Bell Labs, won the National Medal of Technology for their creation of the cellular system.

- **1954 to 1999: 10^6 times wireless capacity increase (1,000,000 = 25 × 5 × 5 × 1600)**
- **Femtocells promise at least another factor of 10**
- **Another big multiplier expected from MIMO (~20) and cognitive radios**

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

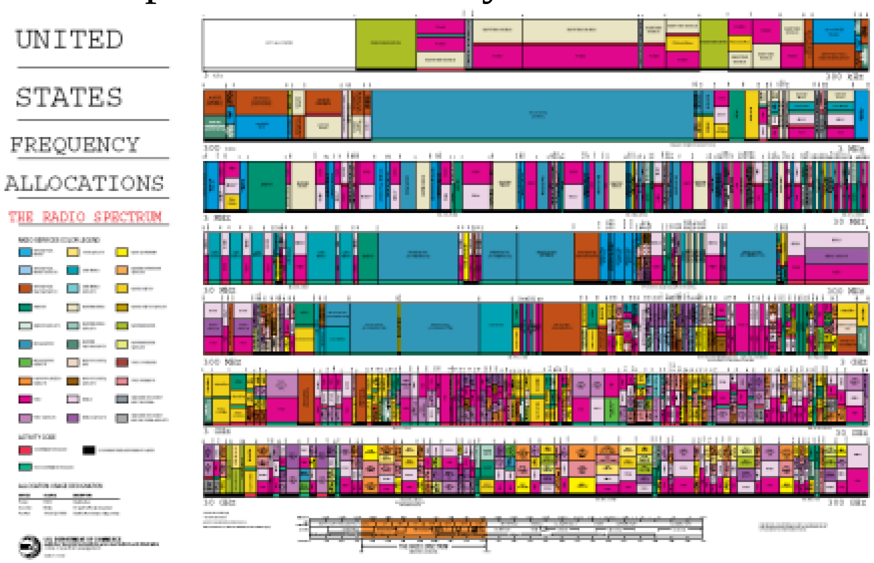


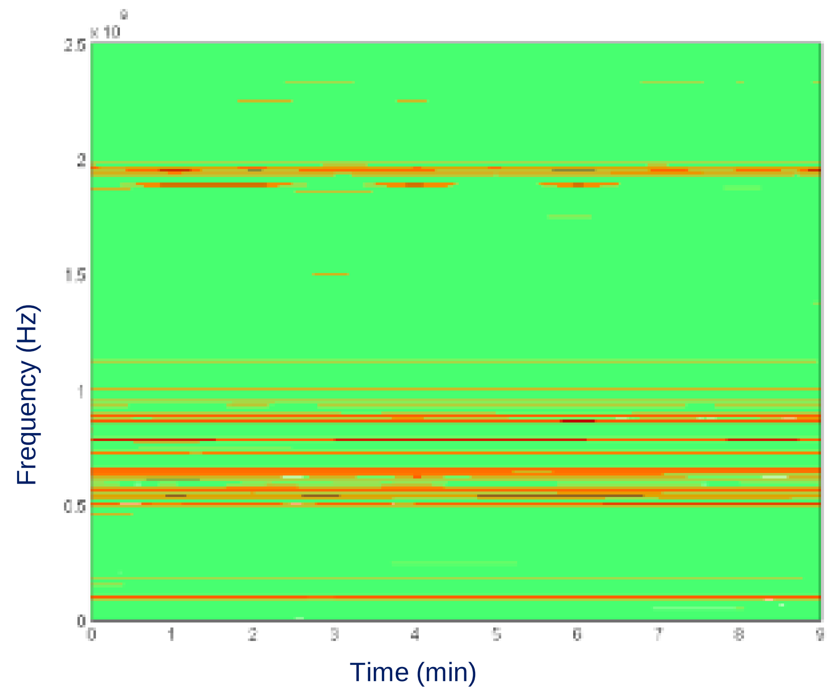
- Multipath scattering scrambles the signals -each receiver has a different combination of signals
- DSP algorithm de-scrambles the received signal to reproduce original signals and deliver the energy to the target receiver.
- Capacity increases ~ linearly with number of antennas with no increase in total power
[MIMO = multiple input multiple output]



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



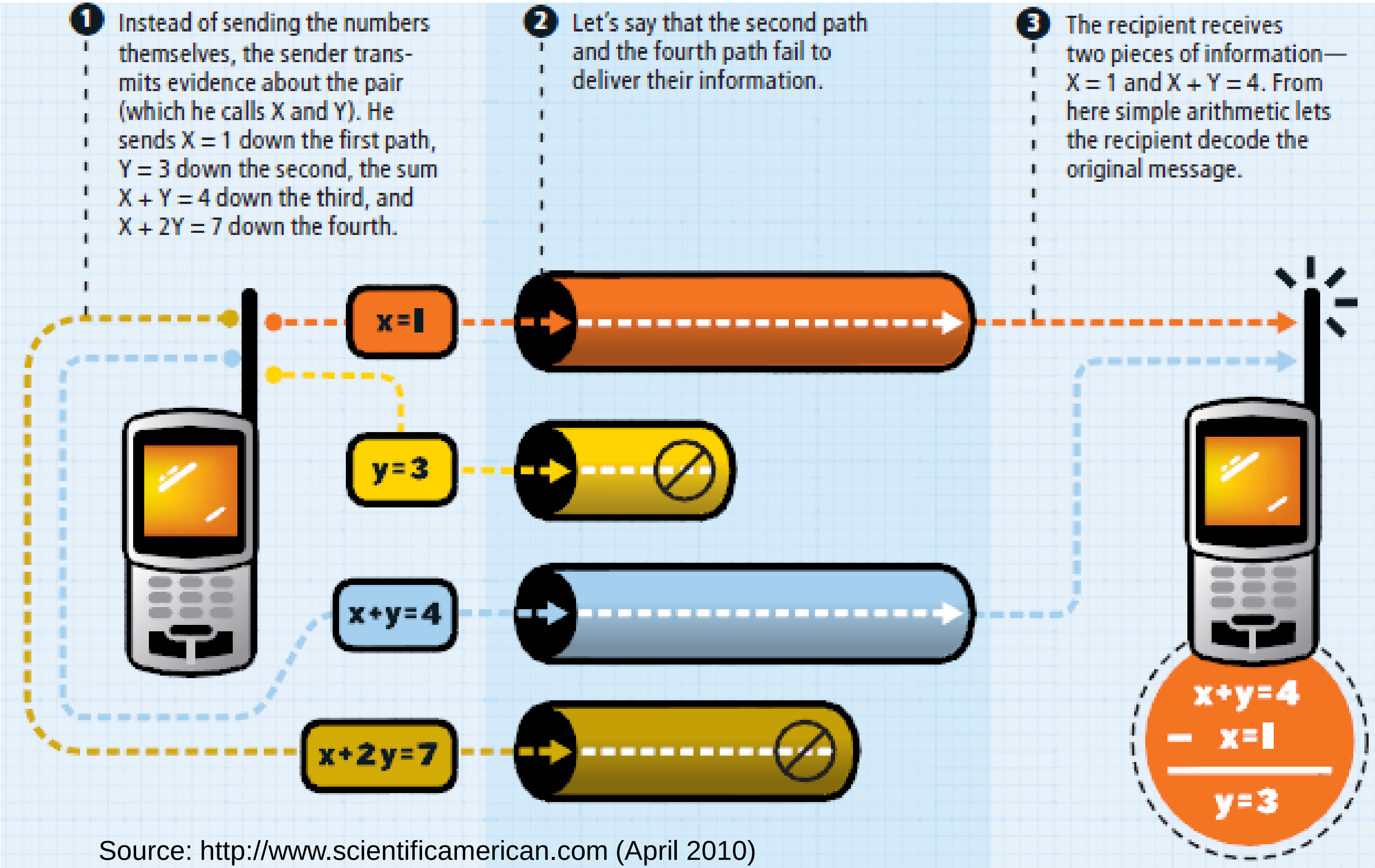


IEEE 802.22 WRAN (R=Regional) uses cognitive radio techniques to allow sharing of geographically unused spectrum allocated to the television broadcast service, on a non-interfering basis, to bring broadband wireless access to hard-to-reach low-population-density areas.

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.)

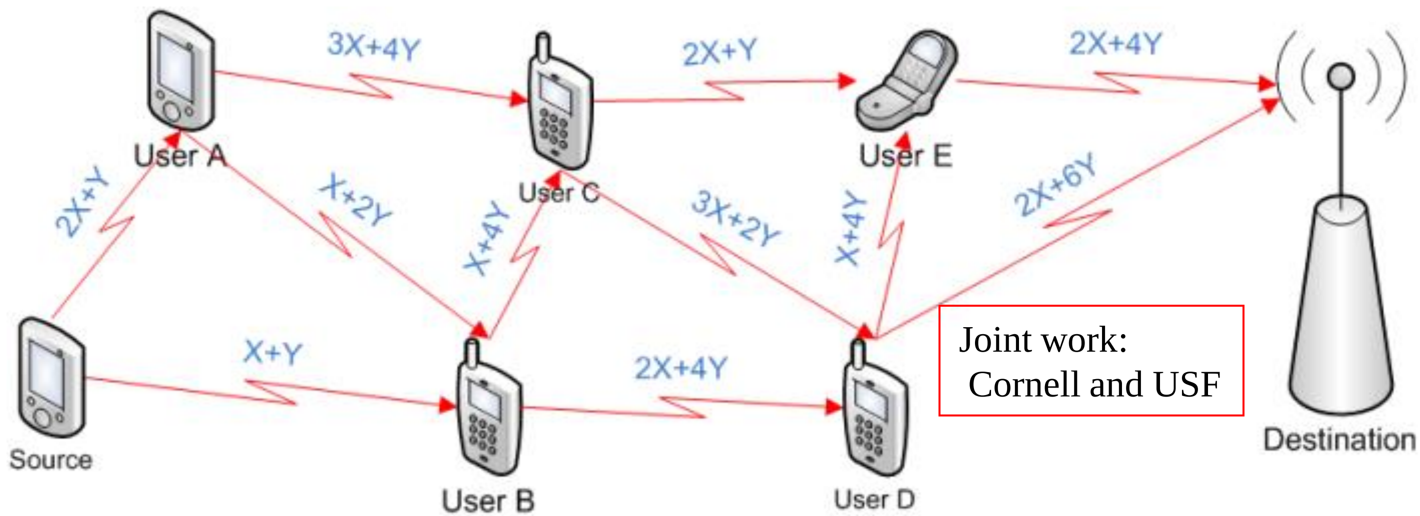


Source: http://www.scientificamerican.com (April 2010)

Advanced Technology: Cooperative Network Coding

Combining Cooperative Communications and Network Coding

- Benefits (power and resource limited *in vivo* devices)
  - Improved probability of successful transmission → network reliability
  - Reduce the number of packet re-transmissions
  - Reduction in transmission energy requirements
- Issues
  - Energy consumption (transmission power and processing power)
  - End-to-end delay due to network coding operations and cooperative cooperation
    - Each node decodes the received signals, creates an innovative packet using the received signals and transmits it towards the destination
  - Effects of mobility such as fading correlation, dynamic behavior of the cooperative cluster nodes, capacity, and security need to be studied

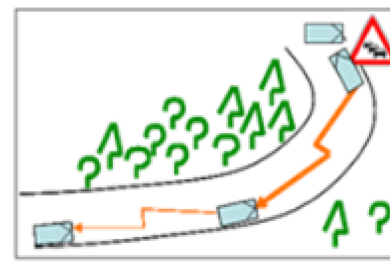


Joint work:
Cornell and USF

Emerging Wireless Application: Vehicular Systems

IEEE 802.11p – **W**ireless **A**ccess in the **V**ehicular **E**nvironment (WAVE)
WAVE = Dedicated short-range communications (DSRC) at 5.9 GHz

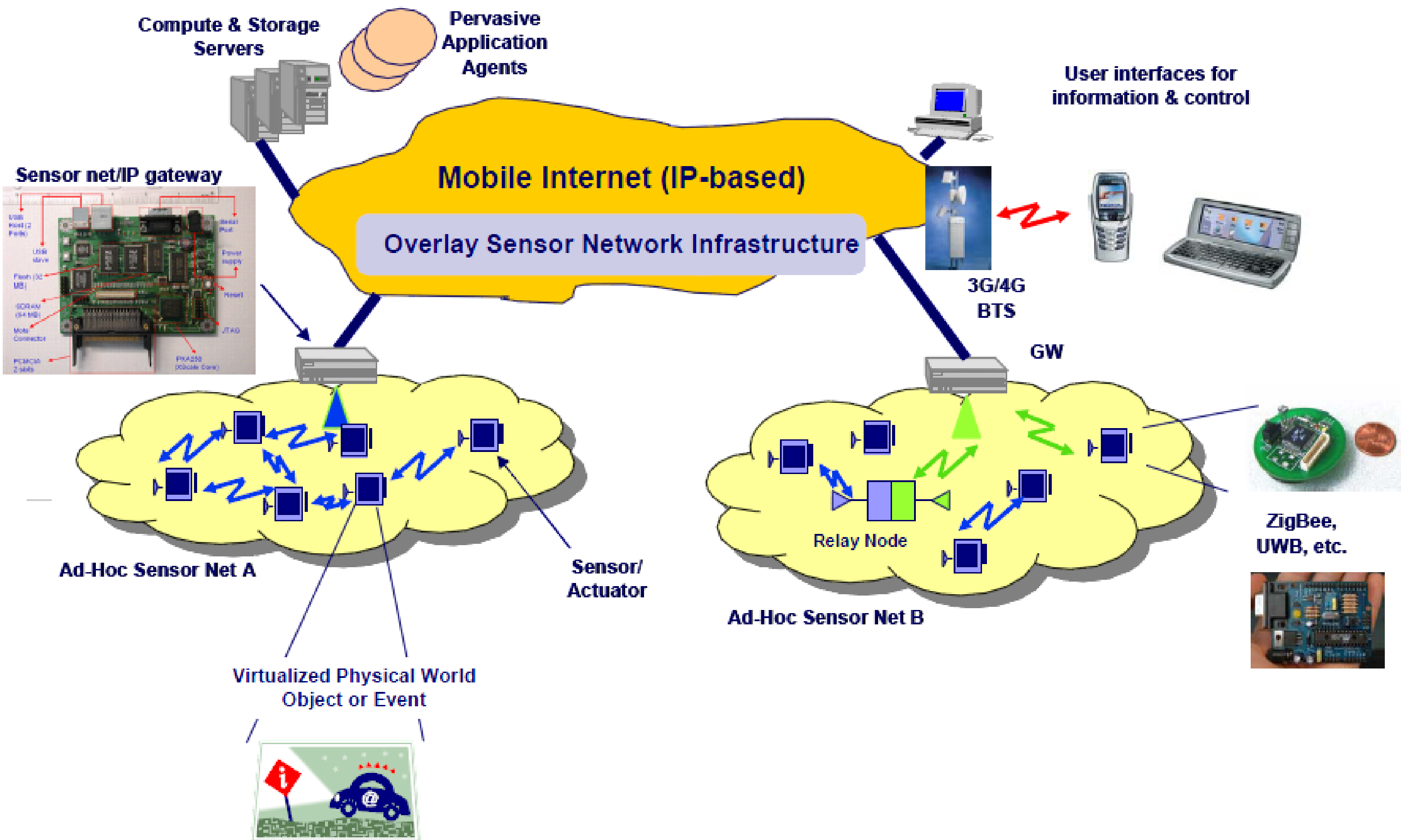
Telematics (maps, communication and networking) will play an increasingly important role in safe and efficient driving.



- Obstacle behind a bend
- Reduced visibility
- Slippery road surface
- Road work

Communications	simple sensors	complex sensors + telematics	telematics
Traffic information	local forecast	regional forecast	wide-ranging forecast

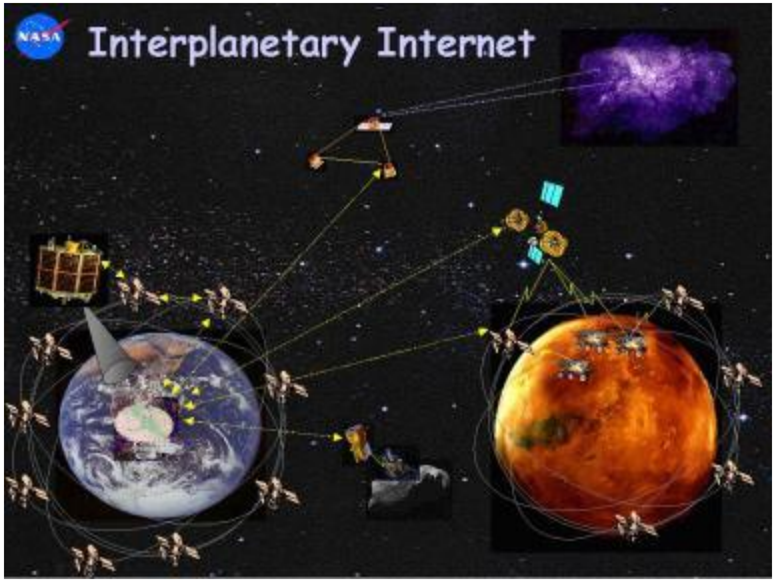
Emerging Wireless Application: Sensor Networks



Sensor and RF ID network scenarios involve:

- Large scale with limited CPU speed and transmit power→ more intelligence
- Intermittent connectivity, low-speeds, *ad-hoc* modes
- Context sensitivity: location and content-awareness
- Part of the mobile internet seamlessly connected via IP enabling interworking and interoperability between heterogeneous networks with enhanced security and user privacy

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



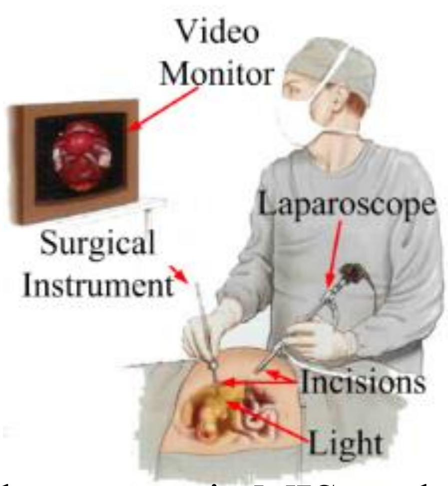
Attenuation: 90dB below GEO satellite
Delay: 10-20 minutes to/from Mars (due to differences in orbital characteristics)
Noise: celestial events, atmospheric conditions, and other spacecraft

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

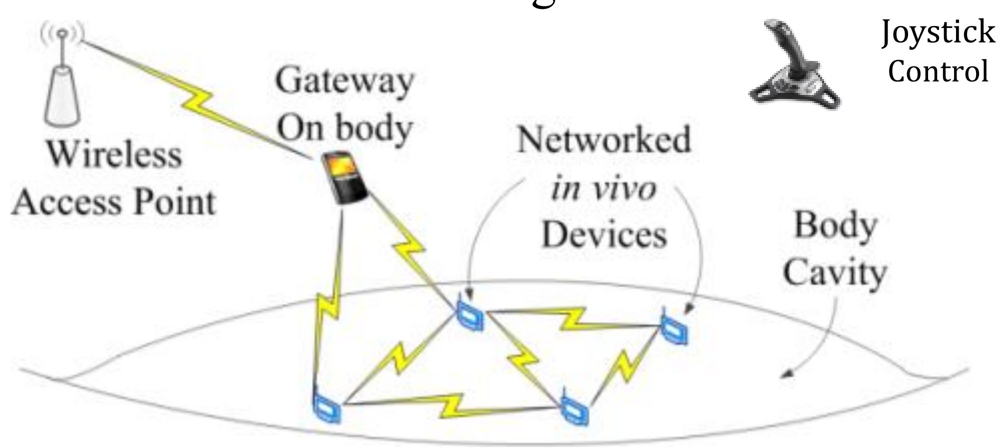
- Planetary internets, in-space routing, and interplanetary gateways --- interplanetary long-haul protocol with layered architecture
- **TCP in space – SCPS** (Space Communications Protocol Standard).
- IP-like protocol suite tailored to operate over long round-trip flight times
- Email-like behavior
- 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 "5G" Vision "Inner Space"---Advancing Minimally Invasive Surgery (MIS) via Wirelessly Networked Devices

- An unconventional view is considering ***in vivo*** **(**inner space) as a new rich domain for the application of wireless technology to create to a cyber-physical network facilitating wirelessly enabled healthcare. This can be viewed as in-body Wireless Body Area Network (WBAN---IEEE 802.15.6)
- The envisioned network is comprised of a plurality of wireless communicating devices --- such as imaging, sensors and actuators, power sources, "cutting" tools (physical, optical, ultrasound, etc.) and other ancillary devices that are inserted into a single port with wireless control and I/O.
- The devices are electronically addressable and controllable and form a distributed wireless network whose capabilities greatly exceed that of any individual device.
- The ***MARVEL*** Camera Module (CM) is the first device in realizing "the vision."



Current laparoscopic MIS technology



Vision: *In vivo* networked MIS

The *MARVEL* Camera Module
The First Step in Creating a New MIS Paradigm

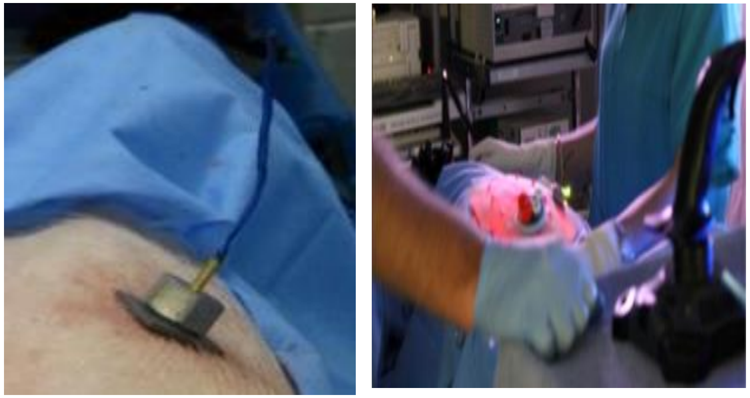
Goal: Advance MIS to the next paradigm by enabling safer, faster, and less-invasive surgery on par with open-cavity surgery without the negative aspects.

***MARVEL*: Miniature Advanced Remote Videoscope for Expedited Laparoscopy -** a robotic wireless camera module attached within the operative cavity and actuated by tiny motors as the first step in advancing MIS with the following benefits

- Removes the need for additional incisions, making trocar ports that were used by cabled laparoscopes available for surgical tools improving the surgical procedure
- Gives surgeons a full hemisphere range of view.
- First step towards realizing a network of distributed devices for "cyber-physical" surgery.

Laparo-Endoscopic
Single Site (LESS) MIS

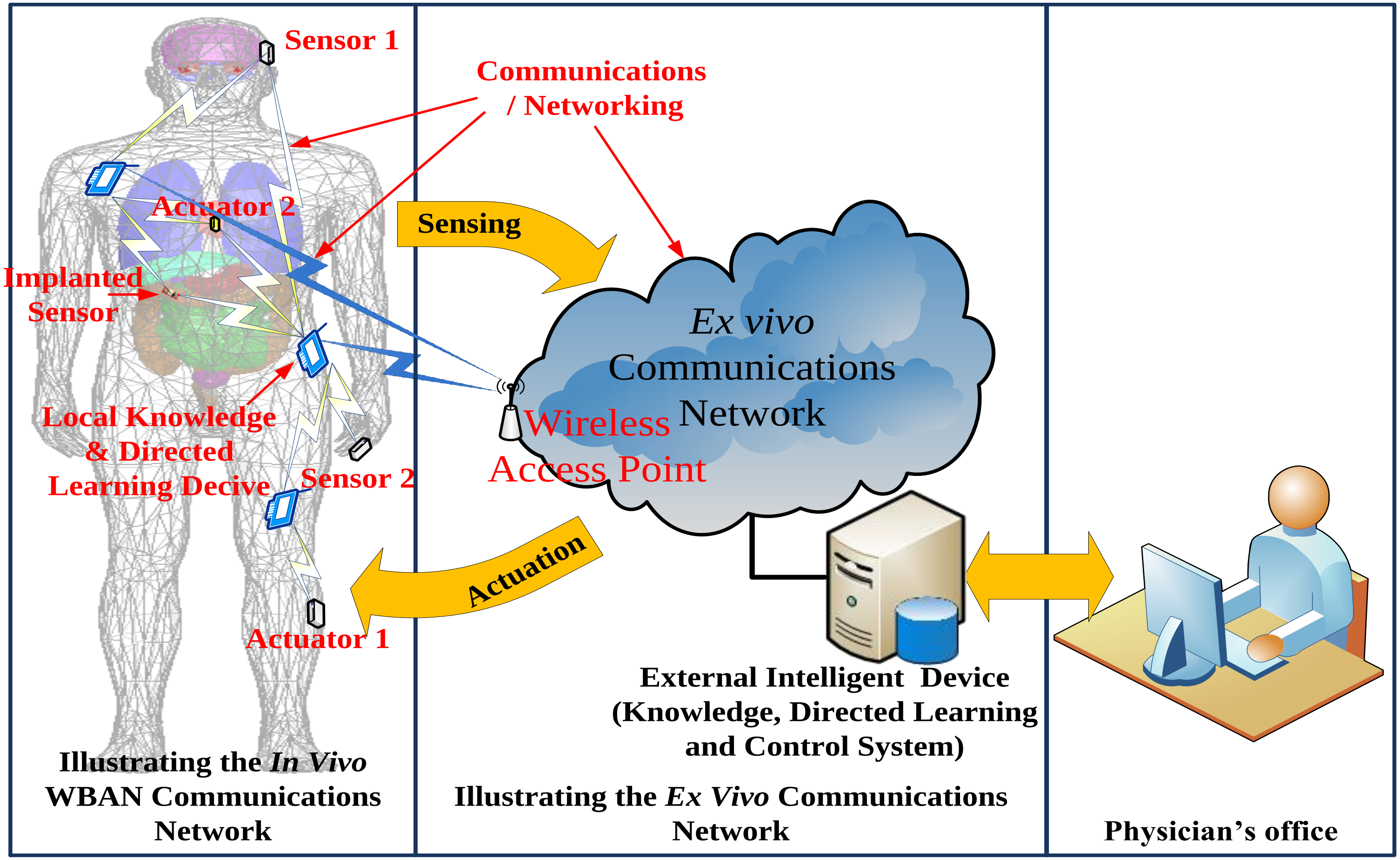
MARVEL CM
research platform



Vivarium experiment
(porcine subject -2012)

Even Bigger Picture: Wireless Enabled Healthcare System

•Wireless technology has the potential to synergistically advance healthcare delivery solutions 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 Wireless Research Areas

Our current areas of interest

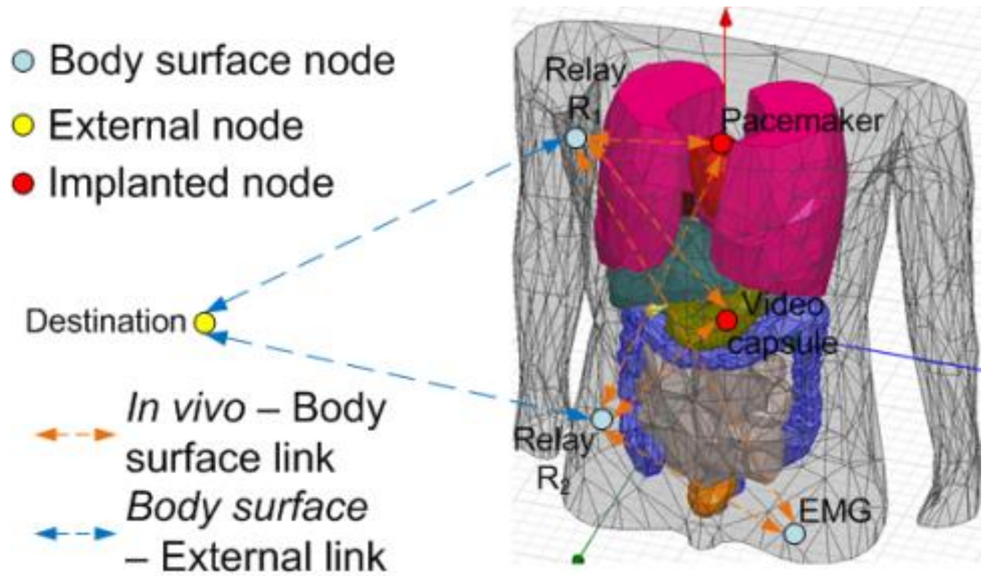
- Sensing and actuation at the micro/nano/molecular level:
  - Low power and power scavenging, biocompatibility, and multi-sensor coordination: Sensors and actuators of multiple length-scales whose functionality is enabled by a deeper understanding of human physiology, material science, and nano/micro-manufacturing.
- New communications and networking paradigms for devices more limited, from a communication and computing standpoint, than any devices that have ever been networked by human-created means:
  - Novel *in vivo* channel models have to be created to facilitate creation of new communications protocols accommodating the limitations of the embedded devices; concurrently, research should be performed at the molecular level for novel biologically inspired communications paradigms.
  - Cooperative networking protocols to optimize energy consumption, throughput (goodput), and reliability on *in vivo* environments.
- New approaches to privacy and security for devices of limited processing capabilities and developing a scalable architecture for data management
  - This can be achieved by leveraging the hierarchical structure of the network from ultra-simple *in vivo* sensors to high-powered servers that store, process and mine medical data.
  - Algorithms for personal privacy for *in vivo* and body area network devices, asymmetric protocols, and probabilistic authentication mechanisms should be explored.
- New knowledge and learning systems that distill complex datasets into actionable information.
  - To achieve this, research to identify machine-learning techniques that extract meaning from next-generation personal health records consisting of streams of physiological, behavioral and contextual data should be conducted.

In Vivo Communications and Networking Research

- Our experience in wireless communications and networking should significantly improve the capabilities and performance of wireless *in vivo* biomedical systems.
- Our research focus is on:

1. Exploring the *in vivo* to on-body communication channel based on detailed simulations and experimental channel measurements. Specifically, we explore the wideband channel response for communication using electromagnetic propagation (RF). Different on-body topologies are considered, including devices that minimally penetrate the body, and those that reside on the body.
2. Low complexity asymmetric communication and distributed networking protocols that have most of the processing complexity in the external receiver, without significantly degrading performance. This approach is necessitated by limited complexity sensors.
3. Cooperative networking architectures for reliability and to accommodate power limitations.

Simulation Software used is ANSYS HFSS 15.0

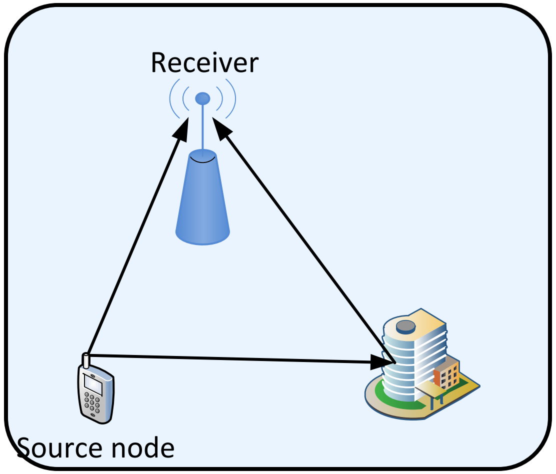


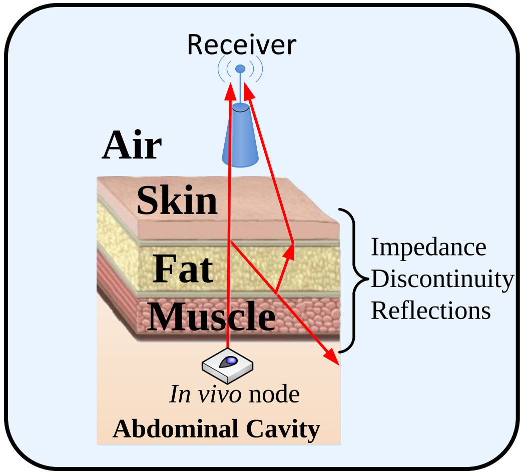
In vivo wireless communications and networking

In vivo Wireless Channel Characterization and Signal Processing

- Well-studied wireless environments include: cellular, WLAN, and deep-space
- The *in vivo* channel is a "new frontier" in wireless propagation and communications
- Many new research issues:
  - Media characterization and communications optimization
  - New communications, networking, and security solutions for embedded devices of limited complexity and power
  - Near-field effects (at low operating frequencies) and multi-path scattering (at high operating frequencies) with propagation through different types of human organs and internal structures between closely spaced transmitter and receiver antennas.

Classic Multi-Path Channel



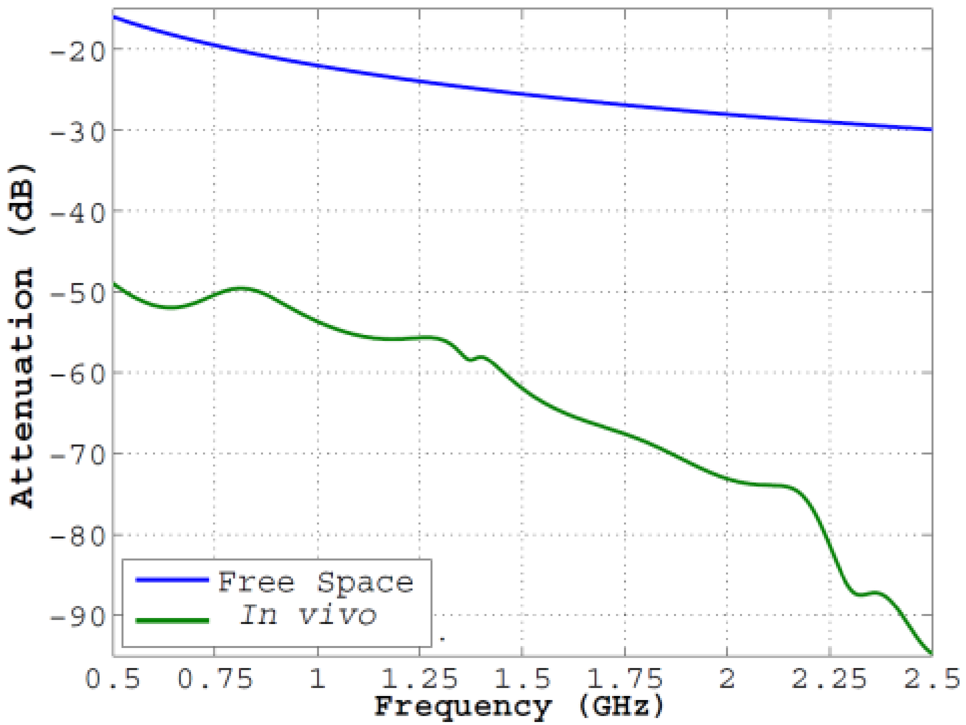


In Vivo Multi-Path Channel

Characterizing *in vivo* wireless propagation is critical in optimizing communications and requires familiarity with both the engineering and the biological environments.

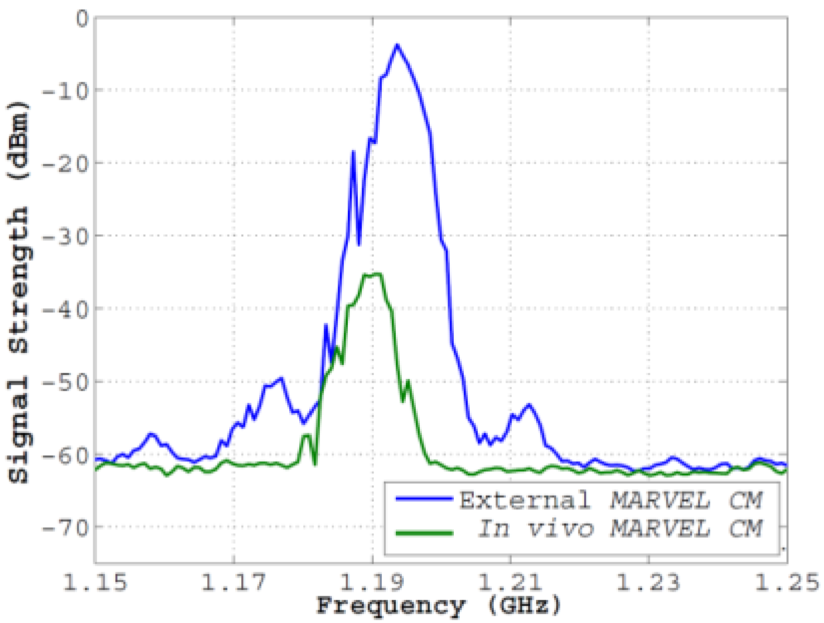
In Vivo Attenuation: Free Space and *In Vivo* Simulation

- Simulated attenuation in HFSS, where a signal travels from a monopole placed inside the abdomen to an external monopole with a 30 cm transmission path (9cm of the path are inside the body).
- Antenna effects have been removed in software by simultaneously matching each antenna port impedance in Agilent ADS.
- Signal loss shown in plot for *in vivo* attenuation and free space loss.
- Attenuation drop-off rate is not constant and is seen to increase more rapidly above 2.2 GHz.

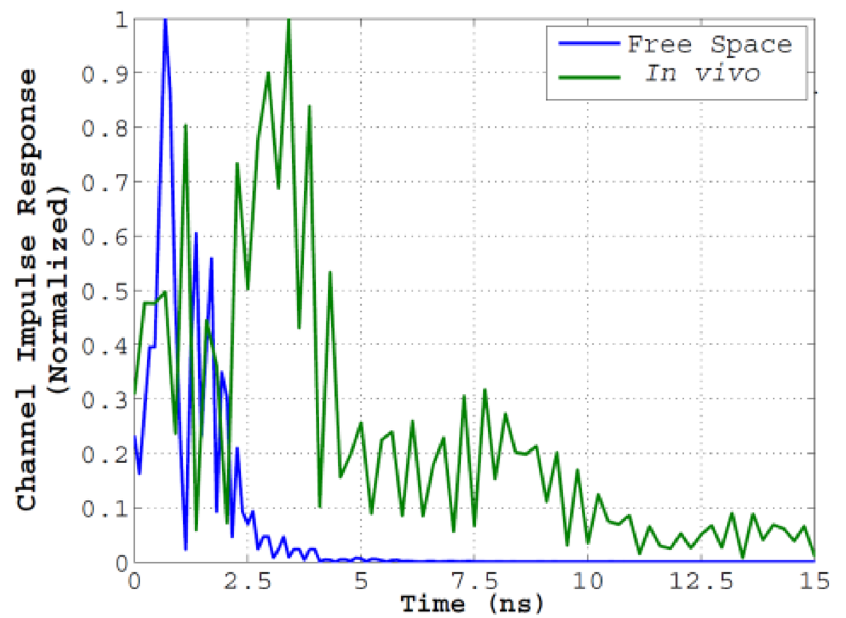


In Vivo Attenuation: Vivarium Results

- MARVEL CM (Camera Module) *in vivo* and external measured signal strength.
- The carrier frequency was ~1.2GHz and the video signal bandwidth is 5MHz. The FM modulation bandwidth was about 11MHz. Transmitter was located inside the abdominal cavity. The receiver was placed ~ 0.5m from the transmitter in front of the abdomen.
- It can be seen that there is about a 30 dB difference in signal strength between the *in vivo* and the external measurement, which shows that there is approximately 30 dB of attenuation through the organic tissue. This seems to be in good agreement in what is shown in the prior chart.
- *In vivo* time dispersion is much greater than expected from the physical dimensions.



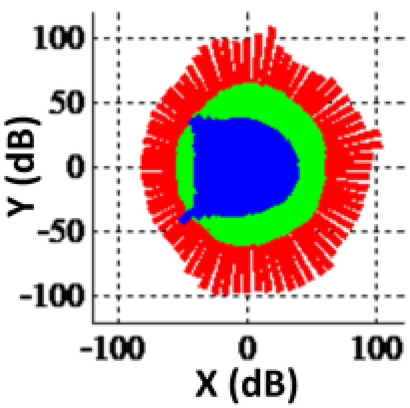
MARVEL Camera Module (CM): Vivarium Experiment

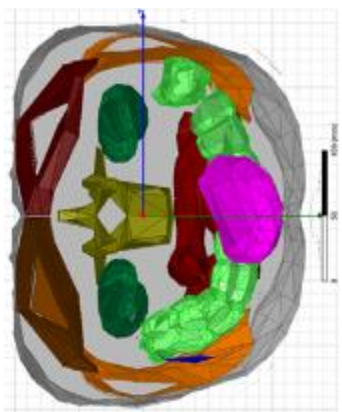


Normalized channel impulse response for the human body for free space and scattered environments.

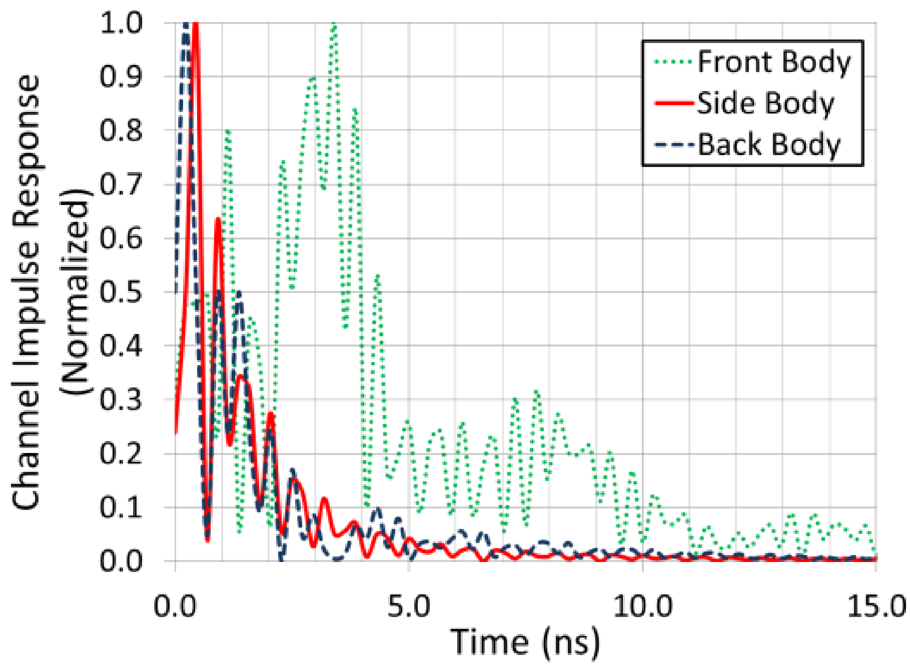
In Vivo Wireless Channel Directional Properties

- 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)
- Lower left figure: the path loss is a function of the frequency and not homogenous around the body. Moreover, the angular dependency is noticeable for 500 MHz as in the right figure (blue curve).
- The distance between transmitter and receiver is 30 cm with center frequencies of: Red=2 GHz, Green=1 GHz, Blue=0.5 GHz





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

Systematic Approach To *In Vivo* Parametric Channel Modeling

1. Use software to simulate the RF channel. Such simulations are key to providing “ball-park” results and intuition before experimentally sounding channels.
2. The experimental channel sounding, with phantoms and live models, will then provide raw data samples of the *in vivo* channel itself and lead to useful datasets.
3. More useful are parametric models will iteratively evolve based on the simulations and experimental measurements. Such models will vastly improve the ability to pursue endeavors in the biomedical device field specifically with regards to wireless communications from *in vivo* devices
4. Given data from simulated, measured, and modeled channels, a thorough analysis includes benefit/cost behavior of implanted devices, performance as a location of devices in the body, power consumption, and degree of invasiveness.
5. Once point-to-point communications are well understood, the possibilities of networking in vivo nodes is examined.
6. Finally, the modality/scenario combinations are tested in phantoms and live models (porcine subjects).

Candidate Parametric Channel Model

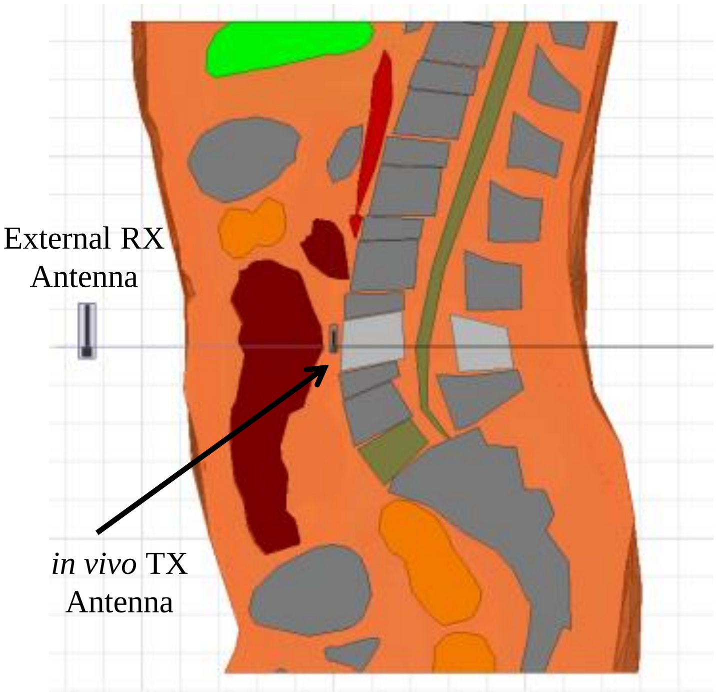
$$R(t,\tau,\varphi)=\sum_{i=1}^{L}\alpha_i(t,\varphi)e^{\theta_i(t,\varphi)}h\big(t-\tau_i(t,\varphi)\big)e^{j2\pi\Delta f_i(t,\varphi)t}$$

In vivo verification

SAR and BER for *In Vivo* Communications

- WBANs must transmit at low power to protect the patients against harmful health effects associated with the radiofrequency (RF) emissions as well as to extend the node's battery lifetime.
- The specific absorption rate (**SAR**) is the rate at which the RF energy is absorbed by a body volume or mass and has units of watts per kilogram (W/Kg).This sets a limit on the transmitted power.
- The SAR limit is frequency dependent, since it depends on the conductivity of the material, which changes with frequency in human organs/tissues

- 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 of the.
- 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 figure shows the location of the *in vivo* and *ex vivo* antennas for our software-based experiments.

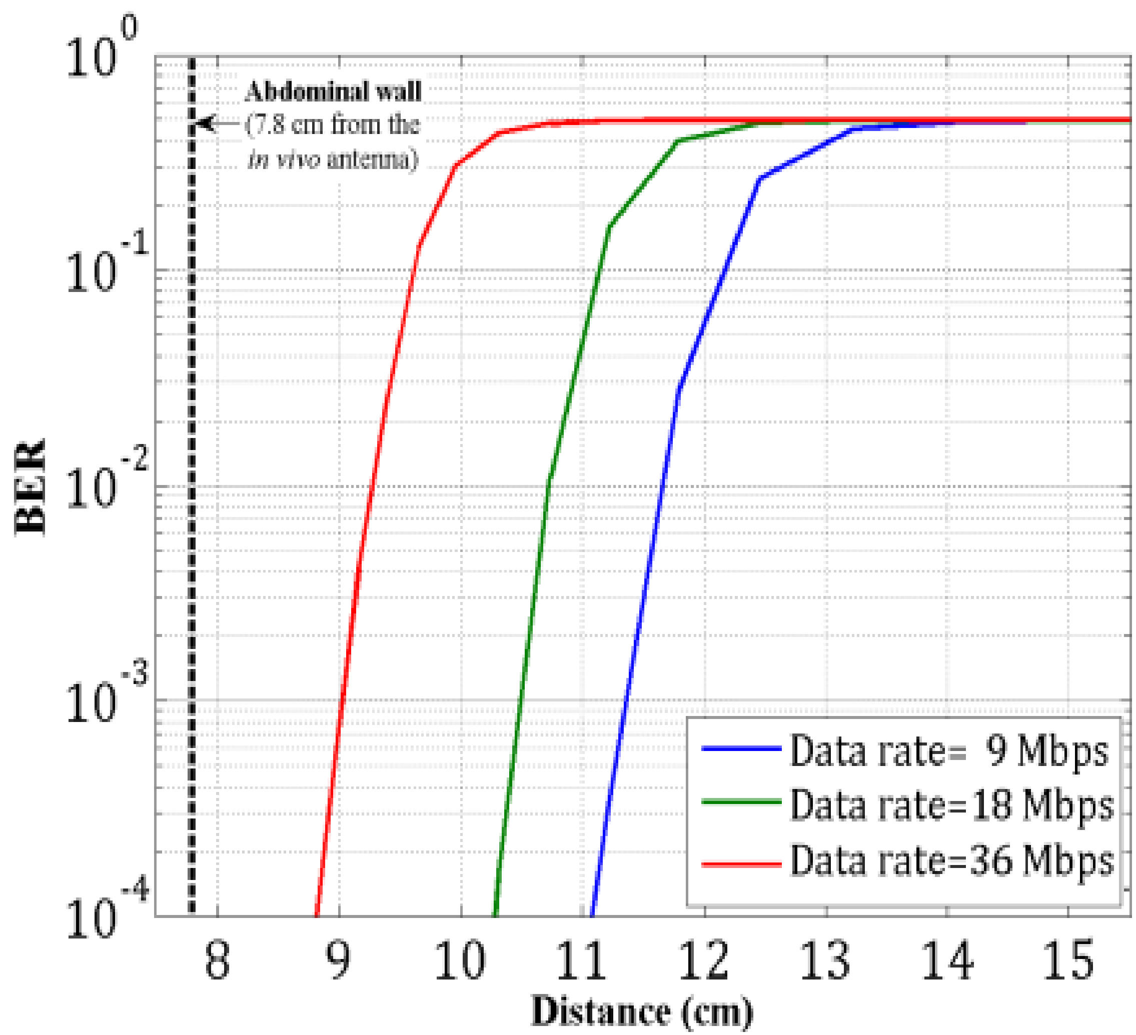


SAR and BER for *In Vivo* Communications

Frequency (GHz)	Max Local SAR @ Transmit Power of 0.412 mW (W/kg)
2.402	1.585
2.412	1.562
2.422	1.539

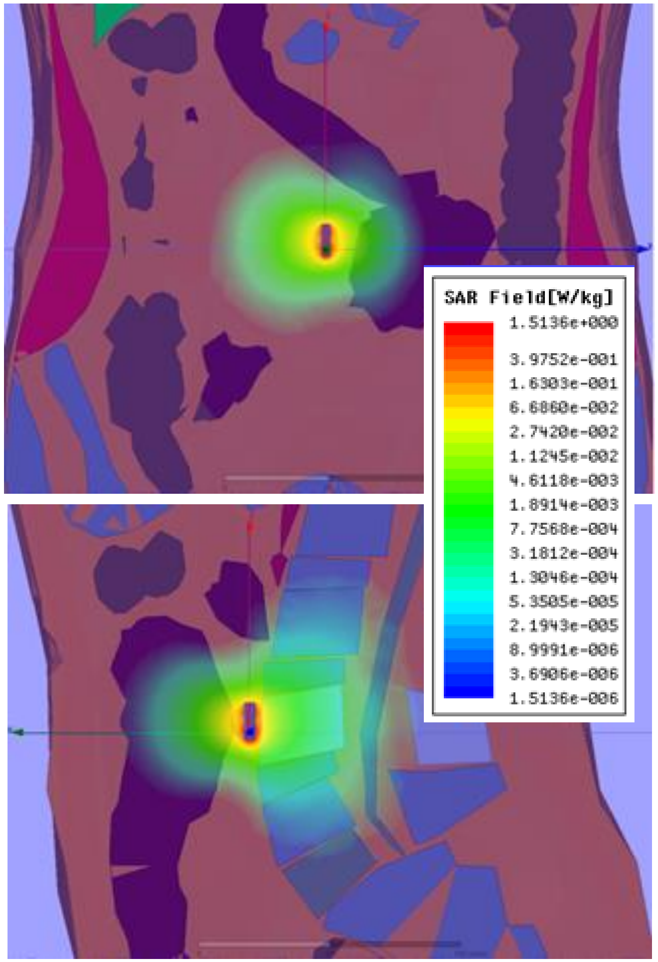
- Above table shows simulated SAR levels for different frequencies in the 2.4 GHz band. These values were found in HFSS using the maximum allowable transmit power (0.412 mW) that assures the SAR limit of 1.6 W/kg across the communication band is met.
- The *in vivo* antenna is located 7.8 cm from the abdominal wall (~laparoscopic surgery). Distance to the external antenna for BER calculations was varied between 8.8 and 17.8 cm.
- With this TX power we simulated a 802/11g OFDM transceiver using a Gaussian noise level of -101dBm, the thermal noise with 20MHz BW.

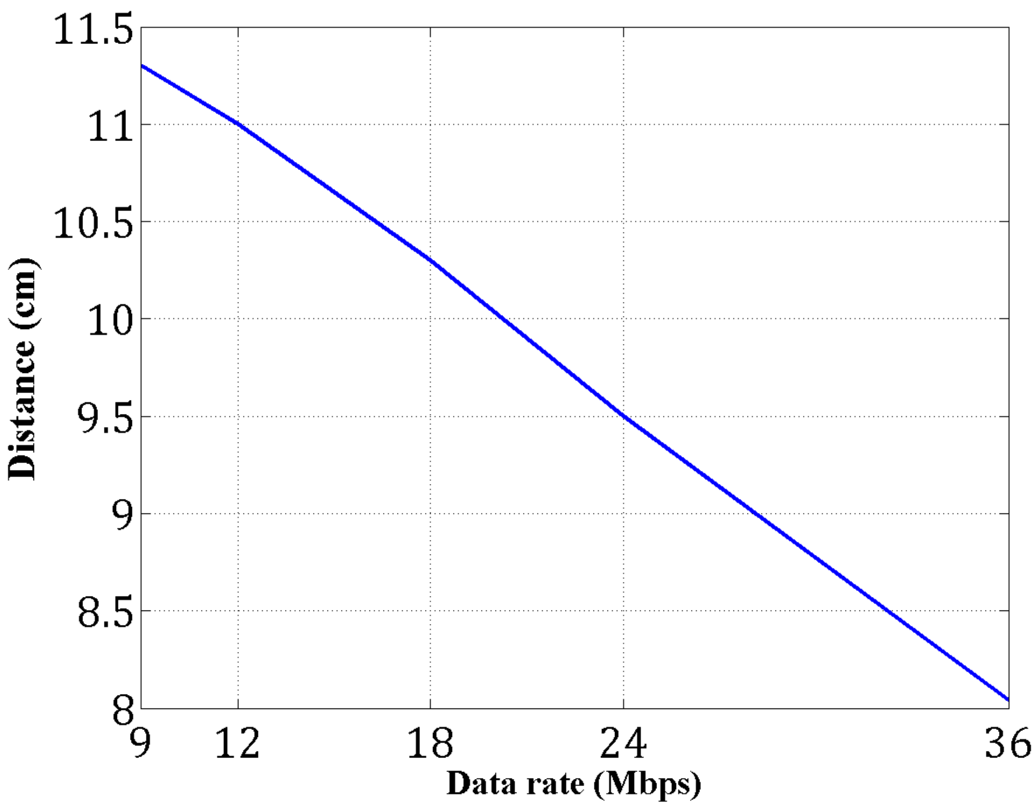
- The figure below shows the BER as a function of distance between the *in vivo* and *ex vivo* antennas.



SAR and BER for *In Vivo* Communications

- The left figure shows the front (top) and side (top) cross-sectional views of the total SAR generated at 2.412 GHz inside the abdomen at a transmit power of 0.412 mW.
- Achievable distance, as a function of bit rate, between *in vivo* and external antennas for a BER of 10^{-6}. is shown in the left figure.

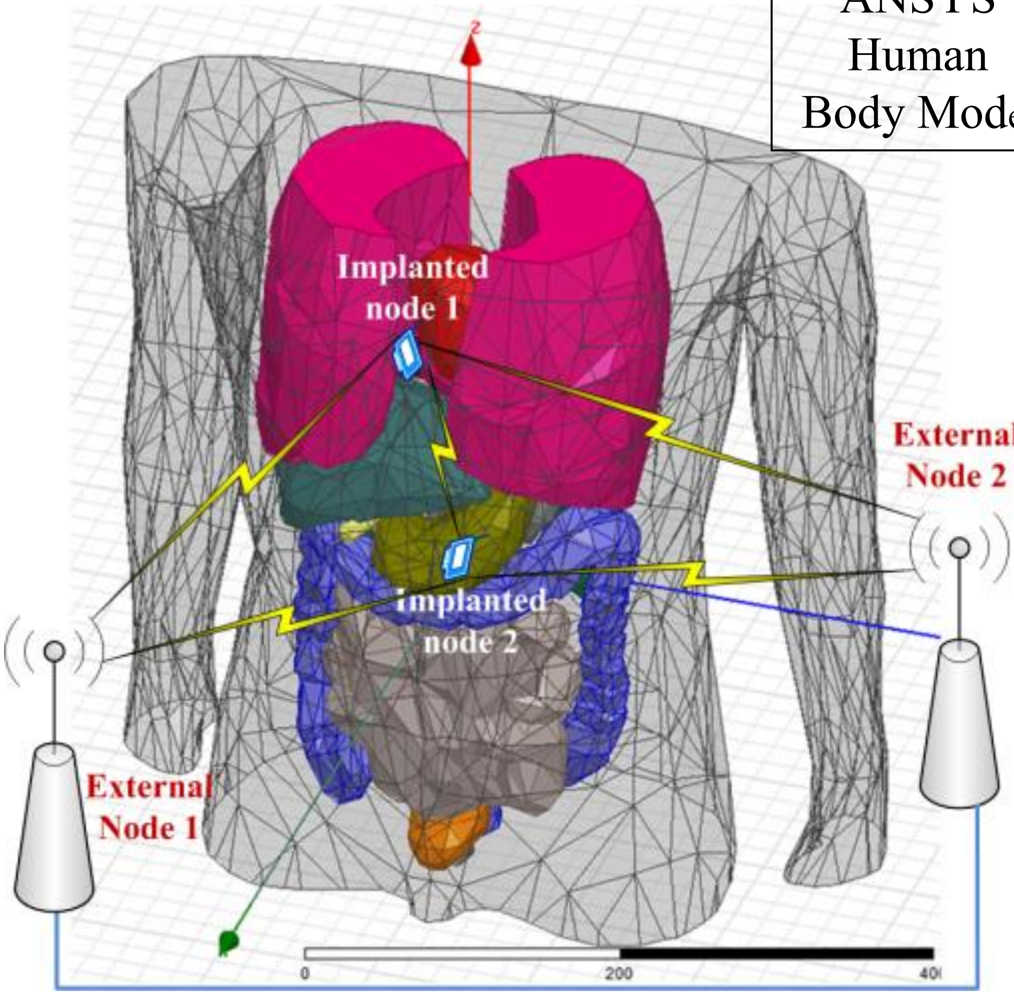




Wireless Body Area Network (WBAN) Research at USF

- ***In vivo*** nodes are limited from communication, power and computing standpoints. This drives several research directions:
- ***Asymmetric communication and networking protocols*** that transfer some of the "intelligence" of the *in vivo* nodes to external nodes.

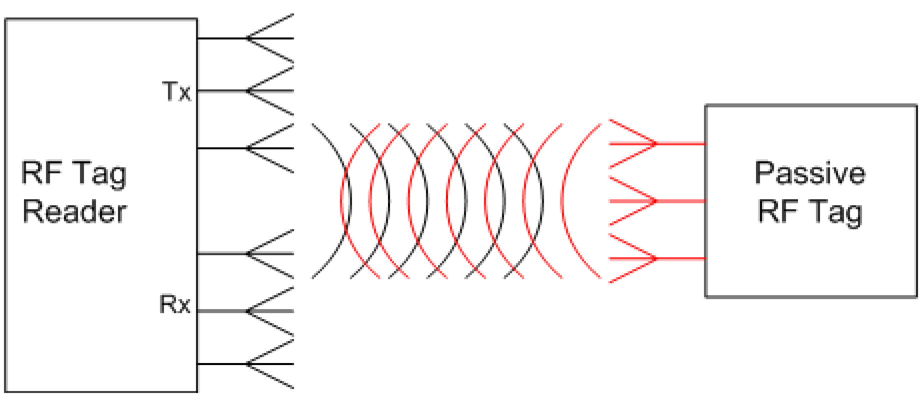
ANSYS Human Body Model



- ***Advanced networking techniques*** such as *Diversity Coding* to optimize energy consumption, throughput, and reliability in *in vivo* environments.
- ***Multi-sensor technology*** including multiple-input multiple-output (MIMO) improve communication reliability and/or performance.

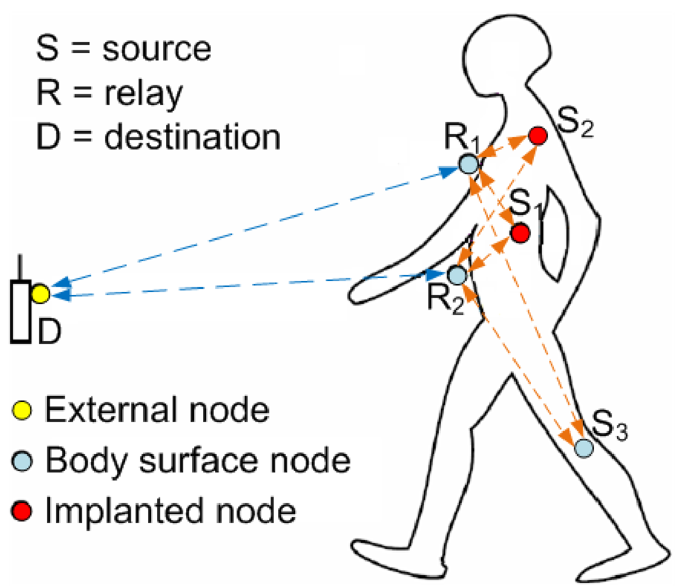
RFID: *MIMO In Vivo*

- MIMO techniques may be used to interrogate power-limited, or passive, sensors.
- If feasible, this could have the potential dual benefit of not only enhancing the data rates possible through spatial multiplexing.
- Advantages:
  - Increased read reliability using spatial diversity
  - Increased read range and throughput
  - No increase in power consumption with higher data rate
  - Full channel information at the reader through sensor backscatter

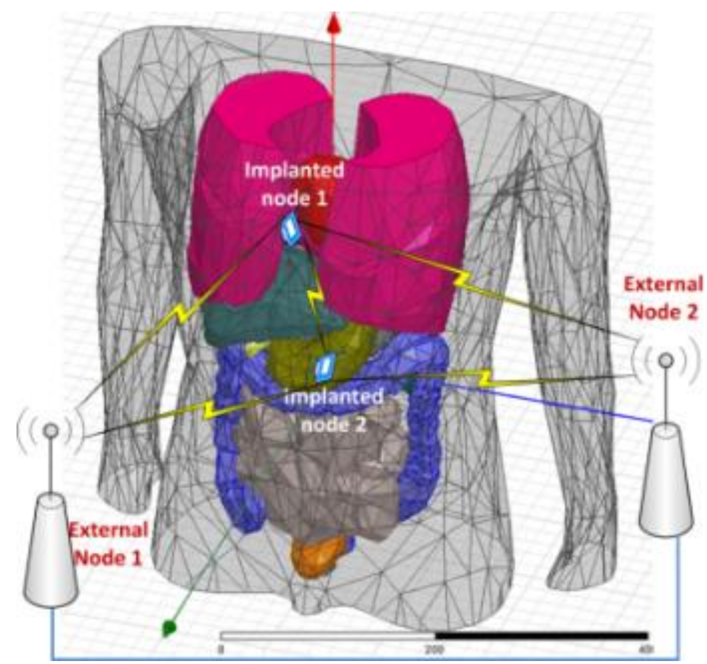


In Vivo Networking

- Implanted nodes are more limited from a communication, power and computing standpoint than any devices that have ever been networked by human-created means.
- Multihop networking of nodes is an established method of increasing network throughput, reliability, and coverage.
- One of our research directions is to investigate asymmetric communication and networking protocols that transfer some of the complexity of the implanted node to the on body nodes, with the expectation that this will provide acceptable performance and increase battery life with acceptable performance degradation.
- Investigating new network technologies, such as Cooperative Diversity Coding for improved reliability, lower power consumption, and improved throughput.



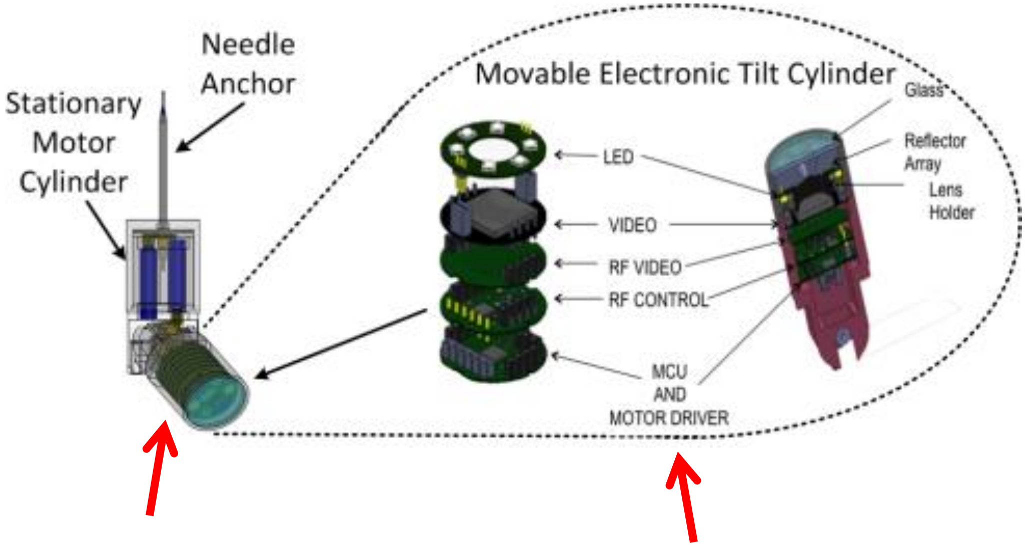
Cooperative System



Cooperative MIMO *In Vivo*

Experimental Progress to Date

- Wirelessly Controlled and Communicating *In Vivo* Networked Devices: MARVEL
  - The first such device that we have implemented is a Miniature Anchored Robotic Videoscope (MARVEL), which is a wirelessly controlled and communicating high-definition video system that will provide the spatial and visual advantages of open-cavity surgeries.
  - To achieve the above objectives several research challenges arise such as (1) reliable, high-throughput and low-latency intra-body wireless communications and networking; (2) electronic and mechanical miniaturization of complex systems; (3) autofocus algorithms for distance compensation; and (4) localization and mapping of the intra-body camera unit and surrounding organs and tissues;
  - Below are several figures that illustrate the MARVEL design and experimental 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

Competitive *In Vivo Imaging* Devices

Device	Type	Size	Imaging Technology	Video Transmission
Given Imaging - PillCam ESO	Ingestible Camera	11mmx26mm	2 imaging sensors 18 fps 256x256 pixel	Wireless 8 body leads
IntroMedic - MicroCam	Ingestible Camera	11mmx24mm	Imaging Sensor with 150° field of view; 3fps	Wireless E-field Propagation
Olympus - EndoCapsule	Ingestible Camera	11mmx26mm	Imaging Sensor with 145° field of view; 2fps	Wireless 8 Body Leads
University of Nebraska – Research Platform	Mobile Robot	20mm diameter	704x480 NTSC	Wired
BioRobotics Institute – Research Platform	Attachable Camera Module	12mmx50mm	UXGA 30 fps	Wired
Columbia University – Research Platform	Insertable Camera Module	11mmx12omm	Multiview camera platform 3D vision 752x582 PAL	Wired

Examples of *In Vivo* Sensors

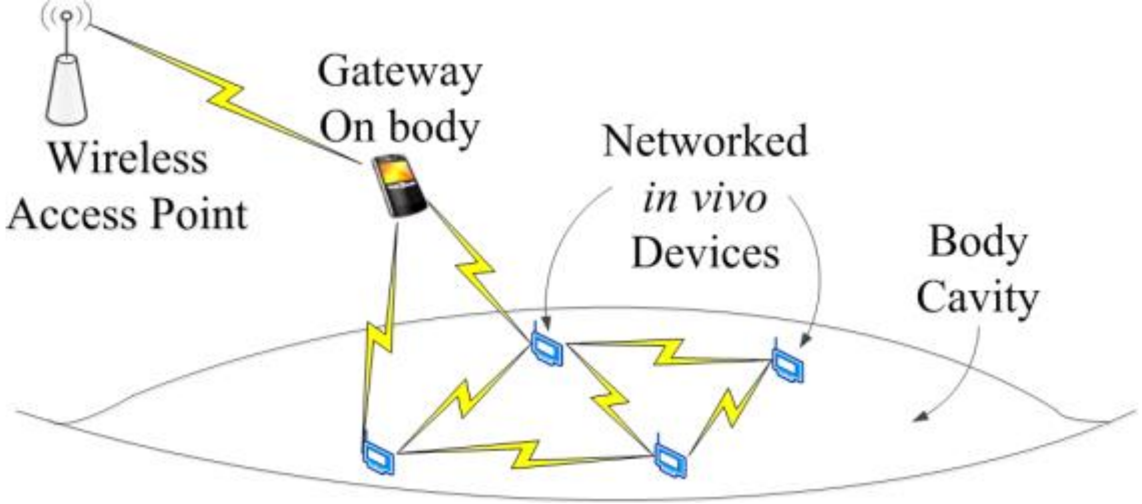
Device	Type	Technology
Biorasis - Glucowizzard	Blood sugar Level Monitor	Solar powered; implanted under the skin; continuous glucose monitoring, size: 0.5x0.5x5.0mm
Medtronic Guardian REAL-Time Continuous Monitor	Blood sugar Level Monitor	Continuous glucose monitoring at 5 min intervals; identify patterns in glucose level variations
Reveal-ICM	Cardiac Monitoring	Implantable ECG sensor; remote monitoring
Biotronik - BioMonitor	Cardiac Monitoring	Implantable ECG sensor; communicates with home monitoring system; 6.4 year longevity
VeriTeQ	Temperature Sensing Chip	Internal temperature monitoring; RFID communication
Innovapaedics	Implant and Surgical Tools Tracking	RFID-based; includes cloud-based server to store data

Examples of *In Vivo* Actuators

Device	Type	Technology
Medtronic – InSyn ICD	Cardioverter Defibrillator	Monitors and regulates a patient’s heart rate
MicroCHIPS - IDDS	Drug Delivery System	Controlled or continuous drug release; wireless communication; individual or multiple drug releases.
Perdue University	Cardiovascular Stent	Uses stent as antenna for wireless communication
Julius-Maximilians-Universität Würzburg	Drug Delivery Device	Can be swallowed; drug delivery is triggered from external RFID device; includes sensors

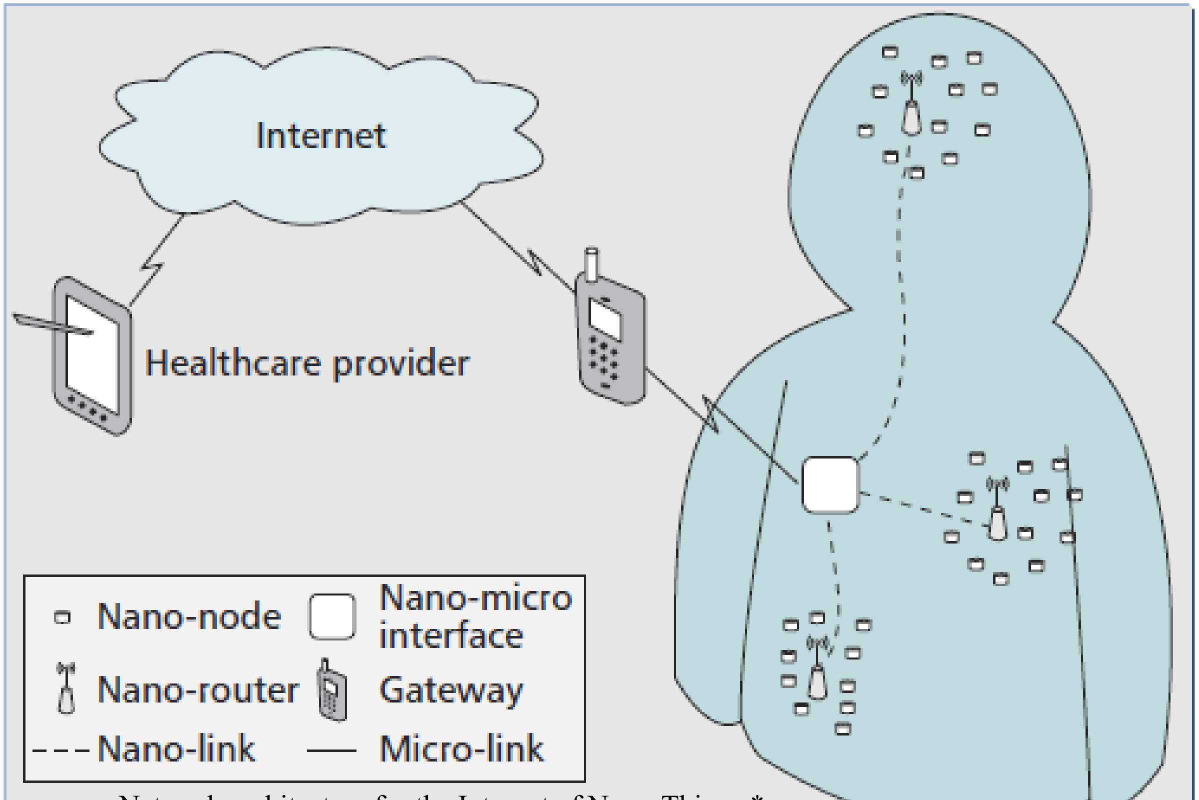
Summary: *MARVEL* Advantages and Benefits

- Decreases the surgical-tool bottleneck experienced by surgeons in LESS procedures
- Eliminates power, video, and light source cabling issues in current laparoscopes
- Increase the dexterity and fine motion options for the surgeon
- Increases the imaging angle and the usable workspace inside the abdominal cavity.
- Next steps: Wireless high definition, reduced physical dimensions, inter-module communications, and 3D Imaging with Multiple CMs
- The ***MARVEL*** Camera Module is the first device in a family of wirelessly networked *in vivo* biosensors and actuators that are capable of wirelessly communicating to one or more external nodes that will enable the next paradigm shift in MIS surgery.



Future Directions: Wireless Nano Networking

- Nanoscale wireless communications challenges:
  - Frequency band of operation of electromagnetic nano-transceivers in the order of Terahertz (0.1THz-10THz) because of the nano-antenna dimensions
  - Understand and model the communications channel in the very short range
  - Simple modulation techniques, network protocols, and security solutions suitable for limited power and complexity of nano-devices
  - Novel channel access mechanisms for nano networks



Network architecture for the Internet of Nano-Things *
Source: http://dx.doi.org/10.1109/MWC.2010.5675779