WCNC 2015

A New Wireless Frontier
In Vivo Wireless Communications and Networking

(and some other things I am doing)

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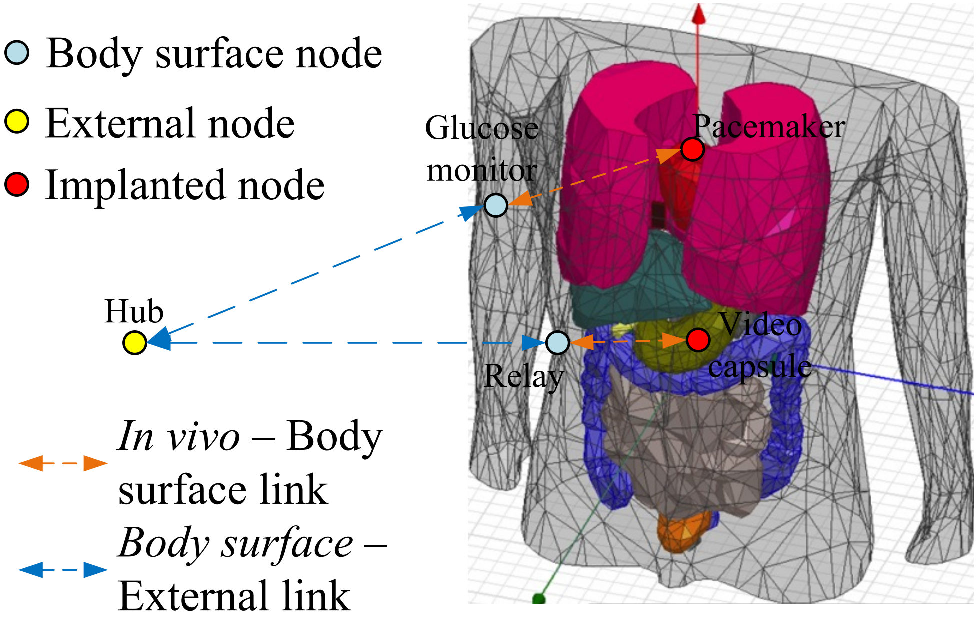
A New Wireless Frontier
In Vivo Wireless Communications and Networking

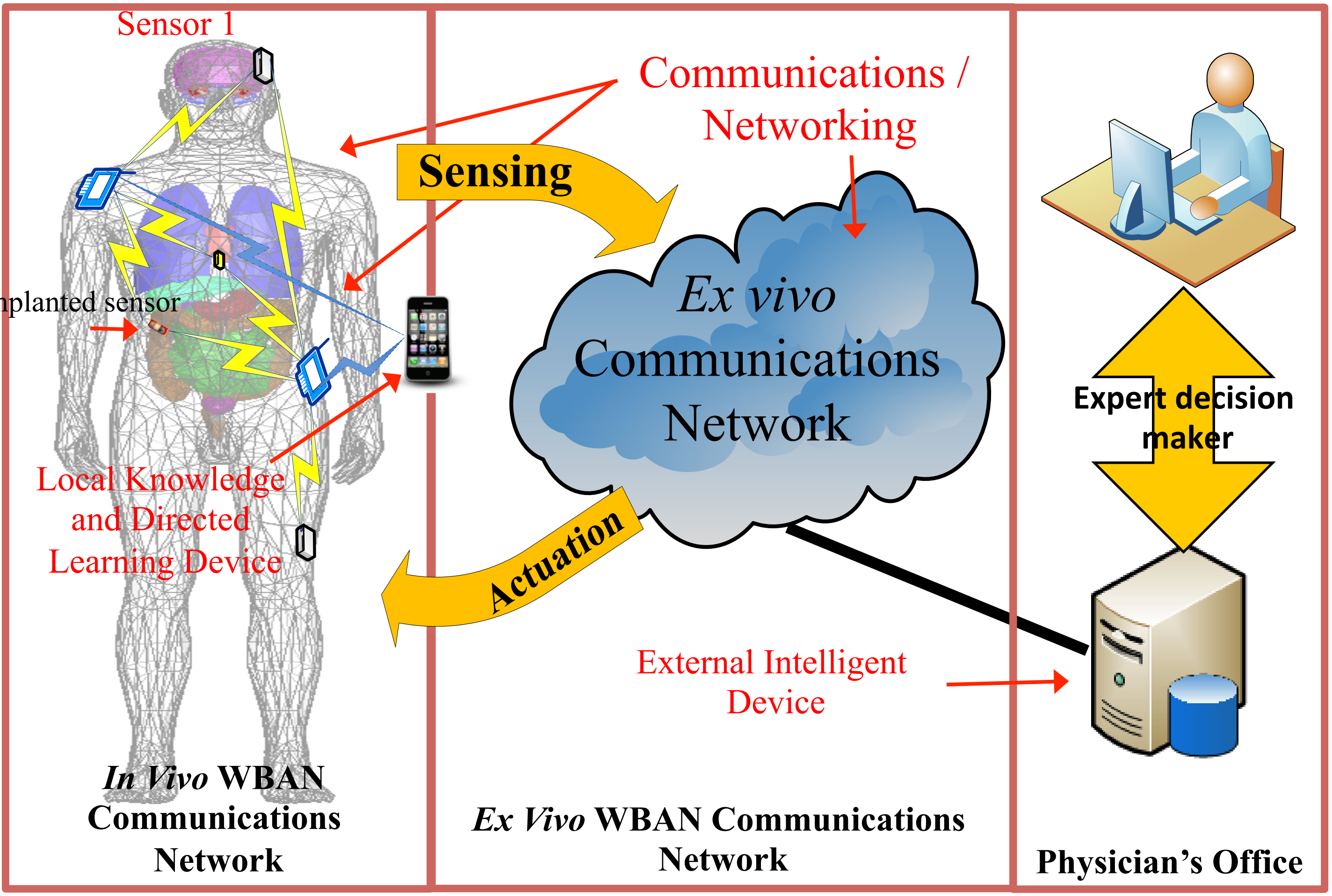
- Vision: Wirelessly enabled cyber-physical healthcare
- Frontier: *In vivo* communications a necessary component of the vision
- *In vivo* communications and networking (selected research areas)
    - Characterization of the wireless *in vivo* channel
    - MIMO *In Vivo*
    - Cooperative Network Coding
- Systems Research Projects
    - *MARVEL* ---- Surgery Inside Out
    - *i*VCG --- Improving the State of the Heart
- Observations and Summary



Vision: Wirelessly Enabled Cyber-Physical Healthcare

- Wireless technology has the potential to advance and transform healthcare delivery by realizing *in vivo* wirelessly networked *cyber-physical systems* that enable rapid, correct, and cost-conscious responses in chronic and emergency circumstances.

- **Characterizing and optimizing *in vivo* wireless communications and networking** requires familiarity with engineering and biological environments.
- Extending 802.15 TG6 [WBAN]
- The "Wireless *In Vivo* Internet of Things" ☺

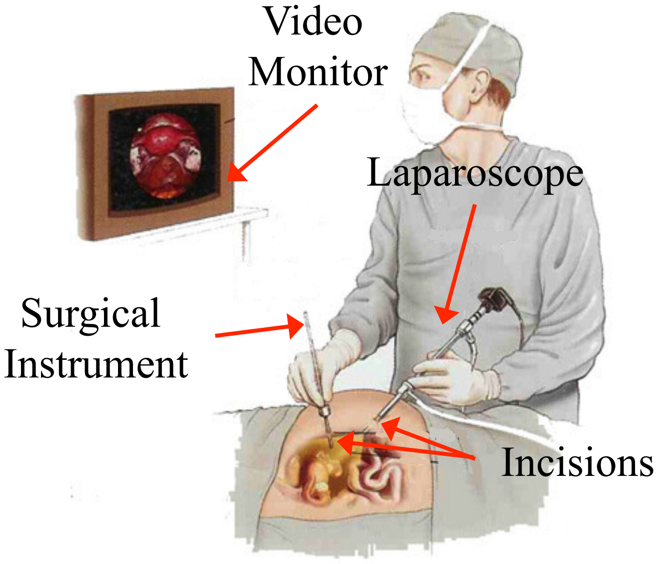


Research opportunities and challenges are abundant

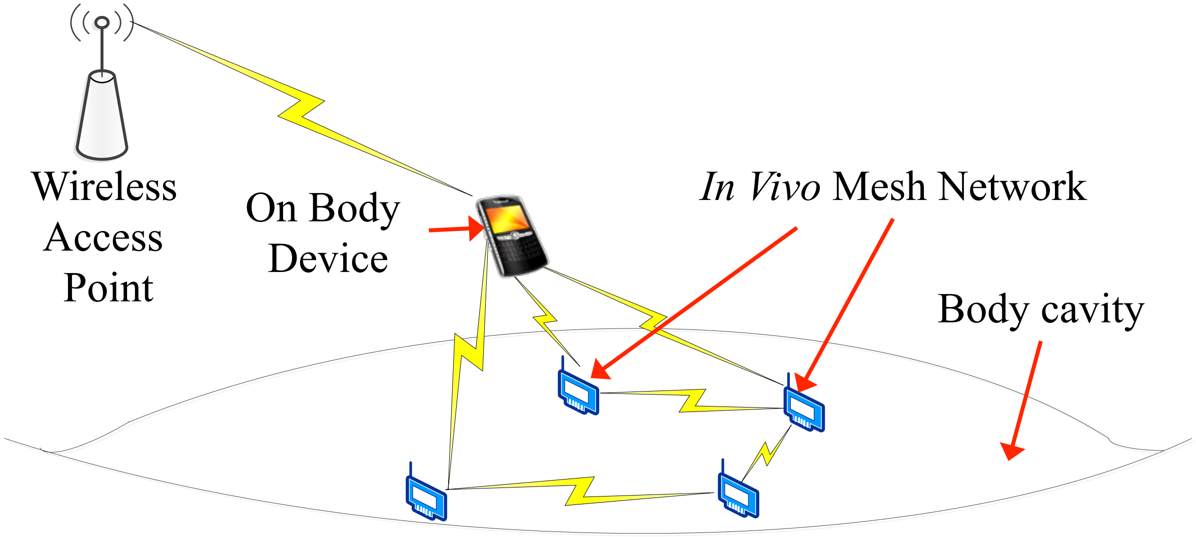
Motivating Application: Advancing Minimally Invasive Surgery (MIS) via Wirelessly Networked Devices

- A cyber-physical mesh network of wirelessly connected *in vivo* devices that enhances and enables innovative MIS surgical and other procedures.
  - Network is comprised of a plurality of communicating devices --- including imaging devices, sensors and actuators, power sources, “cutting” tools.
  - Wirelessly addressable and controllable distributed network.
  - ***MARVEL*** Camera Module is the first device and requires *in vivo* bit rates (~100 Mbps) supporting HD video with low latency (<25ms). **Replaces laparoscope**.

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



Current laparoscopic technology

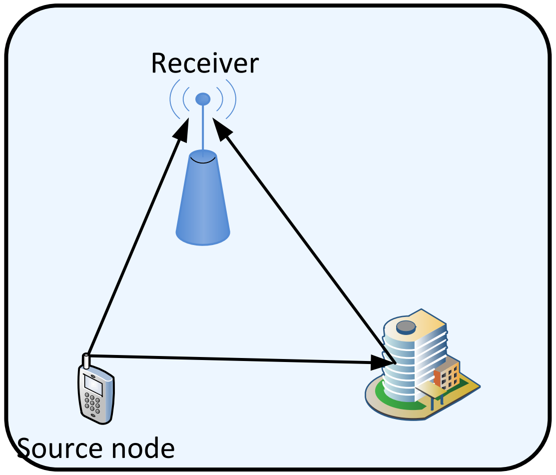


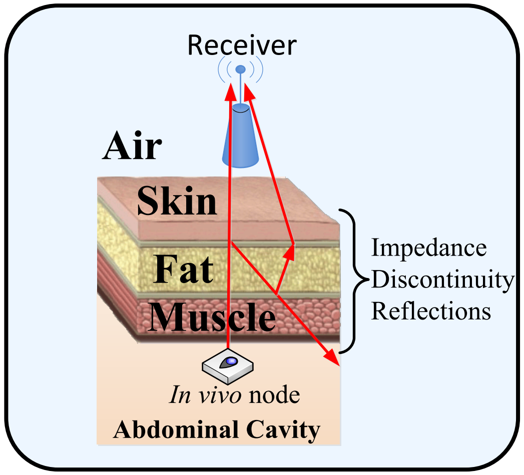
US Patent No. 8,358,981, *Minimally Invasive Networked Surgical System*

In vivo Wireless Channel Characterization

- Many research issues in media characterization and modeling including:
  - Far-field channel models of classic RF wireless communication systems are not always valid for the *in vivo* environment (near-field effects).
  - Multi-path scattering with varying propagation speed through different types of human organs and internal structures.
  - Localized and average power Specific Absorption Rate (SAR) limit will affect the location and directionality of the antennas [SAR limit on nearest organs].

Classic Multi-Path Channel





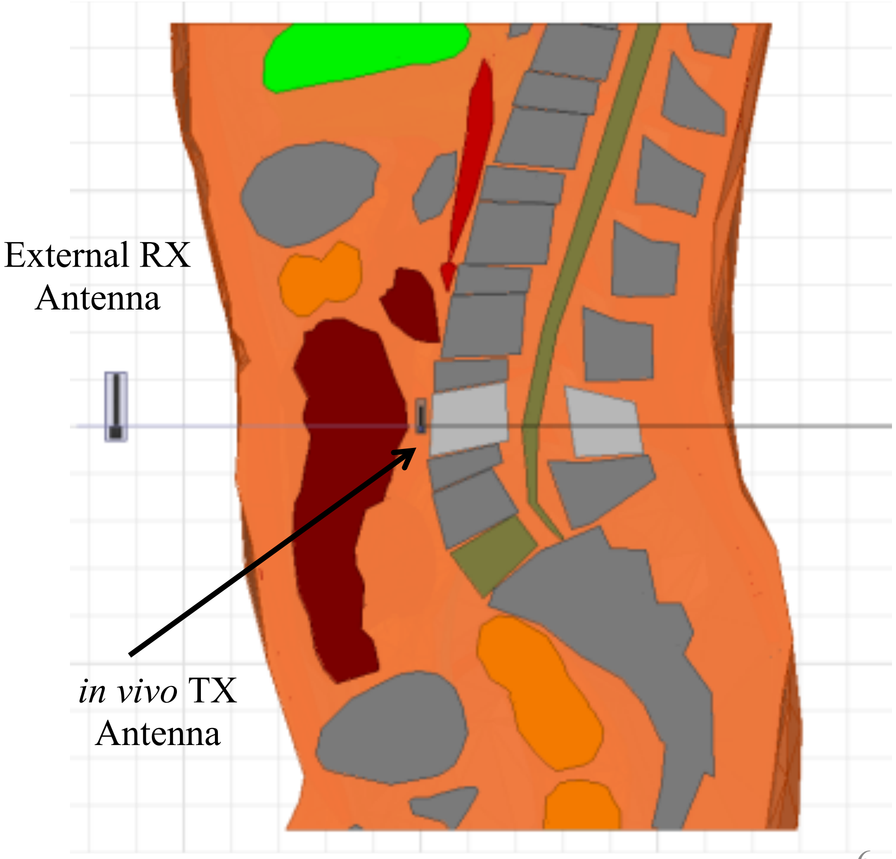
In Vivo Multi-Path Channel

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

"*In Vivo* Wireless Communication Channels," *IEEE WAMICON*, April 2012

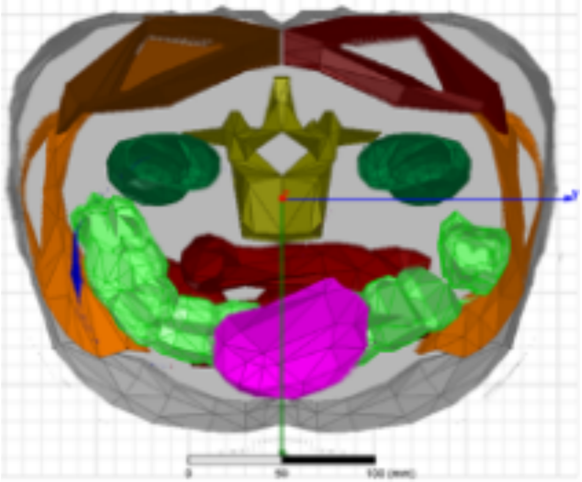
A Complication: SAR Limit for *In Vivo* Communications

- 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). The FCC limit on the local and average SAR are 1.6 W/kg and 0.08 W/kg, respectively.
- SAR limit requires transmission at low enough power to protect organs and tissues against harmful health effects associated with the radiofrequency (RF) emissions.
- The SAR limit is frequency dependent, since it depends on the conductivity of the material, which changes with frequency in human organs/tissues.
- Localized and average SAR limits will affect the TX power, TX antenna location and will impact the directionality of the antennas [SAR limit on nearest organs].
- Networking of *in vivo* nodes may be necessary to maintain the SAR within allowed limits.



In Vivo Simulation with the Human Body Model (HBM)

- ANSYS HFSS-HBM is a 3D electromagnetic (EM) field simulator that utilizes a frequency domain field solver to compute the electrical behavior of the human body model with over 300 muscles, organs, and bones with a geometrical accuracy of 1 mm.
- HFSS calculates the complete EM fields created by a radiating element which includes the entire EM field (near, far, and intermediate fields).
- Frequency dependent parameters (conductivity and permittivity) for each organ and tissue are included from 10 Hz to 100 GHz.
- **TX/RX antennas, or arrays, can be placed at any position inside/outside the model and the RF propagation characteristics of the medium determined.**



Top-down view of the human body showing locations of internal organs, muscles, and bones

Human Body Model

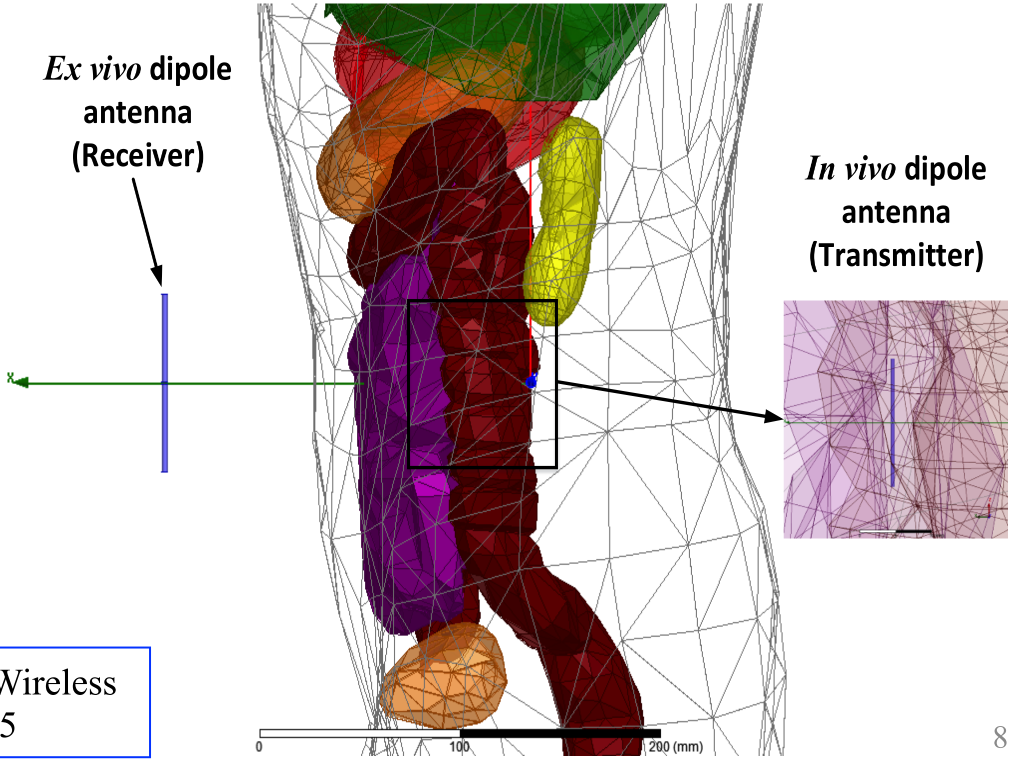
Characterization of the *In Vivo* Channel – Path Loss

- **Approach ---** Simulation of path loss fitted to phenomenological model.
- **Antennas** --- Dipole of small size [λ/2].
- **Frequency range ---** 0.4-6 GHz (dipoles optimized for frequency).
- **Distance range** --- λ/50-3λ.

$$\text{Path Loss Measurement (dB)} = -S_{21} + 10 * \log_{10}(1 - 10^{\frac{S_{11}}{10}}) + 10 * \log_{10}(1 - 10^{\frac{S_{22}}{10}})$$

S_{11} and S_{22} are the return losses of the TX and RX antennas and S_{21} represents the power gain between the two antennas. The last two terms in the equation remove the effects of the antenna gains.

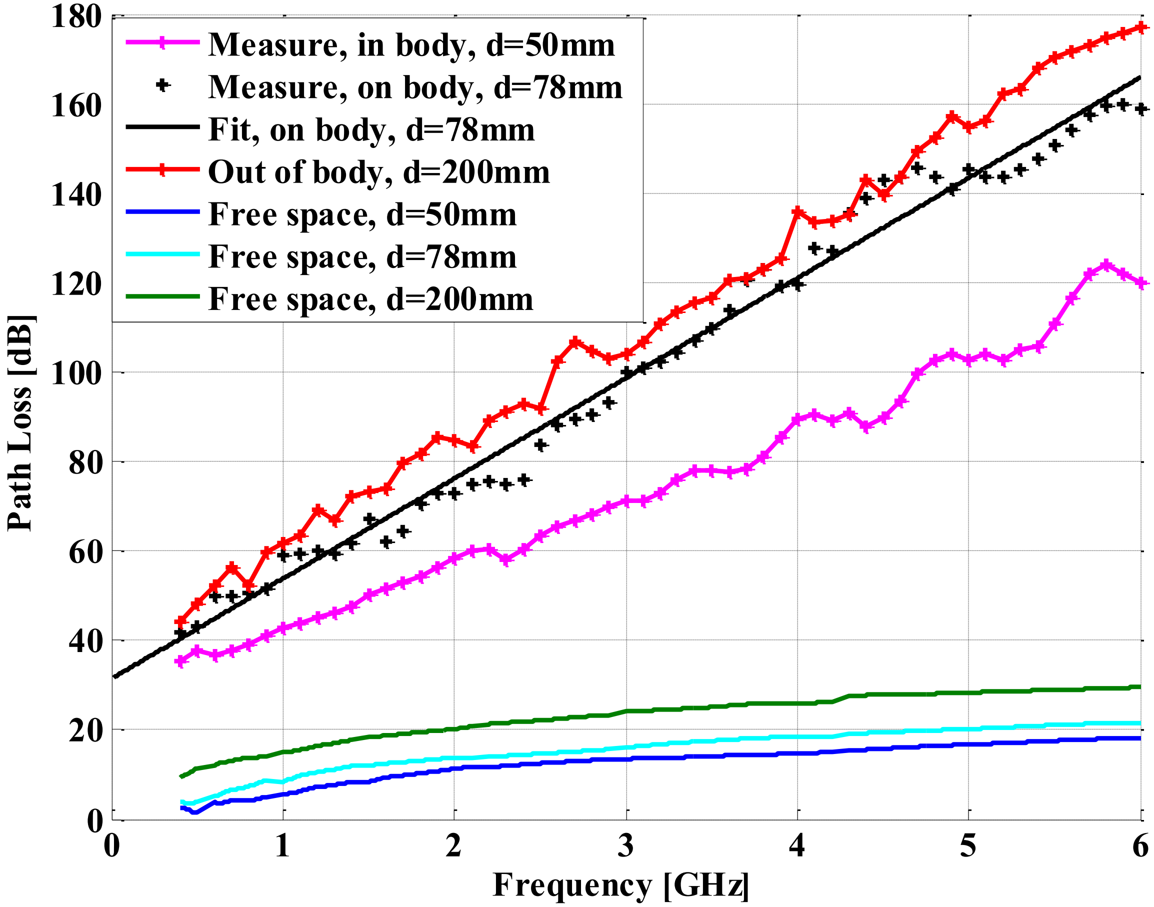
- **Question:** Is the 3-part cellular model [path loss, shadow fading(?), and fast fading] valid?



"A Phenomenological Path Loss Model of the *In Vivo* Wireless Channel," accepted *IEEE WAMICON*, April 2015

In Vivo Path Loss Modeling – Frequency Dependence

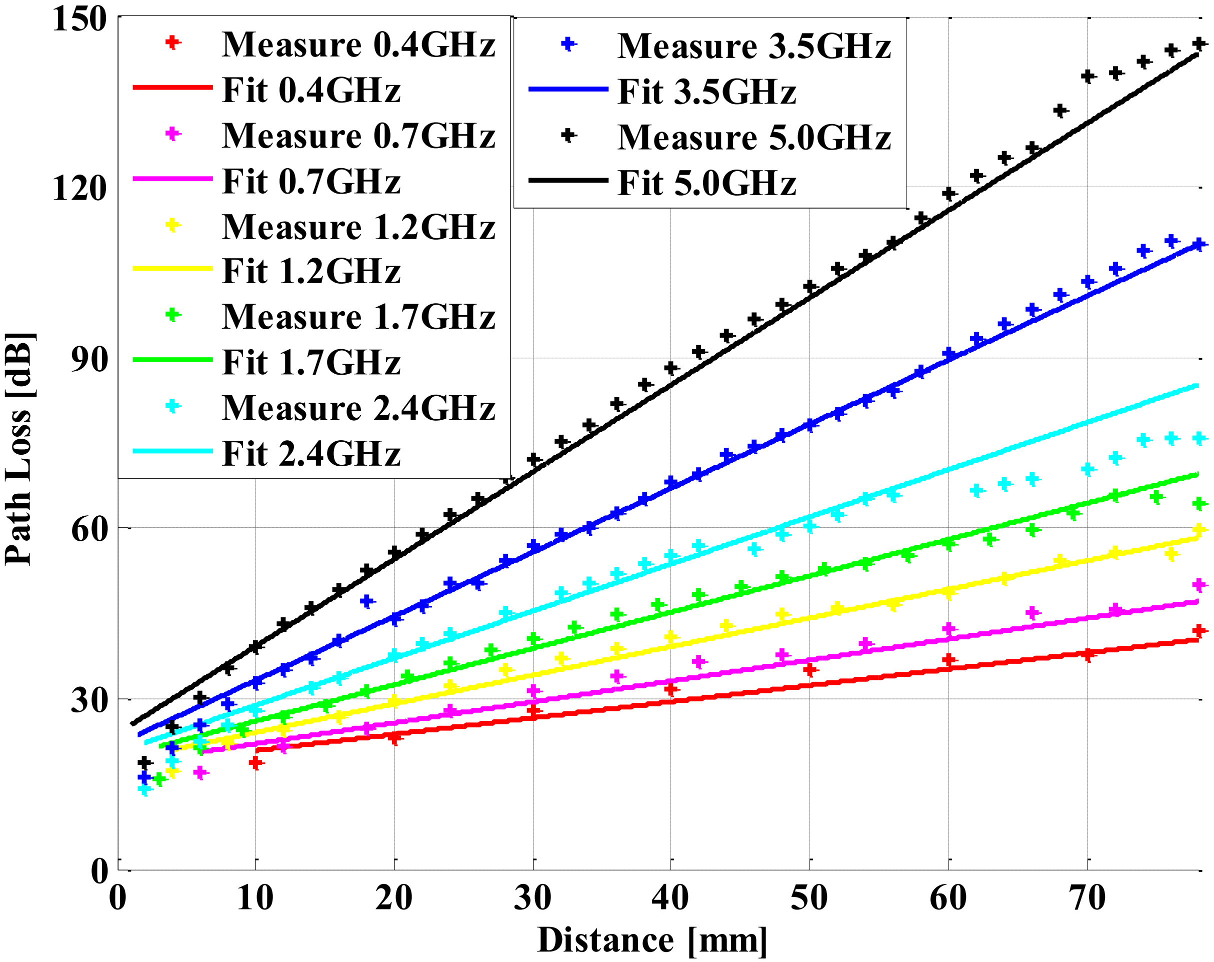
- In/on/out of body path loss vs frequency
  - *In vivo* path loss [in dB] increases linearly --- faster than free space.
  - Fitted model for on body path loss --- PL(on body) = 22.4**f* + 31.4, is used as a reference position for modeling the distance dependent path loss.



- Skin boundary at 78mm from TX
- *d* = distance between TX and RX

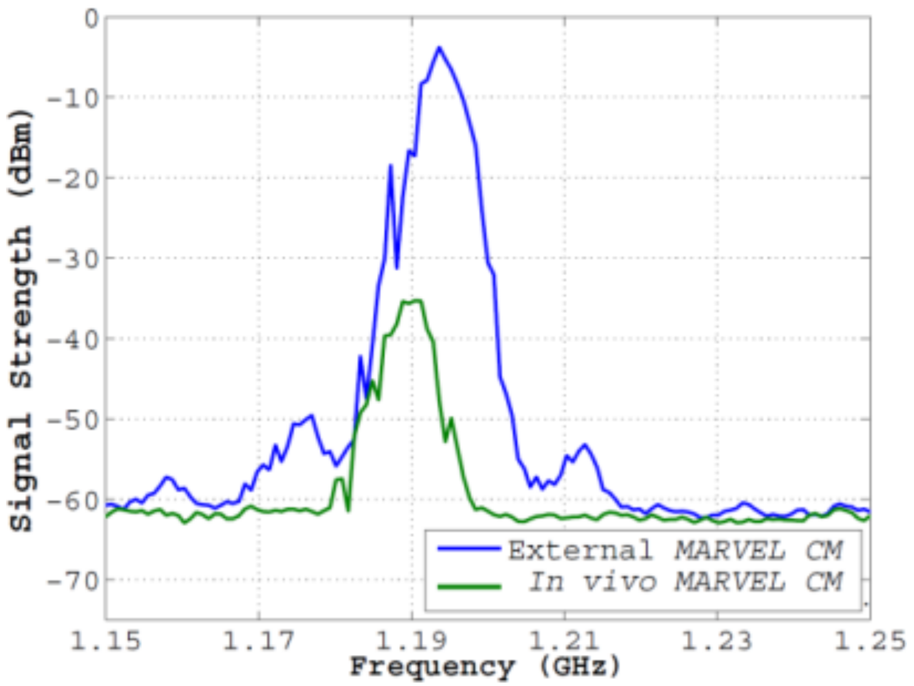
In Vivo Path Loss Modeling – Distance Dependence

- In body path loss [in dB] increases linearly with distance --- faster than free space.
- Fitted model --- PL(in body) = PL(on body) + k*(d - d_0), where d_0 = 78mm is the reference point and the slope is $k = 0.271*f + 0.1782$.

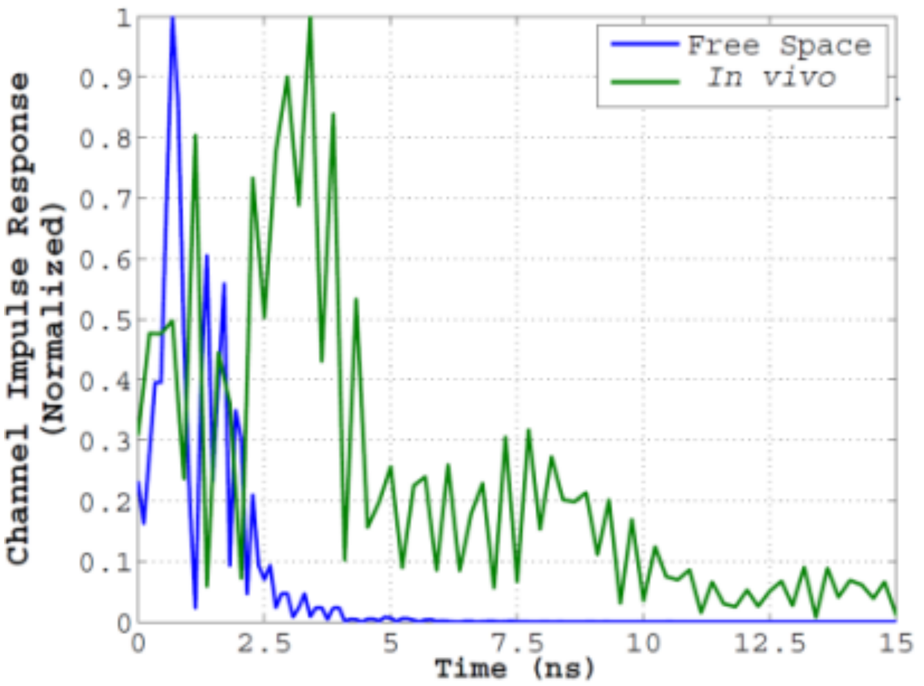


In Vivo Attenuation and Dispersion - Vivarium Experiment

- Carrier frequency 1.2GHz, video bandwidth 5MHz and FM modulation bandwidth of 11 MHz.
- Approximately 30 dB of attenuation through the organic tissue.
- *In vivo* time dispersion is much greater than expected from the physical dimensions (owing to the *in vivo* speed of propagation).



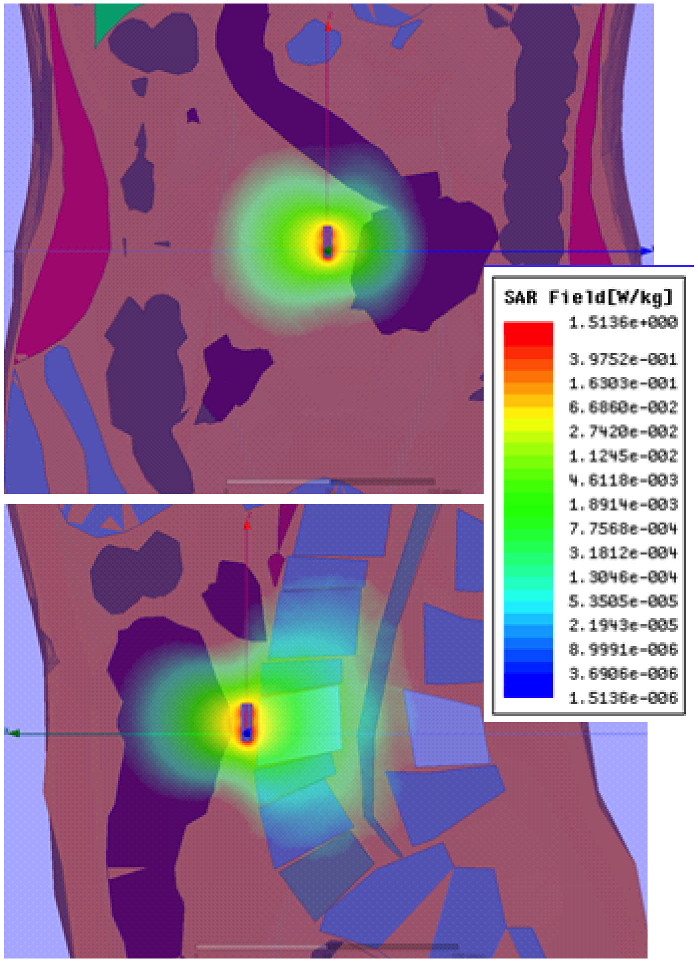
External vs. *in vivo* attenuation versus frequency

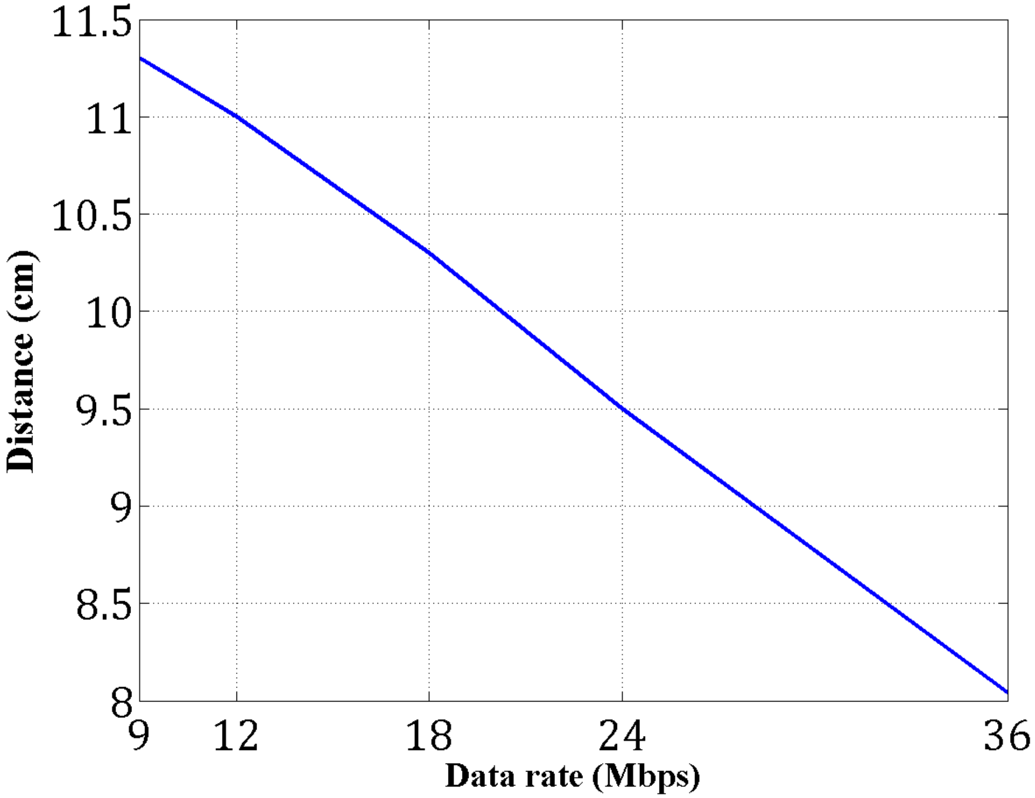


Normalized channel impulse response for free space and the porcine abdomen environments

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 below.





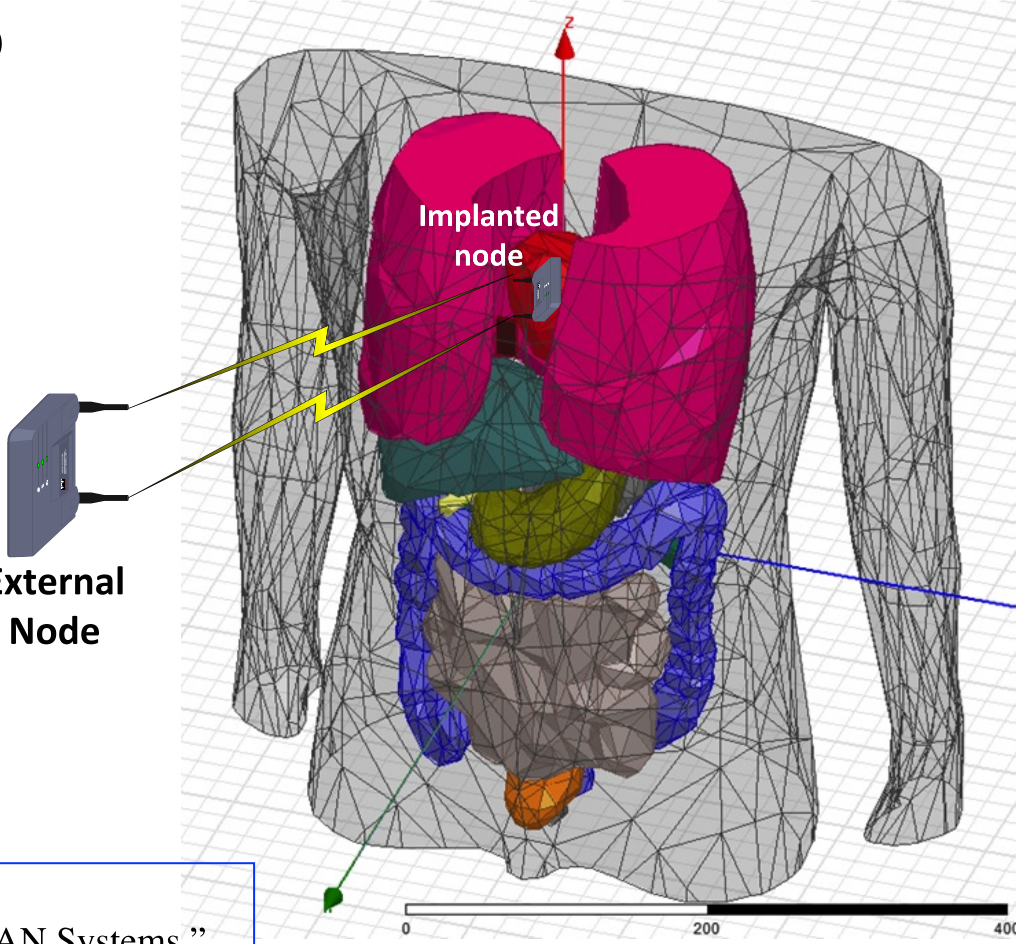
"SAR and BER Evaluation for *In Vivo* Communication," *IEEE WAMICON*, Apr. 2013

Contrasting the *Ex Vivo* and *In Vivo* Channels

Feature	*Ex Vivo*	*In Vivo*
Physical Wave Propagation	• Constant speed • Multipath – reflection, scattering and diffraction	• **Variable speed** • Multipath – plus penetration
Attenuation and Path Loss	• Lossless medium • Increases as the square of distance • Increases as the square of frequency	• Very **lossy** medium • **Angular (directional) dependent** • In body - Increases **exponentially** with distance • In/on/out body - Increases **exponentially** with frequency
Dispersion	• Multipath delays → time dispersion	• **Multipath delays of variable speed** → frequency dependency → time dispersion
Directionality	• Propagation essentially uniform	• Propagation varies with direction • Directionality of antenna changes with position/ orientation
Near Field Communications	• Deterministic near-field region around the antenna	• Inhomogeneous medium → Near field region changes with angles and position inside body
Power Limitations	• Average and Peak	• Plus **specific absorption rate (SAR) limit**
Shadowing	• Follows a *log-normal* distribution	• To be determined
Multipath Fading	• Flat and frequency selective fading	• To be determined
Antenna Gains	• Constant	• Angular and positional dependent • Gains highly attenuated
Wavelength	• The speed of light in free space divided by frequency	• $\lambda = c/\sqrt{\varepsilon_r} f$ → at 2.4GHz, average dielectric constant $\varepsilon_r \approx 30$ → **wavelength roughly 5.5 times smaller than the wavelength in free space.**

MIMO *In Vivo*

- Due to the lossy and highly dispersive nature of the *in vivo* environment, achieving high data rates with reliable performance is a challenge [see ***MARVEL*** application].
- Signals power are limited by the specified specific absorption rate (SAR) limit.
- MIMO *in vivo* to the rescue ☺
- The MIMO *in vivo* capacity is the theoretical performance limit
- Capacity provides insight into how well the system can ultimately perform and provide guidance on how to optimize the MIMO *in vivo* system.
- Impact of various factors is being explored including antenna type, position and correlation, larger system bandwidth etc.

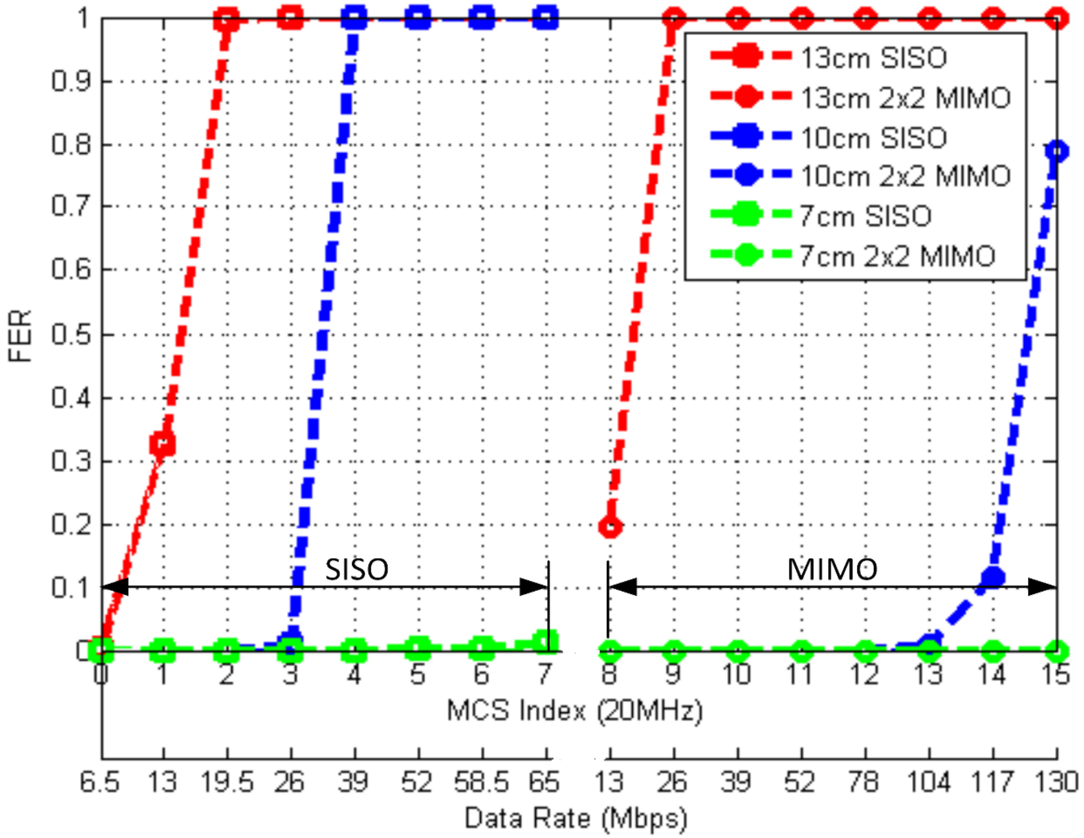


MIMO *In Vivo*

[1] "MIMO *In Vivo*," *IEEE WAMICON*, June 2014.
[2] "Performance Evaluation for MIMO *In Vivo* WBAN Systems," *IEEE IMWS-Bio*, December 2014.

MIMO vs. SISO *In Vivo* Simulation of Frame Error Rate

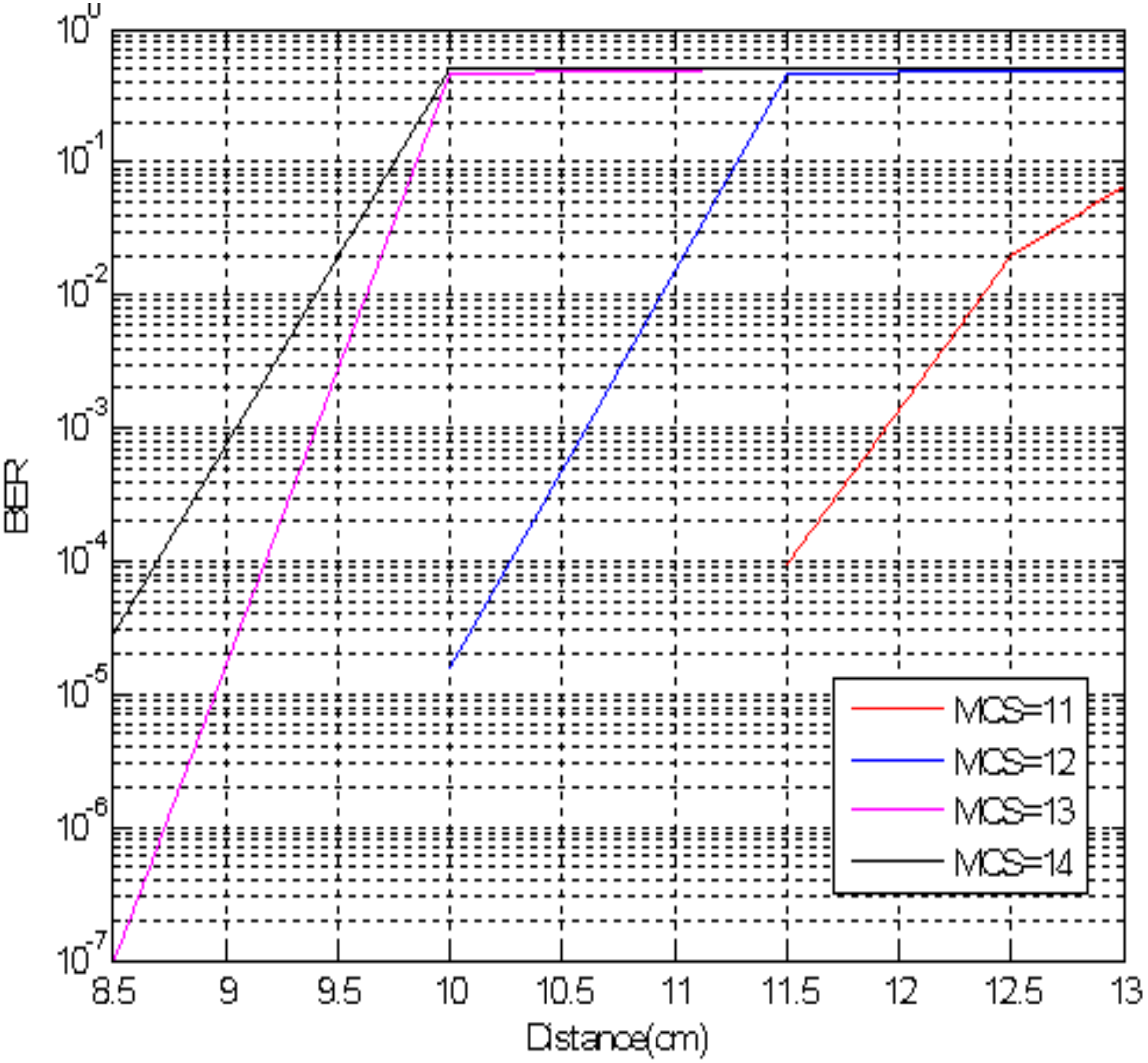
- MIMO *in vivo* can achieve much better system performance than SISO *in vivo*.
- Near field effects impact the signal attenuation depending on antenna placement for MIMO and SISO. So, the MIMO gain is not necessarily proportional to the number of antennas.
- As the separation of Tx and Rx antennas decreases, the performance gain increases



MIMO (2x2) and SISO *in vivo* FER performance comparison as a function of the MCS index value

MIMO *In Vivo* Simulation Results

- BER performance for MIMO *in vivo* systems as a function of the distance between the transmit and receive antennas at different MCS index values equal to 11, 12, 13, 14 corresponding to 52, 78, 104, and 117 Mbps, respectively.
- In the case when transmitting data at MCS equal to 13 (104 Mbps), the receiver antennas need to be placed within 9.5 cm from the body to achieve a minimum BER of 10^{-3} and meet the requirement of at least 100 Mbps.
- For *in vivo* HD video, it is possible to transmit high definition video with low latency from deep inside the human body to support MIS.



MIMO [2x2] *In Vivo* Capacity OFDM model

- The system capacity for subcarrier *k* is:

$$C_k = E\left[\sum_{i=1}^{2}\log_2(1+\frac{\lambda_{ki}}{2N_0\cdot BW})\right] \quad \text{bits/OFDM symbol}$$

where P is the total transmit signal power, BW is the configured system bandwidth in Hz, E denotes expectation, N_0 is power density of white Gaussian noise and λ_{ki} is the square of the *i*th singular value of the frequency domain channel response matrix.

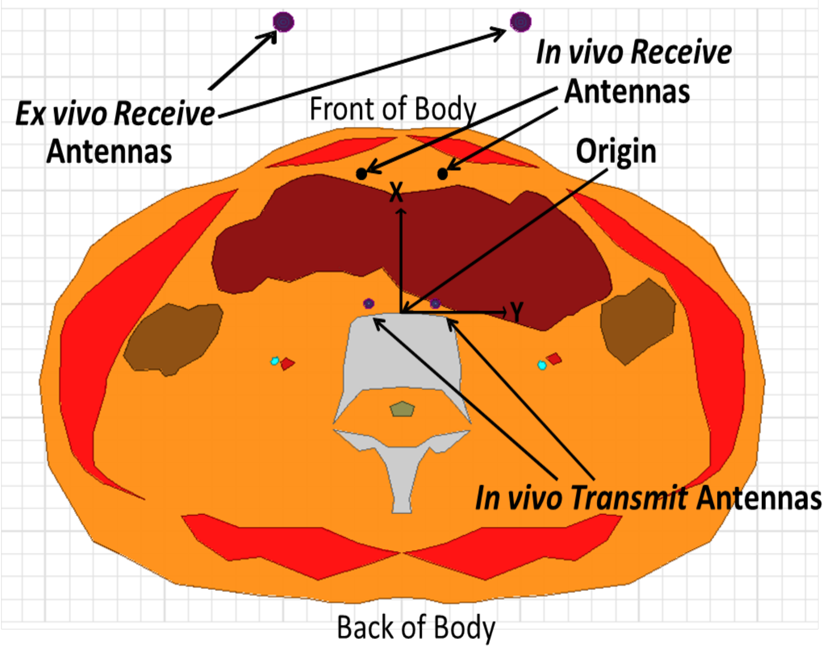
- The total system capacity is calculated as:

$$C = \frac{1}{T_{sym}}\sum_{k=1}^{N_{data}} C_k \ \text{bits/s} = \frac{BW}{(N_{total}+BW\cdot T_{GI})}\sum_{k=1}^{N_{data}} C_k \ \text{bits/s}$$

where N_{data} is the total number of subcarriers configured in the system to carry data, T_{sym} is the duration of each OFDM symbol, N_{total} is the total number of subcarriers in the bandwidth of BW HZ, and T_{GI} is the guard interval duration.

MIMO *In Vivo*: ANSYS Human Body Model Simulation

- The antennas used in the simulations are monopoles designed to operate at the 2.4 GHz ISM band.
- On average, the wavelength is approximately six times smaller *in vivo* than in free space, so that the antenna separation for the Tx and Rx antennas is different for the *ex vivo* and *in vivo* antennas.
- Simulations considered 9 different distances and different angular positions between Tx and Rx antennas [only 3 distances shown below].

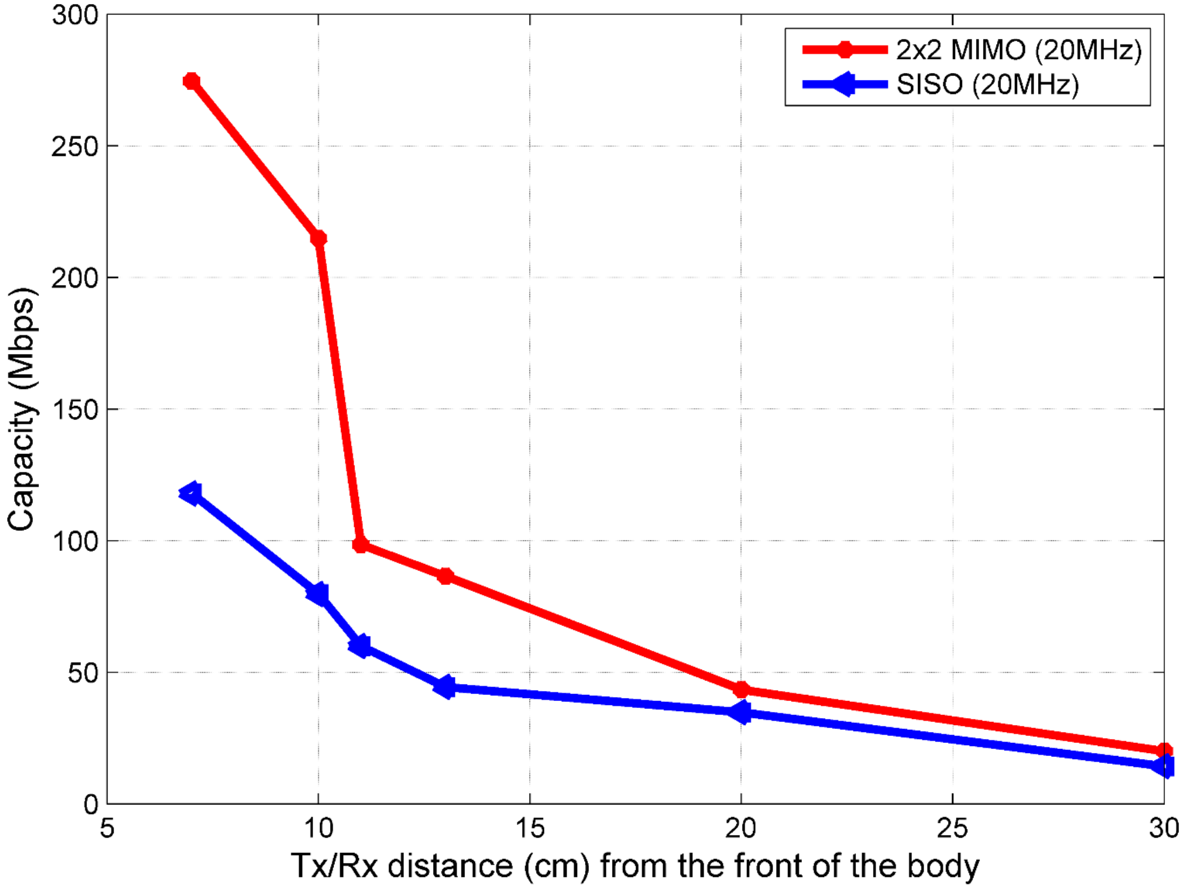


	MIMO				SISO
Simulation Scenario	**Antenna 1**		**Antenna 2**		**Antenna**
	X (mm)	***Y (mm)***	***X (mm)***	***Y (mm)***	***X (mm)***
1	130	50	130	-50	130
2*	100	50	100	-50	100
3*	70	30	70	-30	70

* denotes Rx antennas are located inside body

MIMO *In Vivo* (Capacity vs Distance)

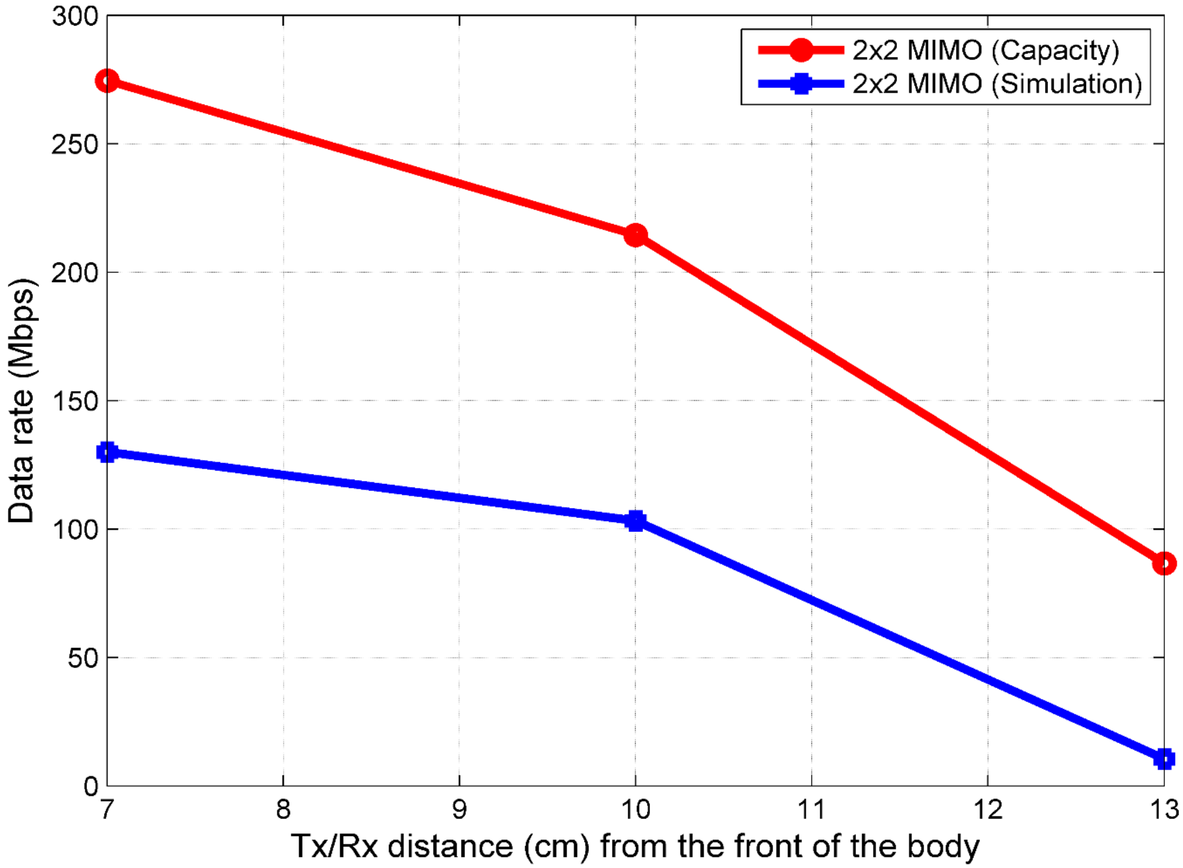
- Capacity decreases rapidly with the distance between the TX and RX antennas.
- For the required ***MARVEL*** data rate of ~100 Mbps, the distance must be ≤11cm.
- A larger system bandwidth or relay is necessary for distances >11cm.



MIMO (2x2) and SISO *in vivo* capacity comparison as a function of the distance of the Tx and Rx antennas in front of the body

MIMO *In Vivo* (Capacity vs Simulation)

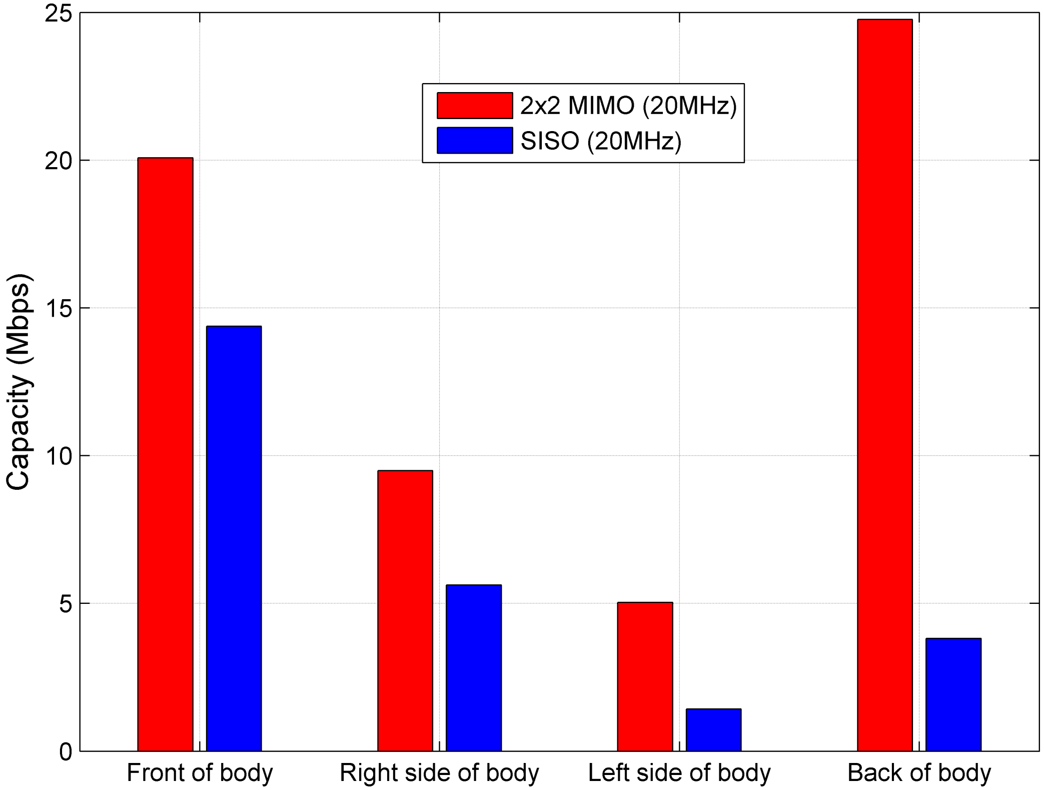
- A large gap can be observed between the theoretical capacity and the achievable data rate through simulation.
- Opportunity for a more efficient PHY layer and antenna placement.



MIMO (2x2) *in vivo* data rate comparison between the capacity and simulation as a function of the distance of the Tx and Rx antennas in front of the body

MIMO and SISO Capacity vs Angular Position

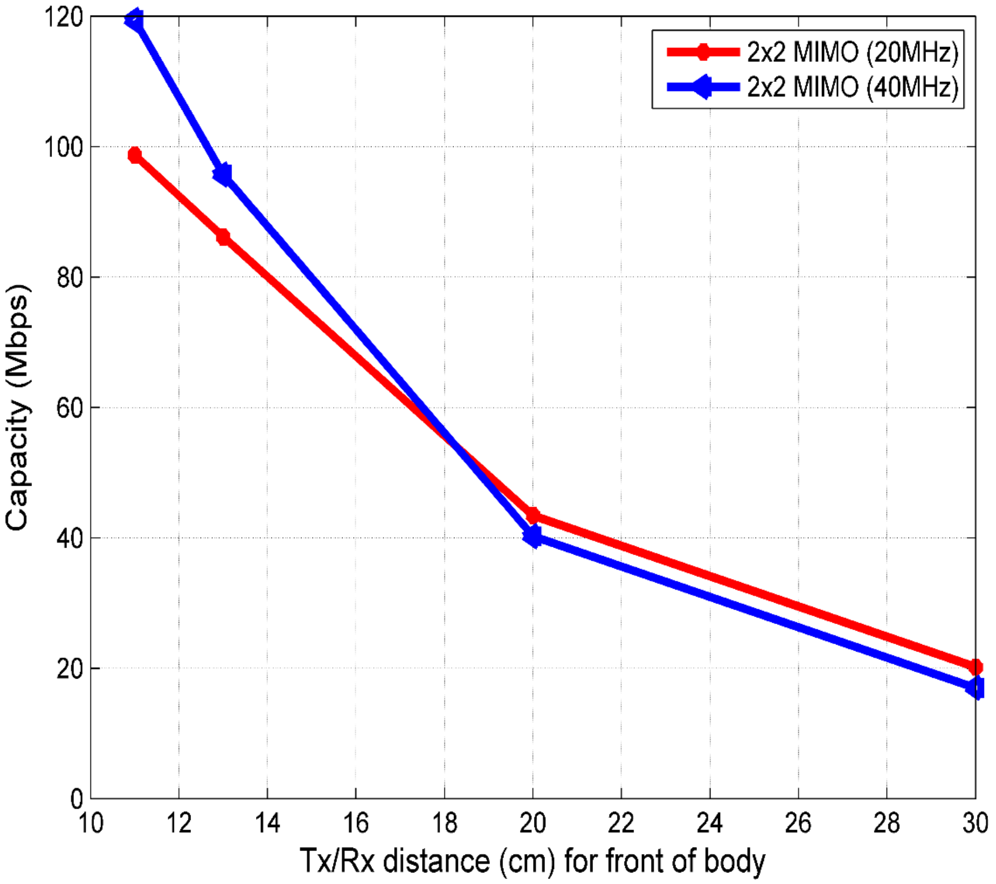
- The system capacity of MIMO *in vivo* for the cases of the front and back of the body are much better than that of the side of the body.
- This is because much higher attenuation exists inside the body due to the greater *in vivo* distance for the side(s) of the body.



MIMO (2x2) and SISO *in vivo* system capacity comparison for front, side, and back of the body

MIMO *In Vivo* (Capacity vs Bandwidth)

- To support the ***MARVEL*** data rate of 100 Mbps, the distance must be ≤ 13 cm for 40 MHz and ≤ 11 cm for 20 MHz.
- As the TX/RX distance increases to more than ~18 cm, the system capacity for the 40 MHz becomes less than that for the 20 MHz.
- This is because to maintain the maximum allowed SAR level, the SNR is very small (i.e., due to the larger distance) and dominates the system capacity rather than the system bandwidth.
- SAR may limit the capacity gains with additional bandwidth.

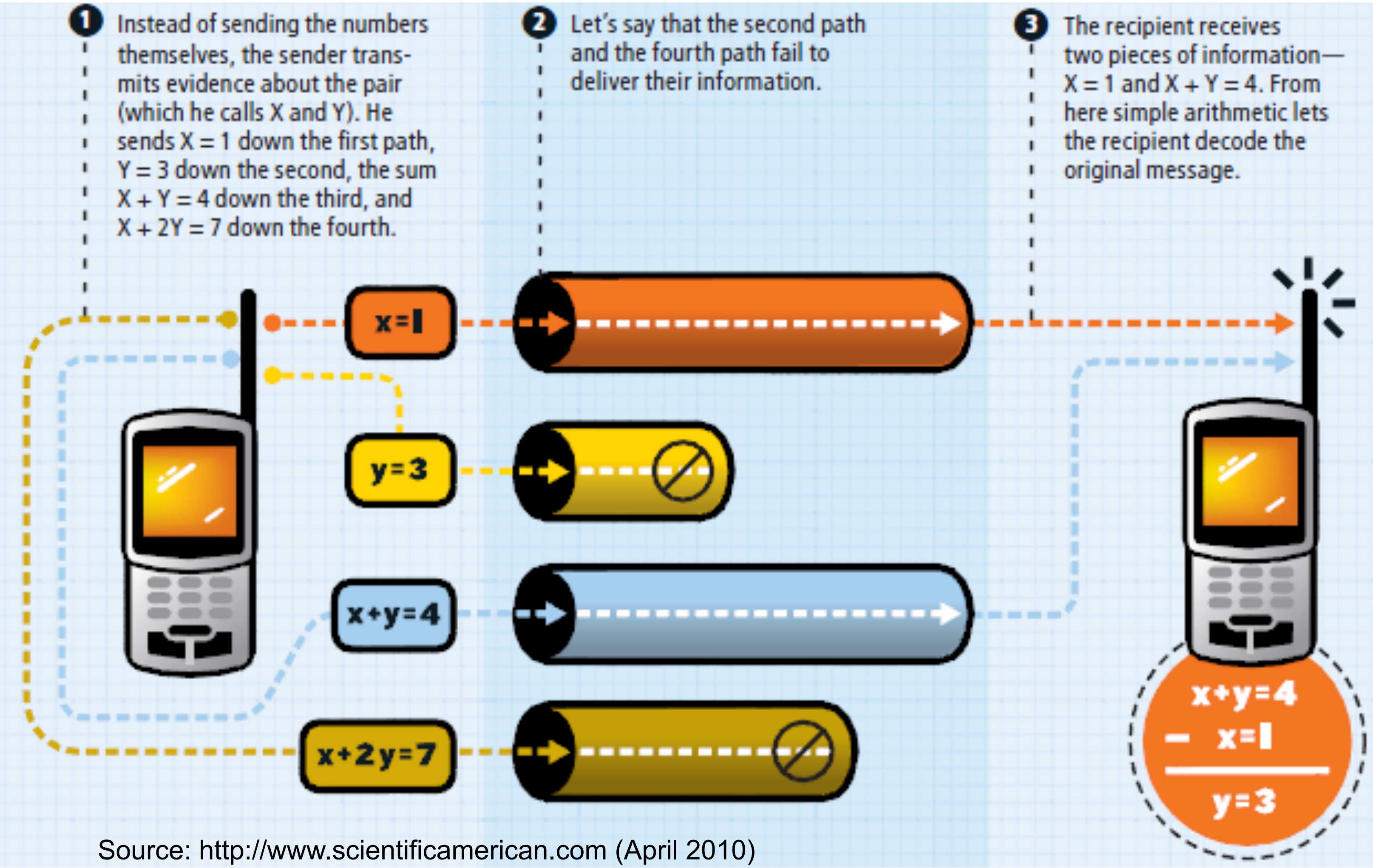


MIMO (2x2) *in vivo* system capacity comparison between 20 MHz and 40 MHz

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.)



❶ Instead of sending the numbers themselves, the sender transmits evidence about the pair (which he calls X and Y). He sends X = 1 down the first path, Y = 3 down the second, the sum X + Y = 4 down the third, and X + 2Y = 7 down the fourth.

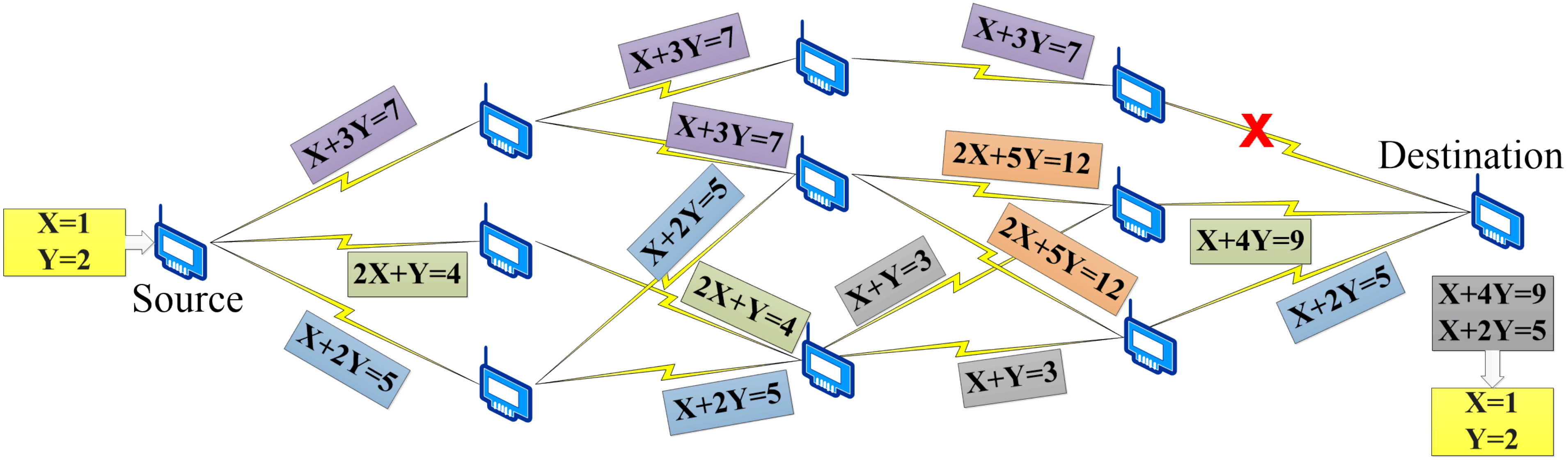
❷ Let's say that the second path and the fourth path fail to deliver their information.

❸ The recipient receives two pieces of information—X = 1 and X + Y = 4. From here simple arithmetic lets the recipient decode the original message.

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

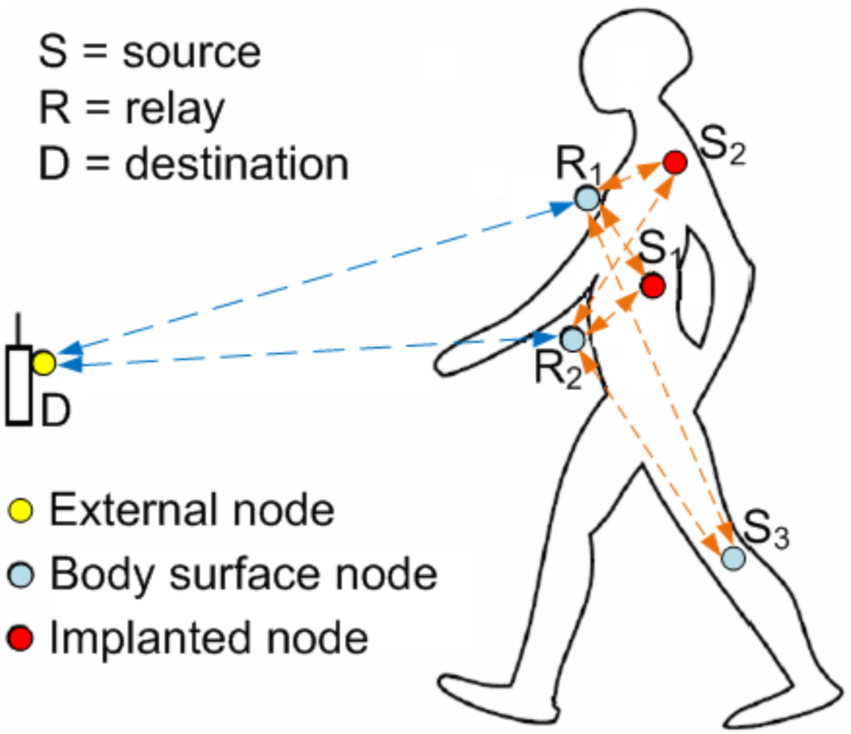
Cooperative Networking Coding [CNC]

- Each node decodes the received signals, creates an innovative [linearly independent] packet using the received signals and transmits it towards the destination.
- Benefits
  - Improved probability of successful reception and improved network reliability.
  - Reduce the number of packet re-transmissions.
  - Reduction in transmission energy requirements.



Cooperative Network Coding for WBANs

- Sensors use CNC to transmit their information through multiple hops to a receiving device (destination) via relays.
- Each node decodes the received signals, creates an innovative packet using the received signals and transmits it towards the destination.
- The relays act as MIMO devices by receiving multiple coded packets from the source and transmitting multiple coded packets to the destination.
- Benefits
  - Improved probability of successful transmission and network reliability.
  - Reduces the number of packet re-transmissions and transmission energy.
  - Single points of failure are avoided by having multiple relays and thus, multiple paths for the information to reach the destination.

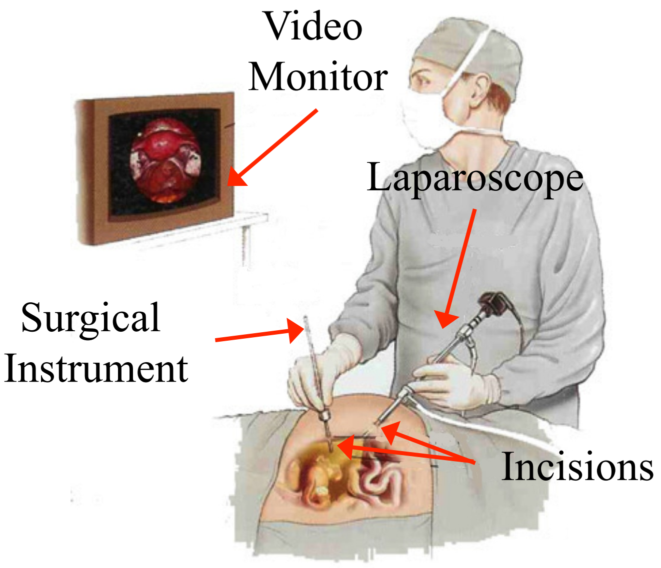


"Temporal Diversity Coding for Improving the Performance of Wireless Body Area Networks," *ACM BodyNets*, Sep. 2012.

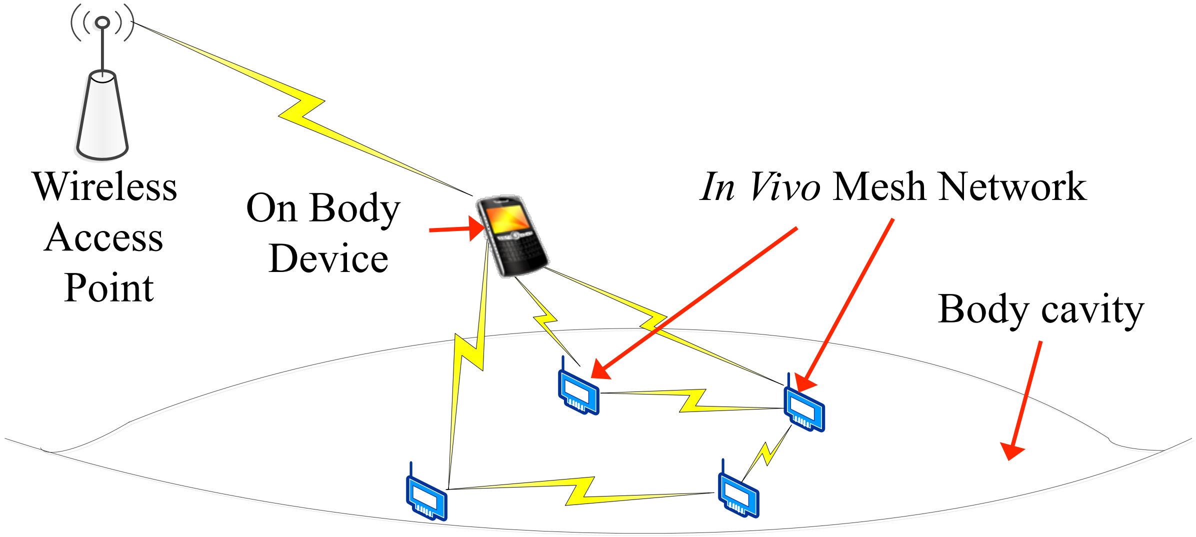
Advancing Minimally Invasive Surgery (MIS) via Wirelessly Networked Devices

- 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 --- including imaging devices, sensors and actuators, power sources, “cutting” tools.
  - Wirelessly addressable and controllable distributed network.
  - ***MARVEL*** Camera Module is the first device and requires *in vivo* bit rates (~100 Mbps) supporting HD video with low latency (<25ms). **Replaces laparoscope**.

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



Current laparoscopic technology



US Patent No. 8,358,981, *Minimally Invasive Networked Surgical System*

MARVEL Motivation

- To advance Minimally Invasive Surgery (MIS) surgery by providing capabilities that allow surgeons to treat diseases with minimal cost, invasiveness, and recovery times by
  - Decreasing the surgical-tool bottleneck experienced by surgeons by embedding surgical modules and using wireless communications and control
  - Eliminating power, video, and light source cabling issues in current laparoscopes
  - Increasing the dexterity and fine motion options for the surgeon
  - Increasing the visual perception of MIS to be equal to open-cavity operations

Laparo-Endoscopic Single Site (LESS) MIS surgery with a multi-port trocar and insufflation tube through the umbilicus

MARVEL is an *in vivo* Camera Module (CM) that is anchored to the abdominal wall and actuated by tiny motors, giving surgeons a full hemisphere range of view with wireless communications and control.

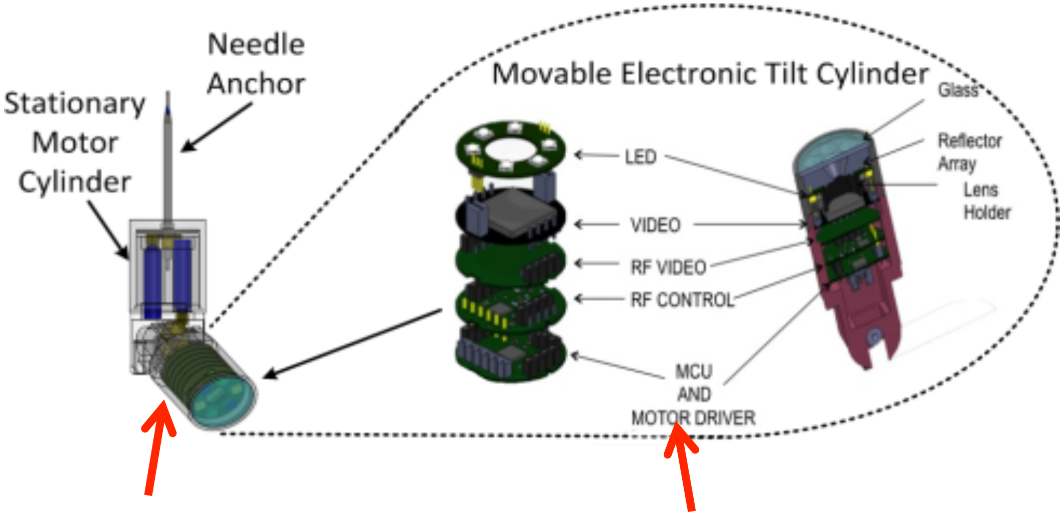
MARVEL Research Challenges

Research Challenges include

- *In vivo* channel modeling, signal processing, and optimization.
- Wireless communications: *in vivo* bit rates (~100 Mbps) supporting high-definition video with low latency (<25ms) during MIS.
- Networking paradigms for devices which are very limited from a communication and computing standpoint: sensing, actuation, authentication and security.

Status

- The figures illustrate the ***MARVEL*** design and USF vivarium experiments.
- ***MARVEL II*** design in progress with OFDM and HD with latency <25ms.



MARVEL CAD model and exploded circuit board stack

MARVEL units in a porcine abdominal cavity

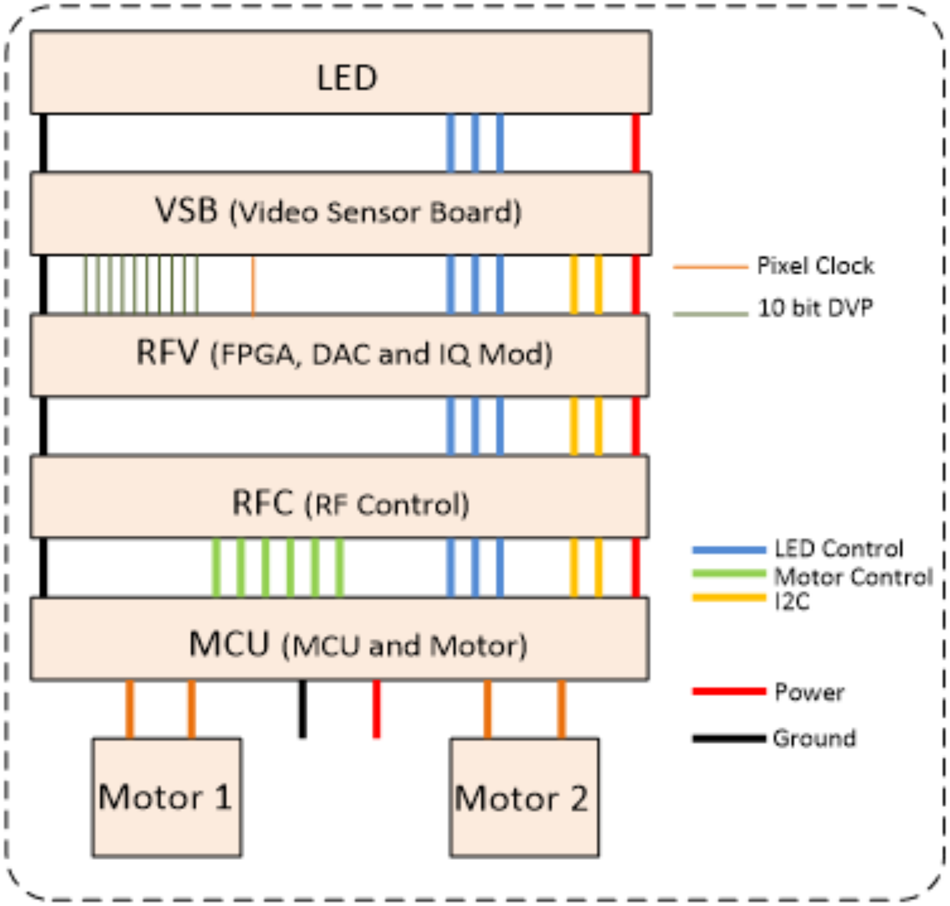
Image of internal organs captured by ***MARVEL***

"A Wireless Miniature Robot for Networked Expedited Laparoscopy," *IEEE Transactions on Biomedical Engineering*, 2013.

MARVEL II -30mm Outer Diameter Research Platform

HD Video and OFDM

- High-definition H.264-based video video and imaging capabilities
- OFDM wireless digital transmission
- HD video (1080p) at 30 fps without noticeable delay (< 25 ms)
- HD video and OFDM transmitter implemented on a FPGA



30 mm *MARVEL II* board arrangement

MARVEL II PCB Description

LED Board – single or multicolor LEDs for illumination

Video Sensor Board (VSB) – HD video sensor IC

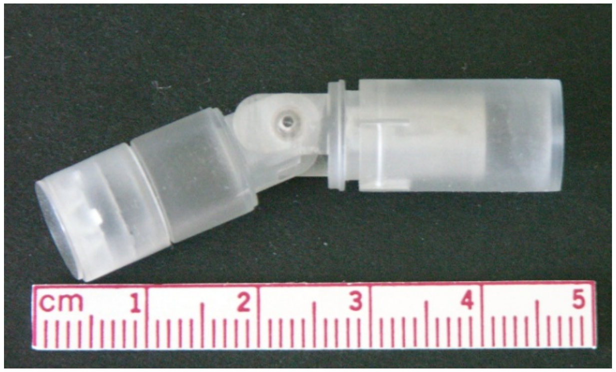
RF Video Board (RFV) – FPGA with HD compression, OFDM TX, and RF front end

RF Control Board (RFC) – Wireless motor control receiver IC

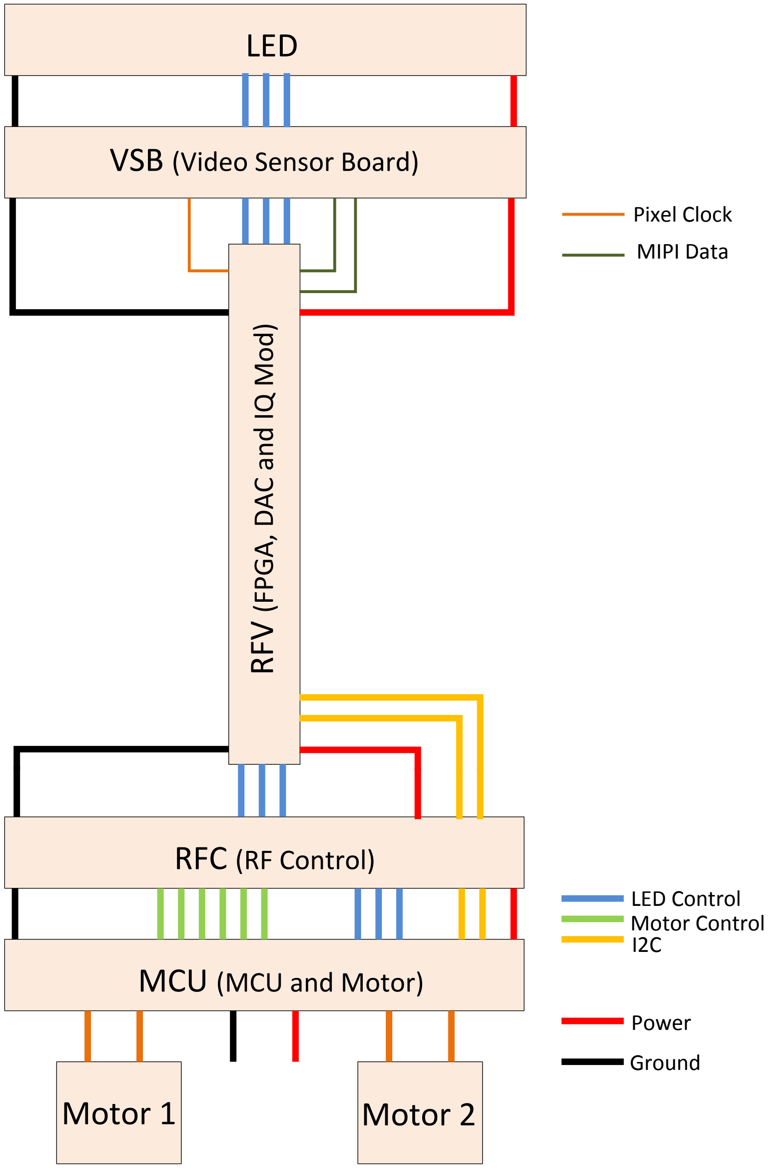
MCU and Motor Board – System processor and motor control ICs

MARVEL III- 10 mm (Right Sized for Surgery)

- 30 mm *MARVEL II* Platform reduced to fit in a 10 mm diameter form factor
- Same functionality as the 30 mm *MARVEL II*
- Due to large size of the current FPGA IC, the PCB holding the FPGA (RFV) will be stacked vertically so the stack can fit inside the 10 mm cylinder.



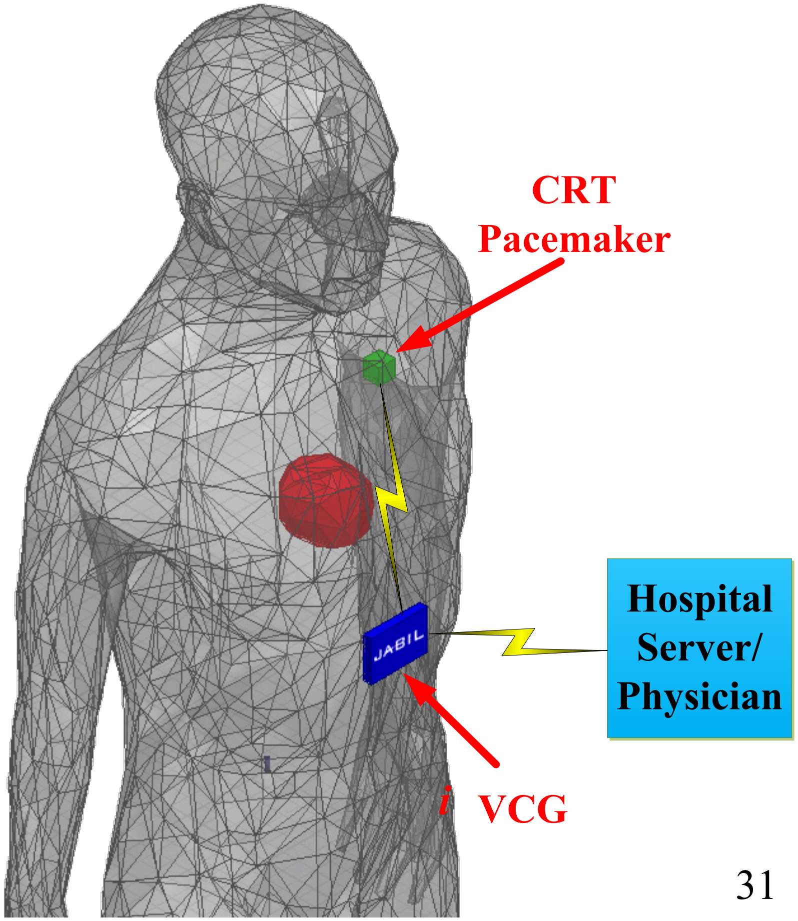
10 mm *MARVEL III* Cylinder



10 mm *MARVEL III* PCB Stack

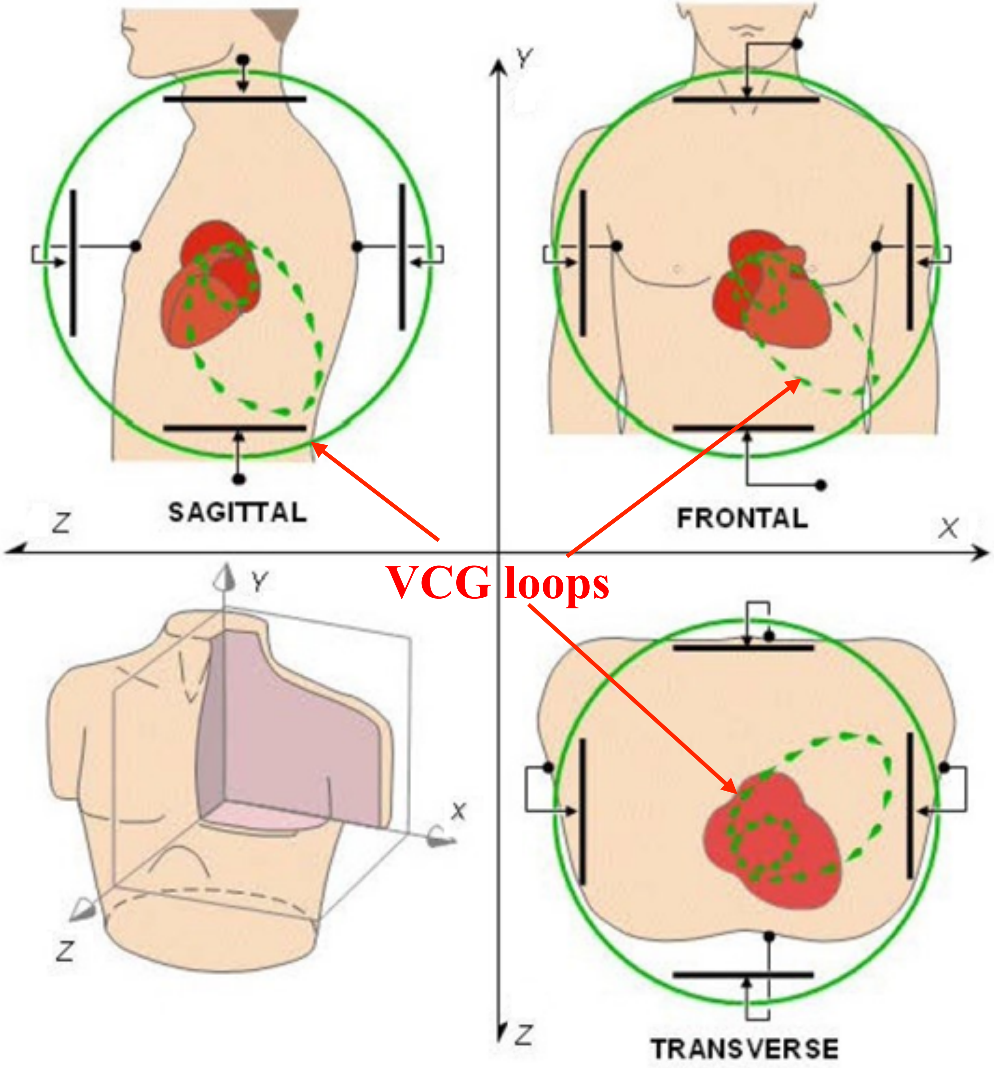
Improving the State of the Heart --- Vectorcardiogram *(iVCG)* Personalized Cardiac Rhythm Monitoring System

- The 3-lead Vectorcardiogram (VCG), invented in the 1930s, provides ≥ information than the 12-lead ECG.
- The VCG uses three orthogonal systems of leads to obtain the 3D electrical representation of the heart. To date, the VCG has only been a pedagogical tool.
- A system may be comprised of an integrated wireless VCG (*i*VCG), CRT pacemaker, and an associated server.
- With today's technology an integrated/ miniaturized VCG, ***iVCG***, can enable <u>diagnostic-quality</u> long term cardiac rhythm data collection ["BIG DATA"] to be continuously wirelessly received and processed. <u>This capability has never been available before.</u>
- **Project Objectives**:
  - A 24x7 on body wireless *iVCG* with machine learning capabilities, the size of a band aid and with the diagnostic capability ≥ ECG.
  - Embedded *iVCG*.



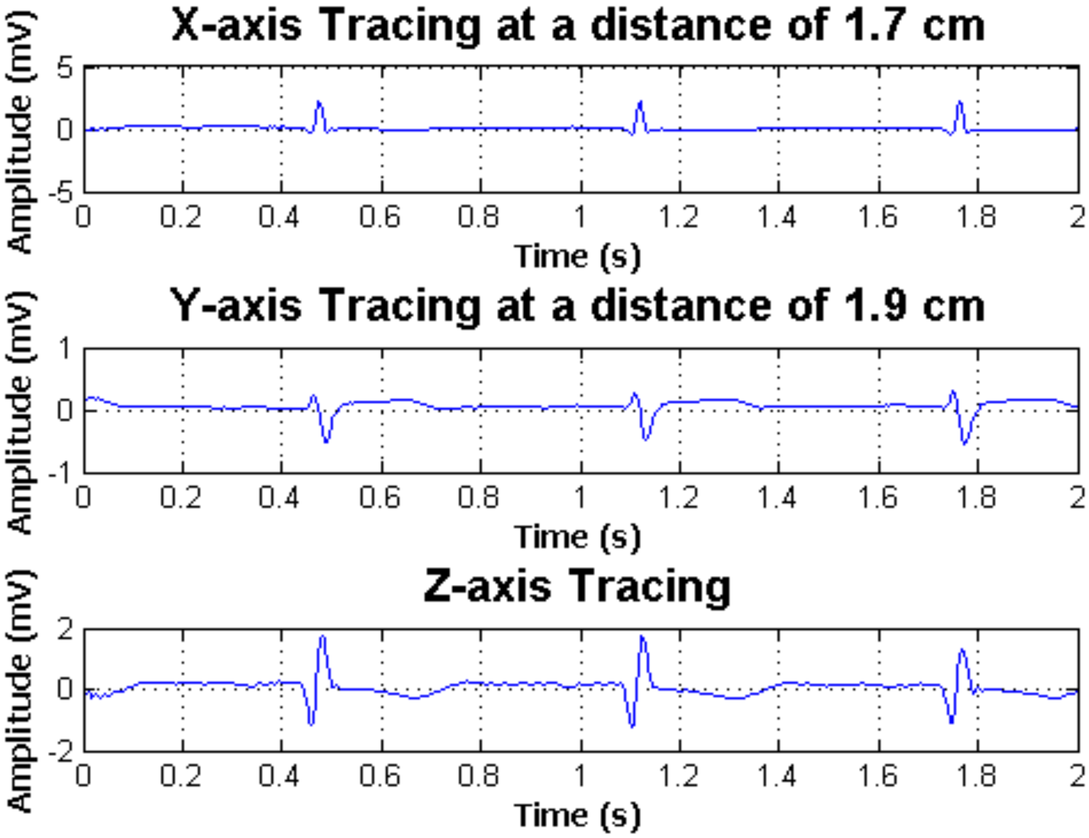
Vectorcardiogram (VCG)

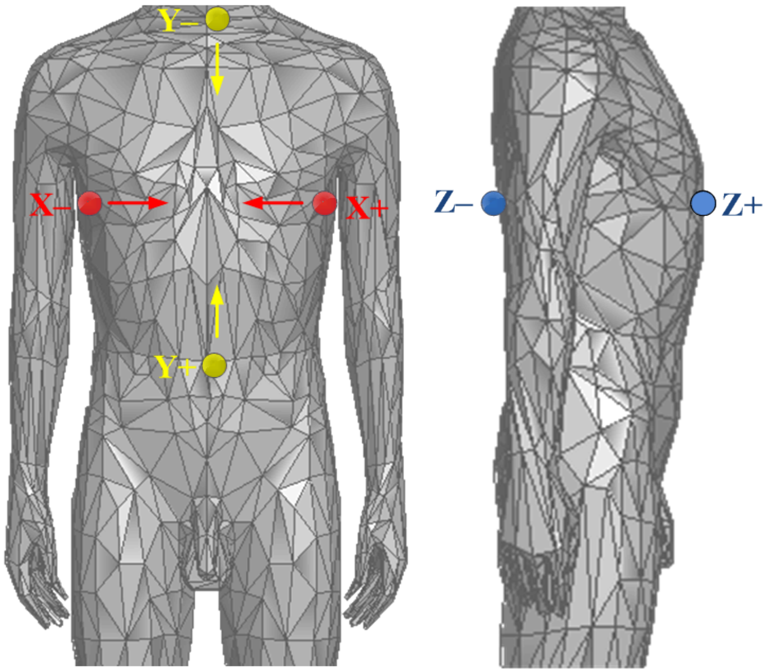
- The VCG uses three orthogonal systems of leads to obtain the 3D electrical representation of the heart.
- The information content of the VCG is the same as that of the leads V2, V6 and aVF in the 12-lead system.
- The figure shows the VCG signal viewed from the three Cartesian planes (X-Y, Y-Z, and X-Z).
- The direction of the heart vector can be computed from the VCG loops (dashed green curves in the figure).
- Each loop is a plot of the magnitude and movement of the cardiac signal vector during the cardiac cycle.



VCG loops

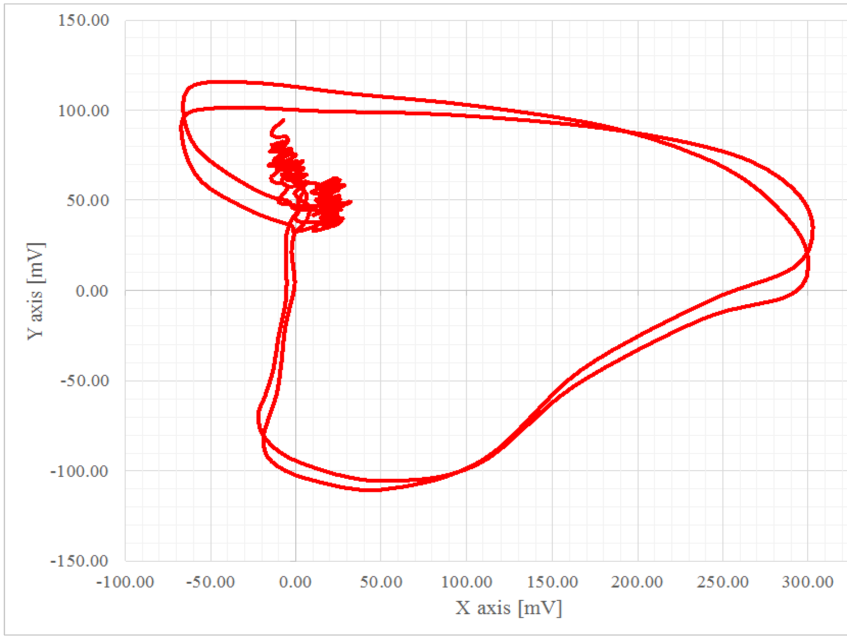
VCG Electrodes at Minimum Distances Maintain Diagnostic Quality



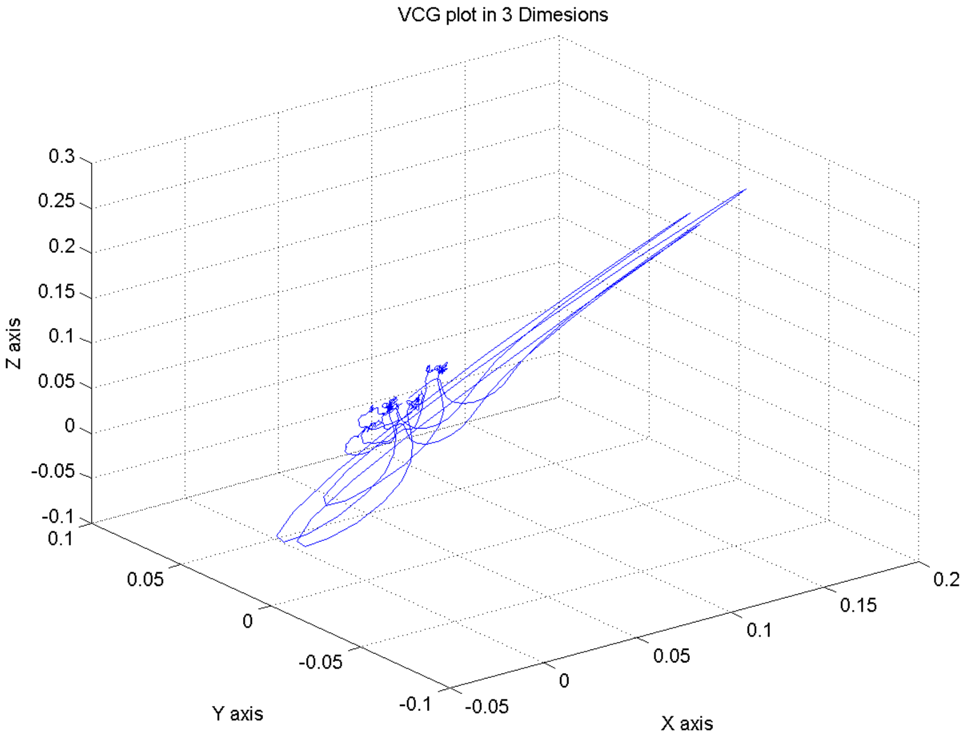


- As the proximity between the leads is decreased, the signals suffer a loss of amplitude and distortion (orthogonality) and are degraded relative to that of a 12-lead ECG.
- To compensate, we are designing post-reception signal processing techniques.
- **Diagnostic quality VCG signals at <2cm distances → personalized device.**

VCG Loops Indicating the Direction of the Heart Vector



VCG X and Y traces showing the frontal (Coronal) Plane

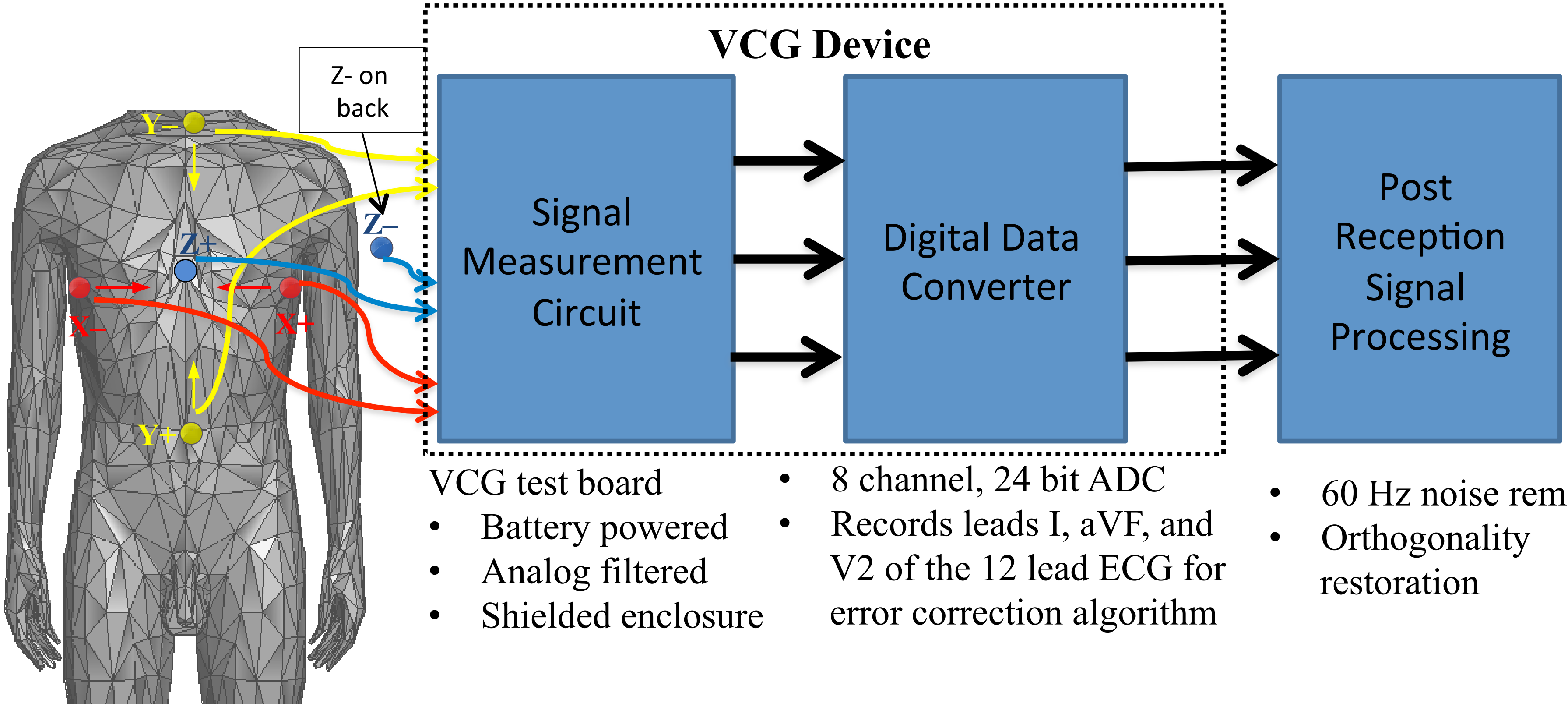


The VCG cardiac rhythm vector as a function of time

VCG loops contain ≥ information than 12-lead ECG

iVCG Research Platform

- The goal of the ***iVCG*** design is a 3x3x2 cm device.



VCG Device

Signal Measurement Circuit

Digital Data Converter

Post Reception Signal Processing

VCG test board
- Battery powered
- Analog filtered
- Shielded enclosure

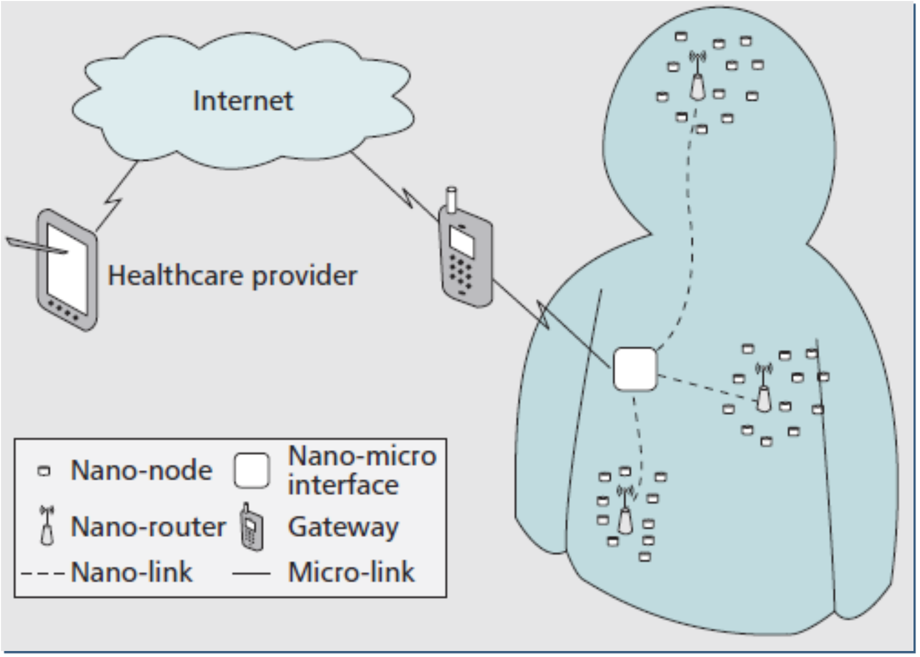
- 8 channel, 24 bit ADC
- Records leads I, aVF, and V2 of the 12 lead ECG for error correction algorithm

- 60 Hz noise removal
- Orthogonality restoration

- At the time of fitting the VCG device to the patient, a 12-lead ECG can be used for calibration and determination of processing parameters.
- The VCG signals and the ECG signals are processed to determine the underlying transformation matrix between the two formats.
- It is expected that this transformation matrix will differ slightly from person to person and will be customized for each patient.

Next Step: Wireless Nano Networking*

- Classical communication paradigms need to be revised for the nanoscale. The two main alternatives for communication in the nanoscale are based either on electromagnetic communication or on molecular communications.
- 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 of a few hundred nanometers or a few micrometers.
  - 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: I. Akyildiz and J.M. Jornet, The Internet of Nano-Things, *IEEE Wireless Communications*, December 2010

*IEEE P1906.1 - Nanoscale and Molecular Communications

In Vivo Wireless Communications and Networking - Observations and Summary

- ***In vivo* Channel Modeling** --- Still in the early stages
  - Path loss can be up to 45 dB greater than the free space path loss.
  - Path loss vs. frequency and distance both increase faster than free space.
  - *In vivo* dispersion can be significantly greater than suggested by the physical dimensions since the speed of propagation is reduced.
- **MIMO *In Vivo*** --- Encouraging results
  - MIMO *in vivo* can achieve significant system capacity gain over SISO.
  - Significantly system capacity gain when RX antennas are placed at the back or the front of body, rather than at the side of the body.
  - The SAR power limit significantly affects the MIMO *in vivo* system performance and increased system bandwidth may not increase MIMO *in vivo* system capacity.

In Vivo Wireless Communications and Networking - Observations and Summary

- **Cooperative Network Coding [CNC]**
  - Cooperative Network Coding improves the probability of successful reception at the destination, transparent self-healing, and fault-tolerance.
  - The feed-forward nature of CNC is an attractive means to improve packet loss and the probability of success for real-time applications.
- The ***MARVEL*** and ***iVCG*** projects are potentially transformative technologies that rely on *in vivo* communications and networking.

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