Wireless *In Vivo* Communications and Networking

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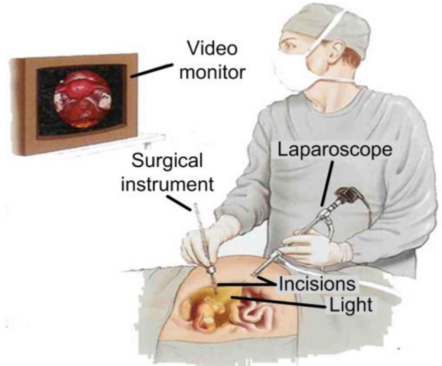
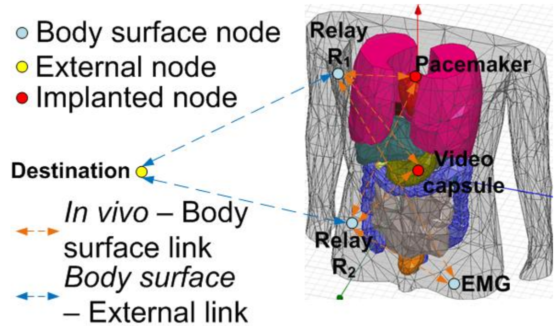
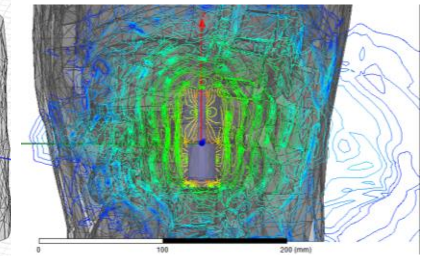


Minimally Invasive Surgery



Wirelessly networked modules


Modeling the *in vivo* communications channel

Motivation: Wireless communications and networking has the potential to significantly advance healthcare delivery solutions by creating *in vivo* wirelessly networked cyber-physical systems of implanted devices. These systems can use real-time data to enable rapid, correct, and cost-conscious responses in surgical, diagnostic, and emergency circumstances. Our initial research focus is on creating a new paradigm for Minimally Invasive Surgery (MIS).

Research Challenges: (1) Modeling the *in vivo* wireless channel, (2) inventing new communications and networking solutions for embedded devices of limited complexity, (3) meeting the high bit rate and low latency requirements of surgical applications (e.g., HDTV), (4) developing new approaches to privacy and security for devices of limited processing capabilities, and (5) machine learning of optimal clinical decisions/actions that are determined in real time by processing the stream of sensor data vectors.

Research Objectives: (1) Architecting and realizing a network of wirelessly controlled and communicating *in vivo* devices that will facilitate a new paradigm for Minimally Invasive Surgery (MIS), (2) creating novel *in vivo* wireless communications and networking technologies, and (3) inventing learning systems to make optimal decision to support these devices and advance the performance wireless body area networks (WBANs) that will support MIS and other biomedical healthcare applications.

***In vivo* wireless communications systems: invention, analysis, design, and implementation**

MARVEL: Miniature Advanced Remote Videoscope for Expedited Laparoscopy

MARVEL: A wirelessly controlled and communicating high-definition video system that provides the visual advantages of open-cavity surgery for Minimally invasive Surgery (MIS).

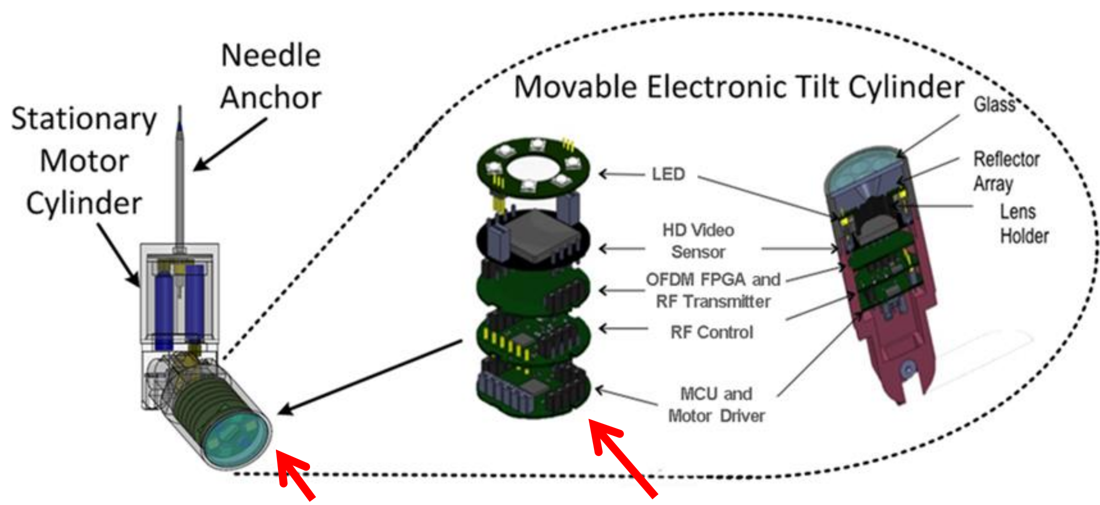
Key Issues and Challenges: (1) achieving reliable, high- throughput and low-latency *in vivo* wireless communications and networking, (2) electronic and mechanical miniaturization of complex systems, (3) localization and mapping of the intra-body camera unit and surrounding organs and tissues and (4) networking of multiple embedded devices with different functions.

Research Directions: *In vivo* wireless *MARVEL* devices that enable control of various functions including motion, video zoom and LED illumination. These devices will also include full digital HD video transmission implemented on a field programmable logic array (FPGA) with near zero latency and will be scalable in architecture and design with the goal of transferring the capabilities of a 30 mm diameter research platform to a 10 mm commercial device.

Impact: The development and demonstration of a semi-autonomous wirelessly controllable *in vivo* device for minimally invasive surgery with scalable architecture can be the first step in a paradigm shift in MIS.

MARVEL CMs inside a porcine subject

Image of porcine internal organs taken by a *MARVEL CM*



CAD model of *MARVEL* 30 mm CM and exploded circuit board stack

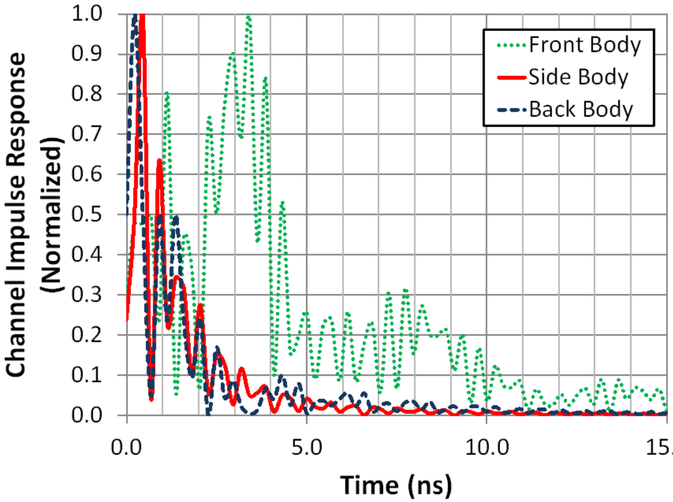
In vivo Channel Modeling

Goal: Understanding the characteristics of the *in vivo* channel and optimizing the *in vivo* physical layer signal processing for high-performance wireless body area networks (WBANs) and remote health monitoring platforms.

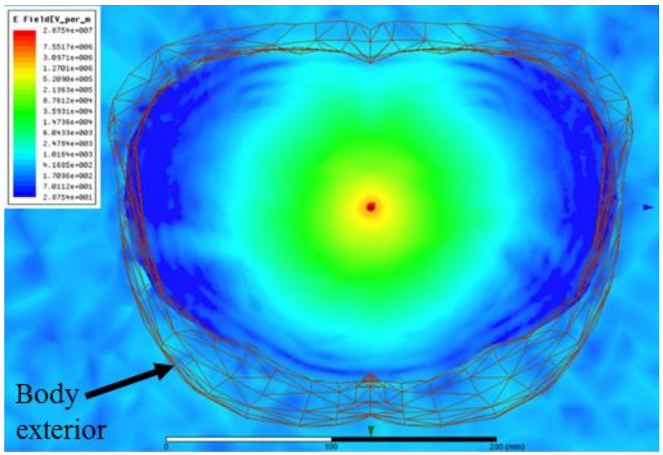
Challenges: High data rate RF communications from *in vivo* devices will likely be challenging given (1) the frequency and spatially dependent dielectric properties of human body tissues (2) the *in vivo* environment is an inhomogeneous and very lossy medium, (3) the far field assumption is not always valid, and (4) additional factors such as highly variable propagation speeds due to different organs and tissues that lead to angular dependent dispersive properties.

Approaches: The ANSYS HFSS human body model software includes muscles, bones and organs modeled to 1 mm. The software computes the total electromagnetic fields produced by radiating elements in the *in vivo* environment and are used to derive path loss and the corresponding channel impulse response as a function of frequency, antenna type and form factor, and antenna location.

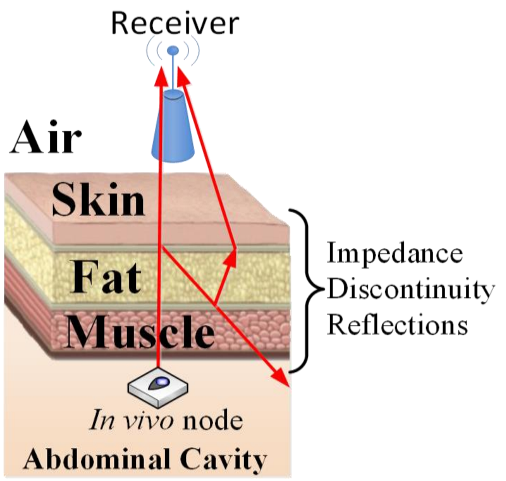
Impact: Knowledge of the *in vivo* channel facilitates the design of optimized implanted antennas, the optimal location of the transmitters and receivers, and the design of MIMO *in vivo* systems.



Channel Impulse Response of signals traveling in different direction from center of body



Top view of the *E* field (in the XY plane) radiated by Hertzian-Dipole at 2.4GHz.



In vivo wireless channel

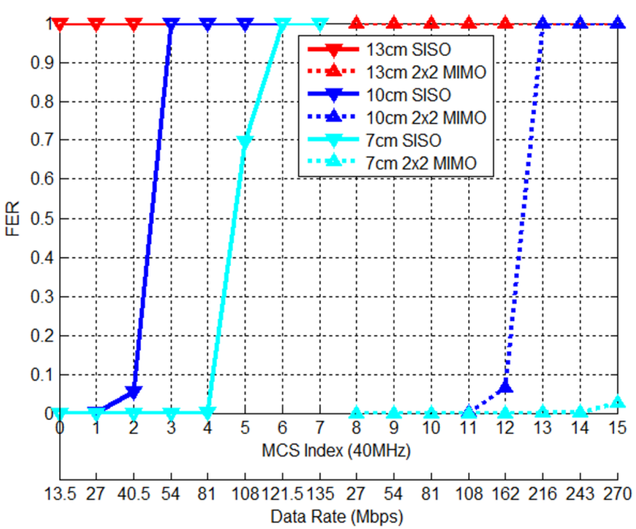
MIMO *in vivo*

Motivation: The lossy and highly dispersive nature of the *in vivo* environment, makes achieving high data rates with reliable performance a challenge. Power levels are limited by the specified specific absorption rate (SAR).

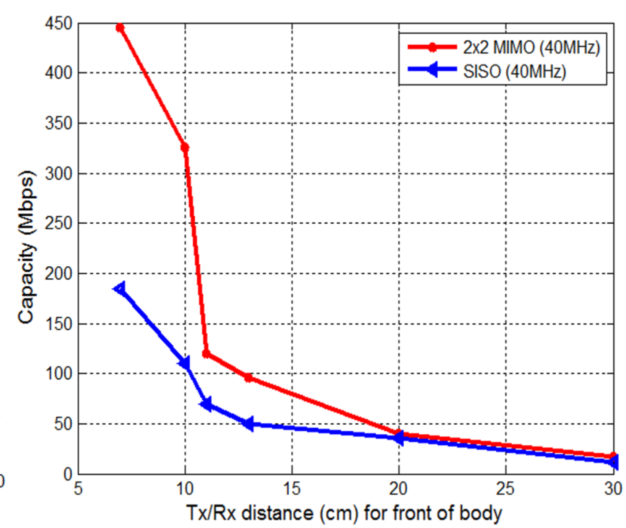
Approach: Demonstrating increased data rates and reliable *in vivo* communications by the use of multiple-input multiple-output (MIMO *in vivo*) antenna technology. Performance is evaluated by SystemVue/HFSS simulation methods considering various factors such as antenna separation, antenna angular positions, and channel bandwidth.

Objectives: Analyze and optimize MIMO *in vivo* performance based upon static and statistical *in vivo* channels to explore the potential of MIMO *in vivo* to achieve stringent requirements of high data rate applications.

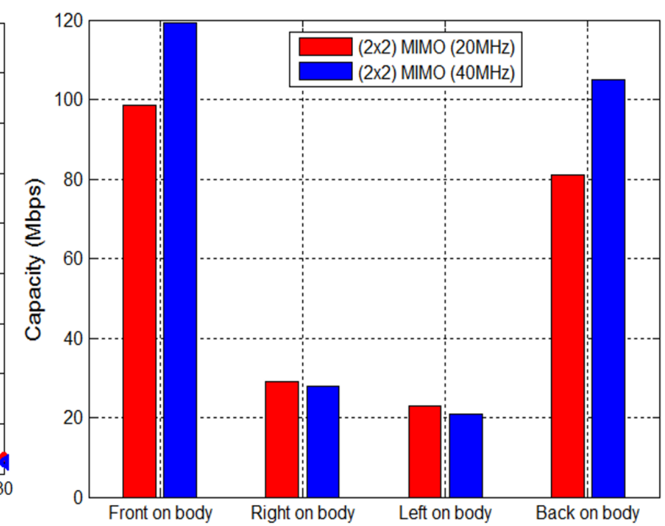
Results: Compared with single-input single-output (SISO) systems, MIMO *in vivo a*chieves significant performance gains, while meeting the maximum SAR levels, making it possible to achieve target data rates of 100 Mbps with a system bandwidth of 40 MHz.



MIMO vs SISO *in vivo* FER (Frame Error Rate)



Capacity vs distance



Capacity vs Rx antenna locations

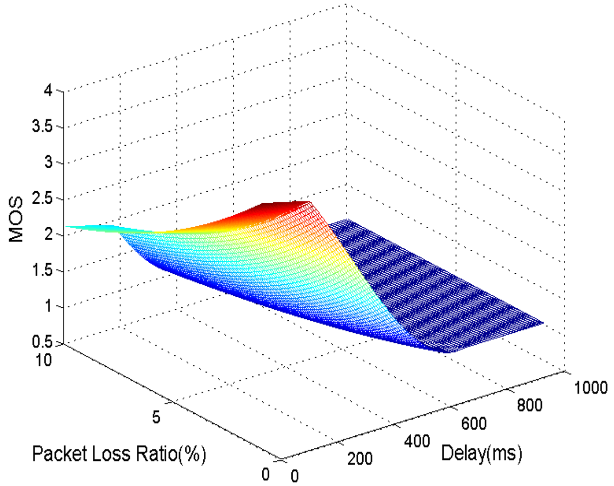
HAMCR---Holistically Application-Aware Multi-Dimensional Cognitive Radio

Motivation: In today's wireless 4G LTE networks, the spectral allocation of resources relies on a set of pre-defined fixed priorities. The QoS [Quality of Service] required by a given application can be quite variable for different users. For example, the spectral content of voice and video can be reduced for older people to improve quality for other users and/or to increase capacity.

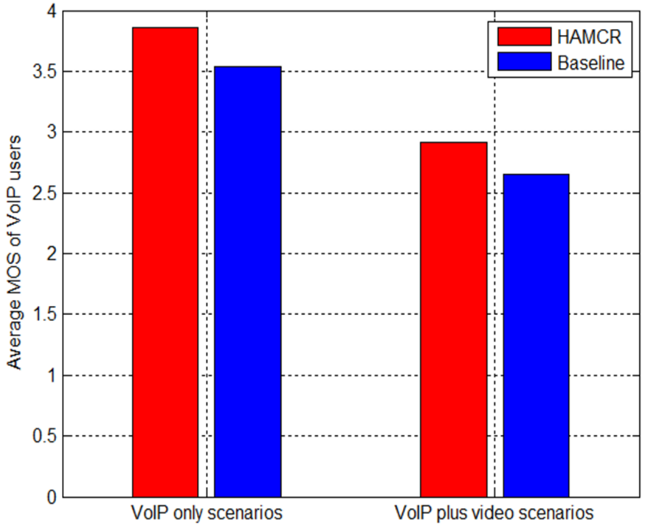
Approach: We created: (1) User-specific utility functions to differentiate categories of users, (2) resource schedulers that process the User-Specific QoS [US-QoS] to optimize the spectral allocation, and (3) a wireless testbed to evaluate the quality and capacity gain of US-QoS schedulers in realistic communication scenarios.

Objectives: Design US-QoS aware wireless resource MAC schedulers to (1) improve user satisfaction, as measured by the Mean Opinion Score (MOS), and/or (2) improve system capacity by trading off the spectral resource allocations for the US-QoS requirements, while still maintaining acceptable levels of MOS.

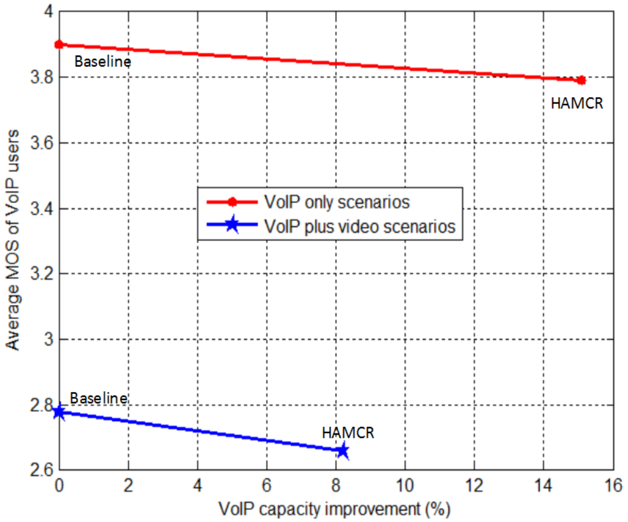
Results: Approximately 10% MOS or system capacity improvements can be achieved if US-QoS requirements are considered in the user-specific QoS aware schedulers.



VoIP MOS utility function



VoIP MOS improvement



VoIP MOS and capacity tradeoff

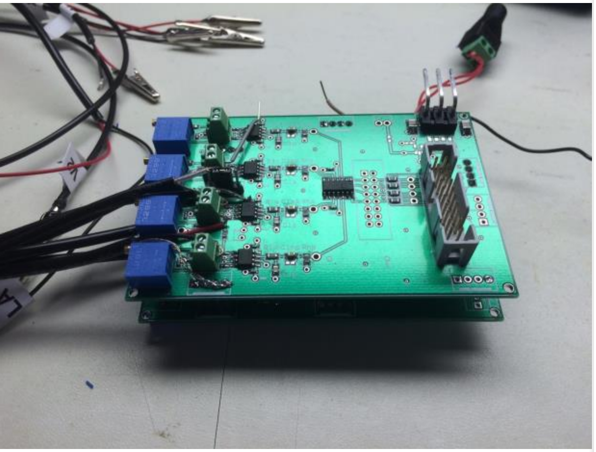
Cardiac Rhythm Monitoring – Vectorcardiogram (VCG)

Motivation: The vectorcardiogram (VCG) is a compact external cardiac rhythm monitor that uses three orthogonal signal (leads) to obtain a 24x7 "big data" electrical representation of the heart that is equivalent to the 12-lead "gold standard" electrocardiogram (ECG). The VCG wirelessly communicates data to a server and/or a physician.

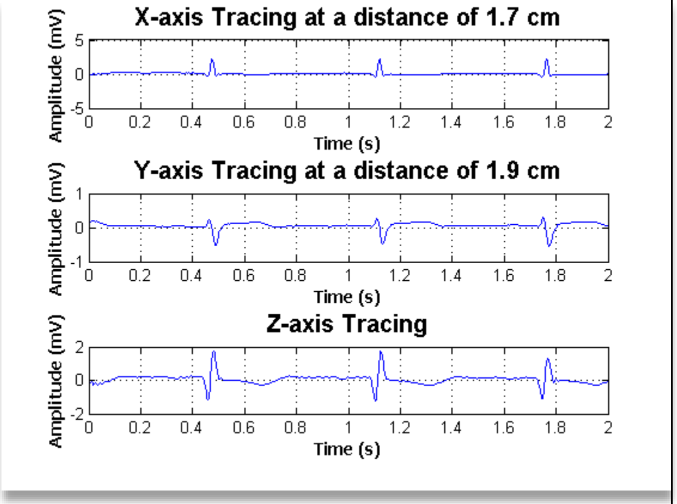
Key Issue and Challenges: To provide long-term and, continuous cardiac rhythm monitoring, the research challenges include (1) miniaturization of the VCG system, (2) develop highly sensitive contact and non-contact voltage sensing electrodes, and (3) post-processing of the measured heart signals to remove noise, restore signal orthogonality and converting to 12-lead ECG format (4) designing an implanted VCG.

Research Directions: (1) A VCG with a very small form factor (the size of a band aid), (2) integrate learning and wireless communication capabilities into the VCG, (3) feasibility of using the VCG as a multi-sensor platform, and (4) predictive algorithms that can leverage VCG BIG DATA for cardiac event forecasting.

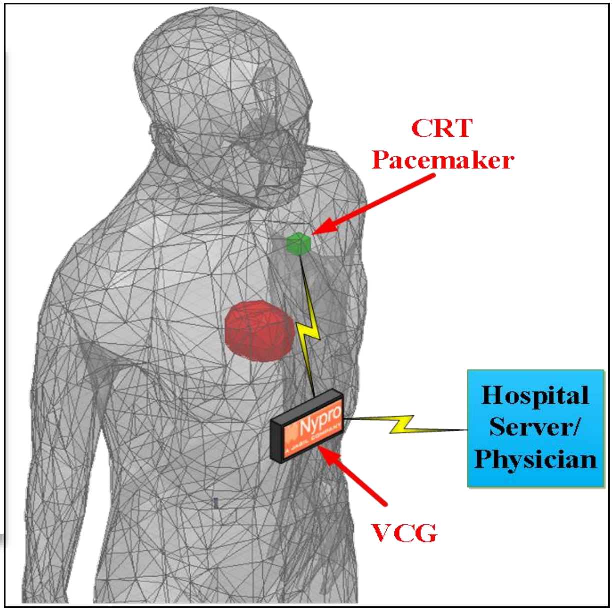
Impact: The VCG is a breakthrough CRM technology that allows long term and continuous remote diagnostic-quality monitoring of a patient's electrical heart activity.



Prototype VCG system



VCG signals at minimum distances



VCG System

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