Smart Cooperative Wireless Sensor Networks for Healthcare and Performance Monitoring: ***Antennas and Radios Prospective***

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Outline

- Introduction
  - Why Body-Centric Communications for healthcare?
  - Applications
  - Challenges
- Domains of Body-Centric Wireless Communications
  - In-Body
  - On-Body
  - Off-Body
- Going Smarter ...
  - The smarter and the greener … the better
  - From Recognition to Cognition!
  - Scaling down to Nano

Contribution & Acknowledgement

- Queen Mary, University of London
  - Prof. Yang Hao
  - Prof. Clive G. Parini
  - Dr Yan Zhao
  - Dr Andrea Sani
  - Dr Raffaele Di Bari
  - Dr Qammer H. Abbasi
  - Dr Sheng Wang
  - Dr Max Ovidio Munoz Torrico
  - Tamer Aboufoul
  - Richa Bharadwaj
  - Ke Yang
  - Nanda Khaorapapong
- Imperial College London, UK
- University of Birmingham, UK
- Institute for Infocomm Research (I^2R), Singapore
- Dublin City University, Ireland
- University of Pisa, Italy
- National ICT Australia

Why Body-Centric Wireless Comms?

- Replaces cables and provide flexibility to today's demanding users
- Natural progression of Wireless PAN
- Should provide constant availability, re-configurability, unobtrusiveness and true extension of a human's mind

© Reima Smart Clothing, Finland

Why Body-Centric Wireless Comms?

- Wearable computers used in various applications such as:
  - Military
  - Healthcare
  - Sport
  - Education
  - Industrial control
  - Research
  - Fashion

Wearable computers courtesy of Xybernaut, Germany

Motivations & Needs

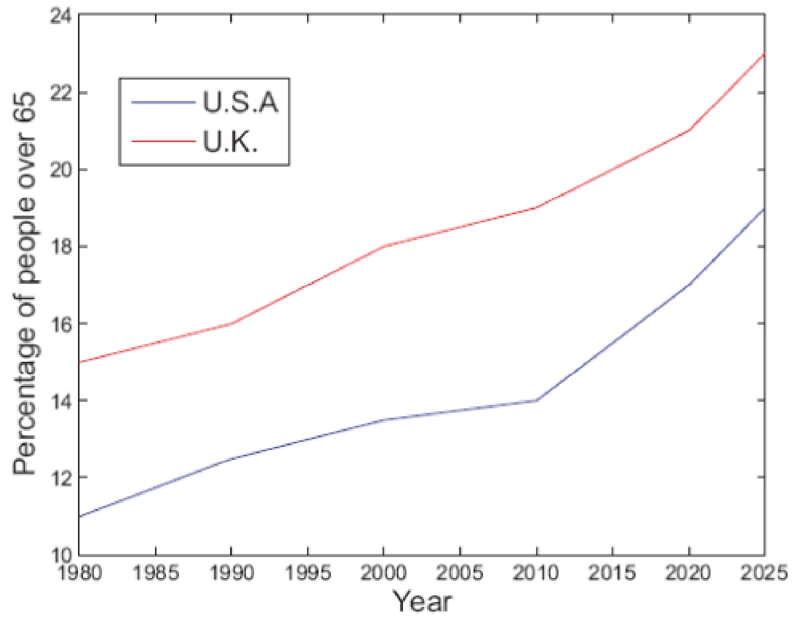
- Wireless sensor networks for healthcare applications is forecasted to save around $25 billion worldwide*
- Estimates suggest patient monitoring WSNs, including outpatient and self-monitoring applications made up half of the total units sold in 2012, or ~ 2.8 million units
  - 120,000 units were sold during 2007.
- In 2012 it is estimated that there was around 429,000 wireless sensor networks shipped worldwide for hospital or clinical applications for patient monitoring applications worth around $528 million, including services.

BodyTel™
(www.bodytel.com)

*WSN for Healthcare: A Market Dynamics Report Published August 2008, URL: http://www.onworld.com/healthcare/index.html

Aging Population

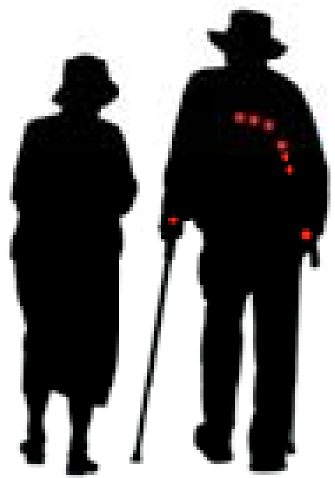
- Market size for assistive living technology in 2015*:
  - EU → $525.7m
  - UK → $141m



- Aging population (over 65) in the UK is projected to grow to 2.6m in 2018 and to 5.1m in 2028

- By 2030:

UK	USA	China
24%	20%	13%



*Older People in The United Kingdom – Key facts and statistics, Age Concern's Policy Unit 2008

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Body-Centric Wireless Comms (BCWC)

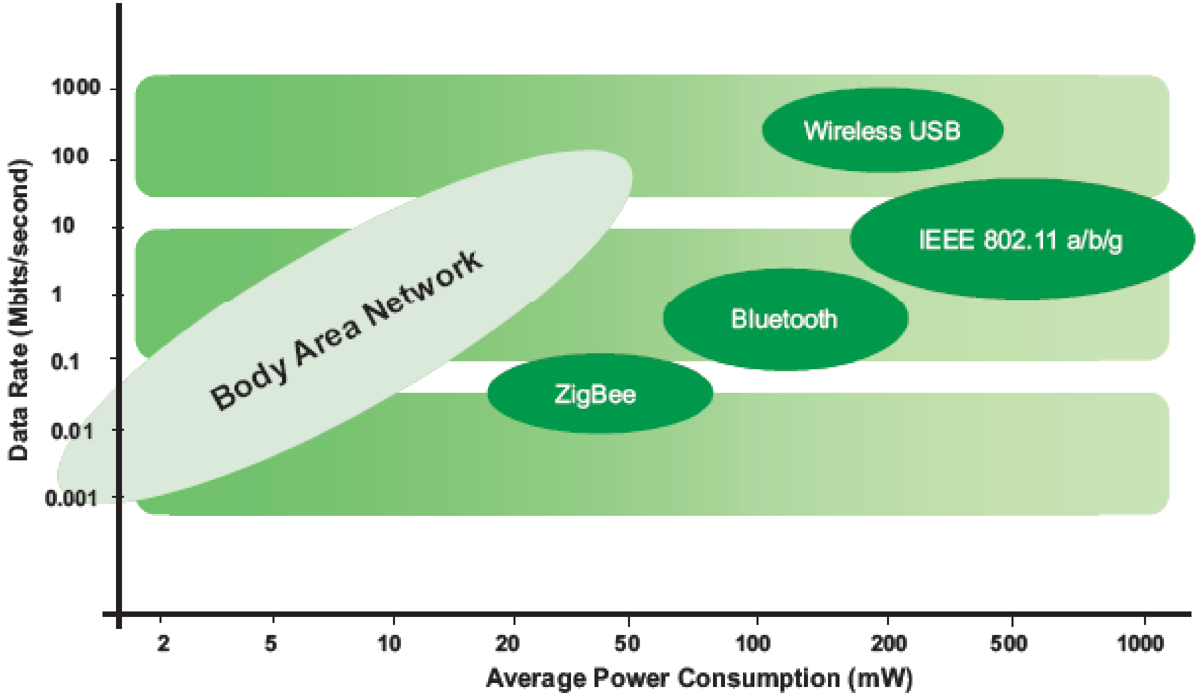
- Human-self and human-to-human networking with the use of wearable and implantable wireless sensors.

- It combines wireless body-area networks (WBANs), Wireless Sensor Networks (WSNs) and Wireless Personal Area Networks (WPANs).

- IEEE 802.15 WPAN^{TM} Task Group 6 Body Area Networks (BAN)

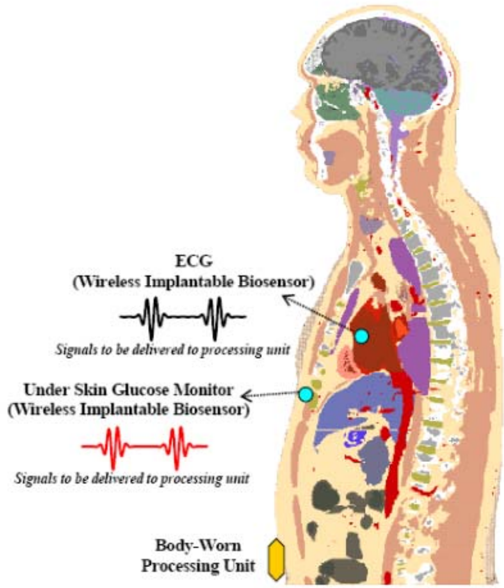
IEEE 802.15 Task Group 6 - BAN

- ***formed in November 2007 and standard released in February 2012***
- Setting a communication standard optimized for low power devices and operation on, in or around the human body (but not limited to humans) to serve a variety of applications including medical, consumer electronics, personal entertainment and other.

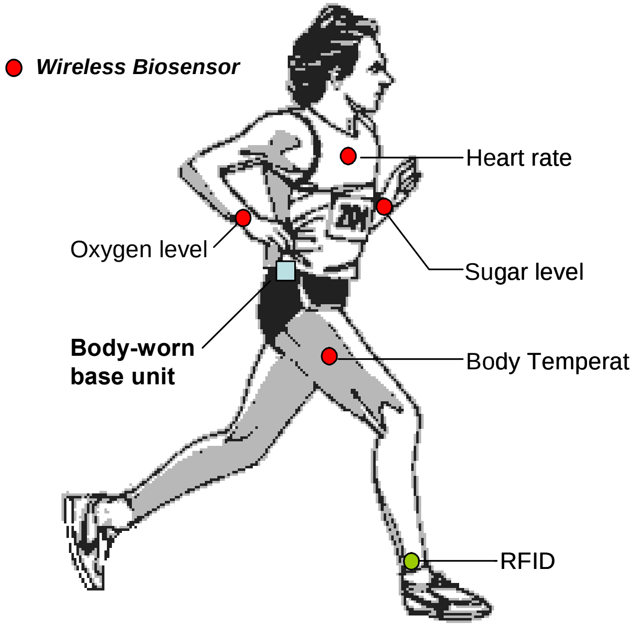


Applications of Interest

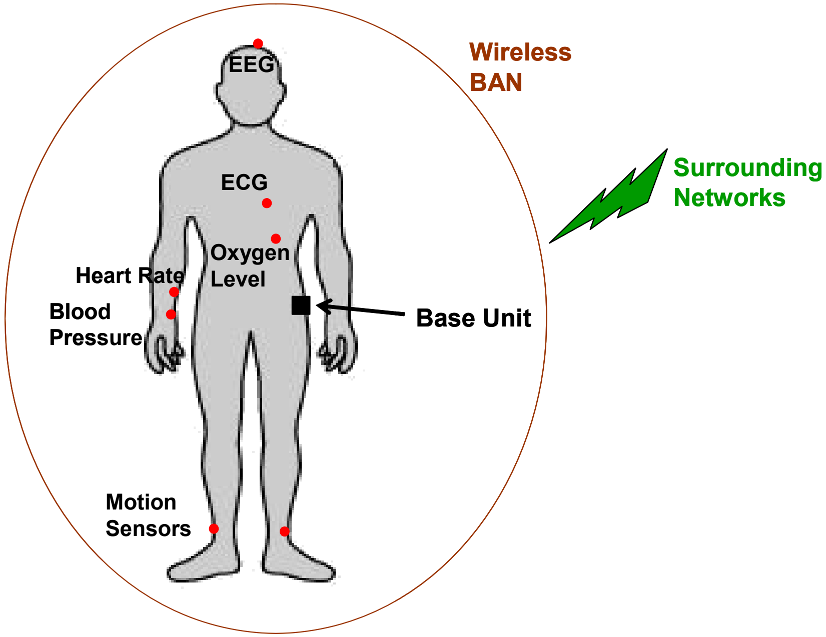
In-body



On-body



Off/on-body



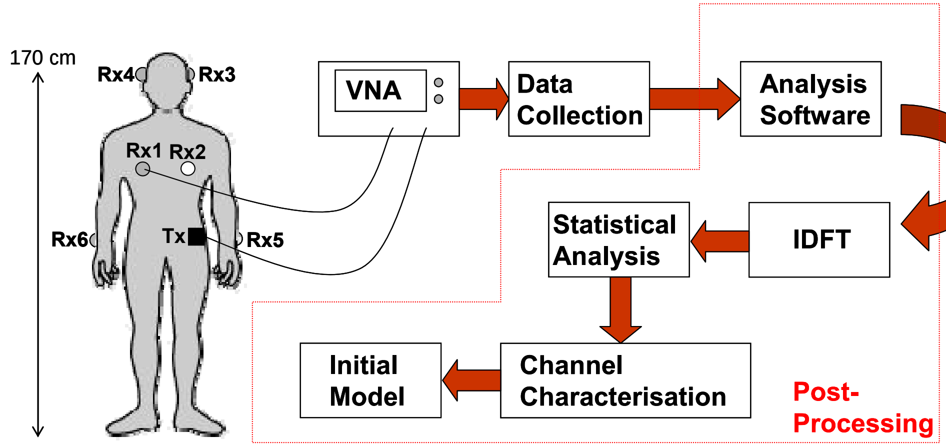
Sport Performance Monitoring

Healthcare & Medical Applications

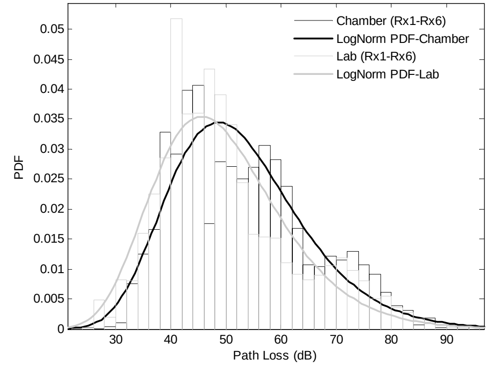
Challenges

- Technology
  - Antennas
  - Wave propagation
  - Radio transceivers
  - Power consumption
- Architecture
  - Context-awareness
  - application-specific
  - user friendly
- Software Systems
  - Recognition of gestures and commands
  - Communication adjustment

Research Activities for Body-Centric Wireless Comms

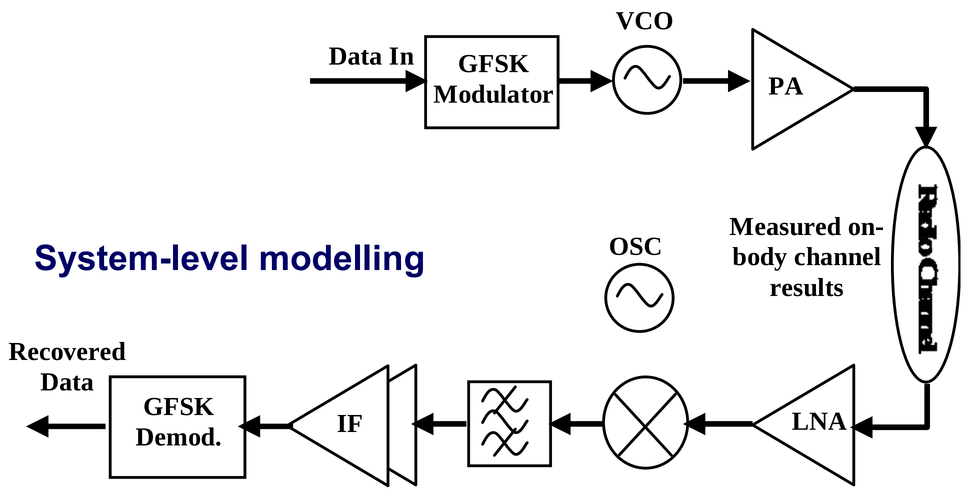


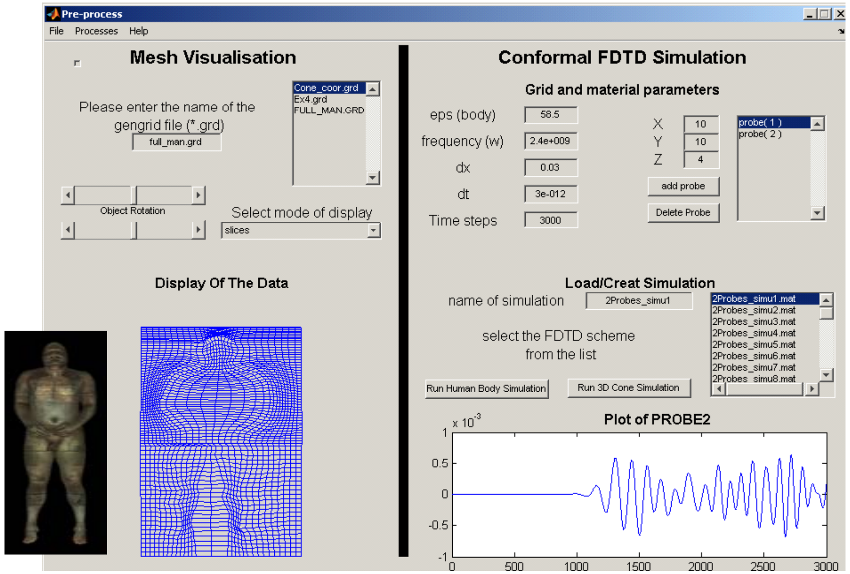
Radio channel characterisation and modelling



In-house conformal FDTD

System-level modelling





*Peter Hall and Yang Hao, "**Antennas and Propagation for Body-Centric Wireless Communications**", 2006, Artech House.*

Alomainy et al., "Statistical Analysis and Performance Evaluation for On-body Radio Propagation with Microstrip Patch Antennas", IEEE Transactions on Antennas and Propagation, Vol. 55, Issue 1, January 2007, pp:245 - 248.
Alomainy et al., "UWB On-Body Radio Propagation and System Modelling for Wireless Body-Centric Networks", IEE Proceedings Communications-Special Issue on Ultra Wideband Systems, Technologies and Applications, Vol. 153, No. 1, February 2006.

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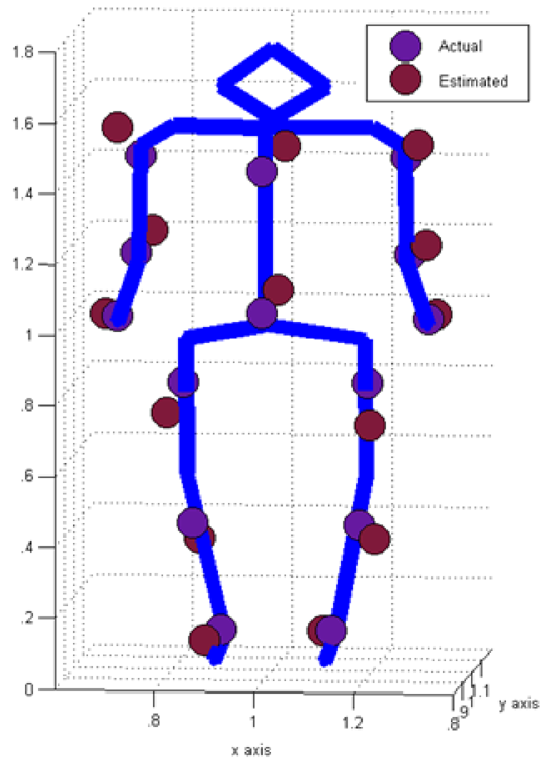
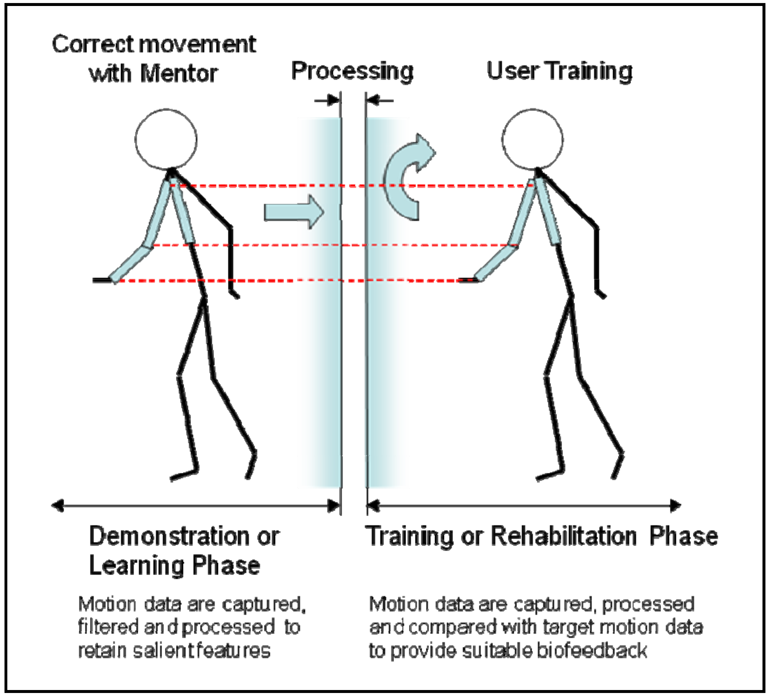
Accurate Localisation using Prior Knowledge

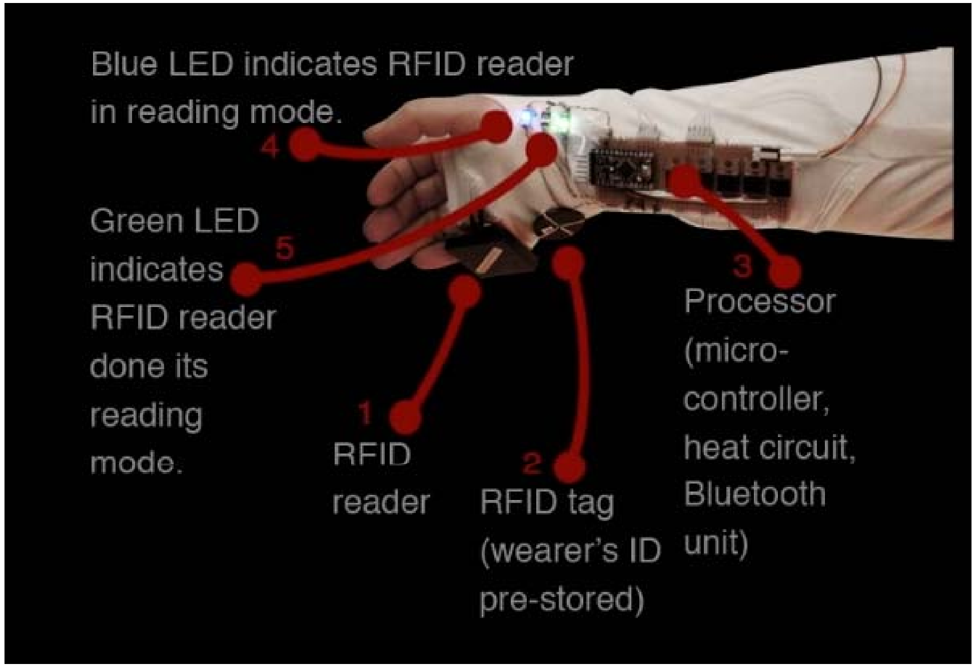
- **New techniques and methods to enable the development of a portable yet accurate hand motion capture system with ease of use and reasonable degree of freedom.**

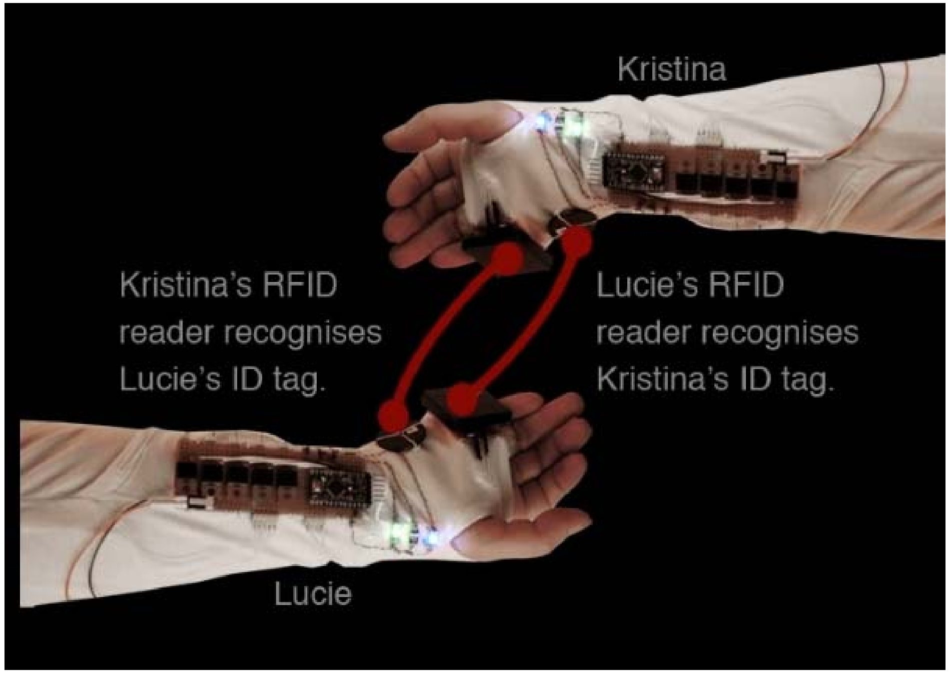


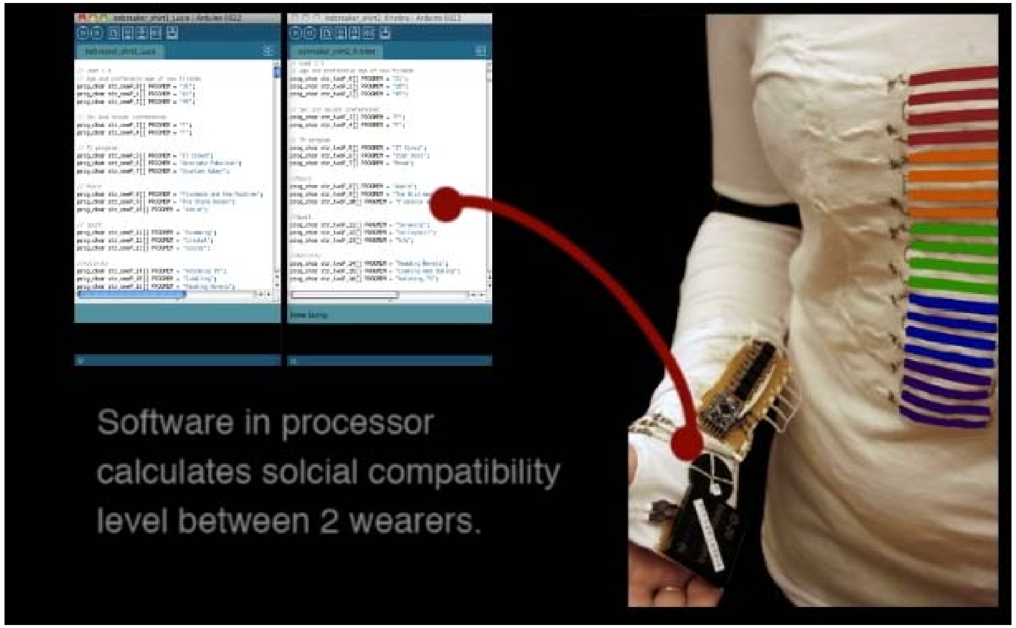


Controlling Robotic Hands

Augmenting Social Interaction







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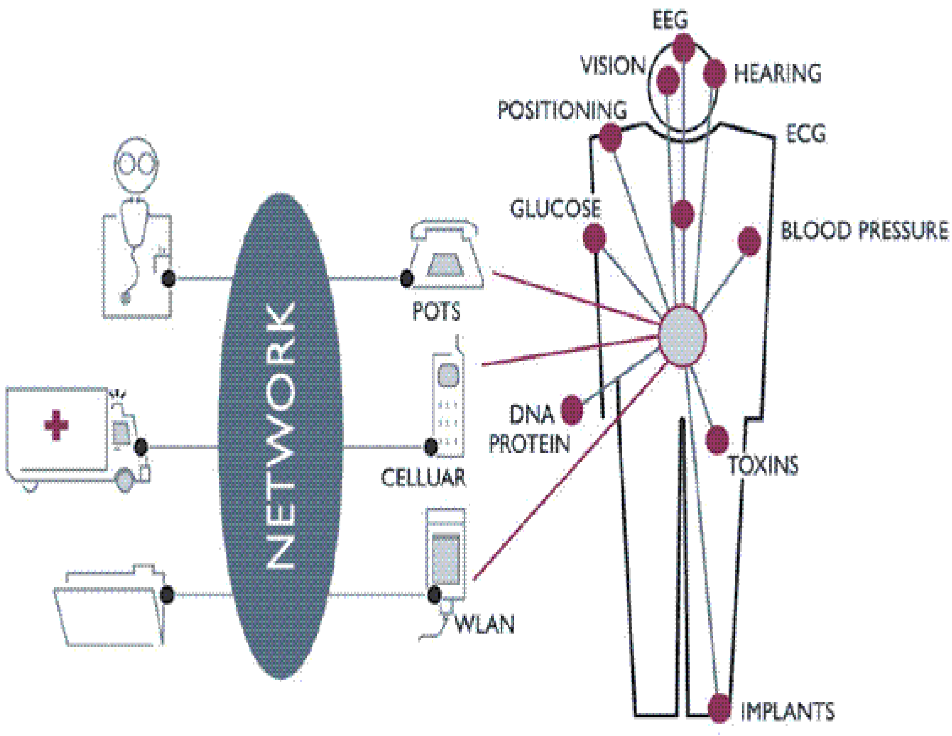
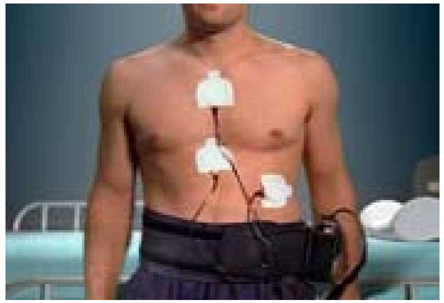
Domains of Body-Centric Communications

- Off-body
  - Human-to-Human or Human-to-Base Units
- On-body
  - Within on-body networks and wearable systems
- In-body
  - With medical implants and sensors using hierarchal or direct links



Antennas and Propagation for Wireless Implants

- Flexibility to the patience and the surgeon in terms of replacement and long life time.
- Constant availability and ease of operation is required for future patient monitoring and diagnosis systems.
- Applications include but not limited to:
  - Accurate drug delivery.
  - Non-Invasive Endoscopy.
  - Patient diagnosis and locator.
  - Muscle stimulator.
  - Brain signals analysis and control.



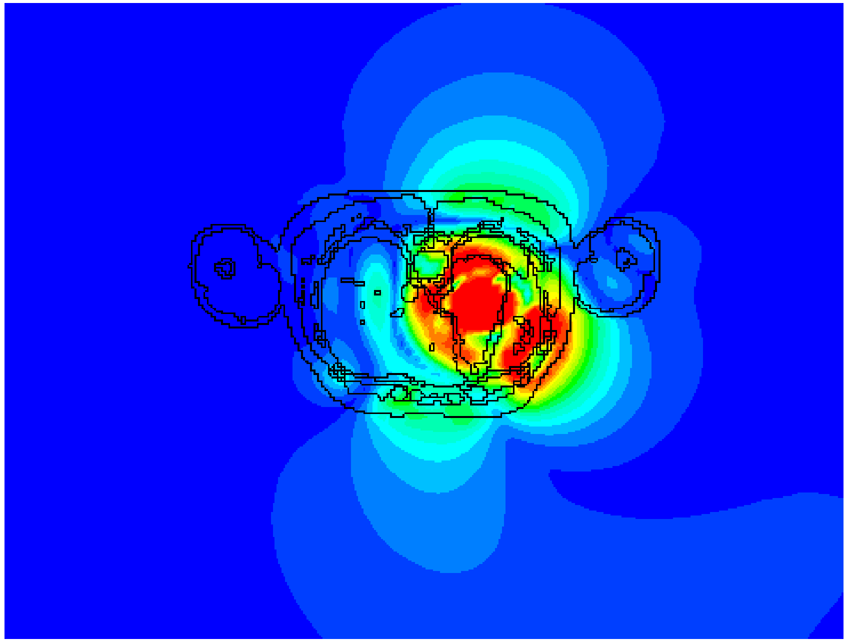
Kenneth R. Foster and Jan Jaeger, "RFID Inside", IEEE Spectrum, March 2007, INT

Source: http://www.givenimaging.com/

Numerical & Experimental Analysis

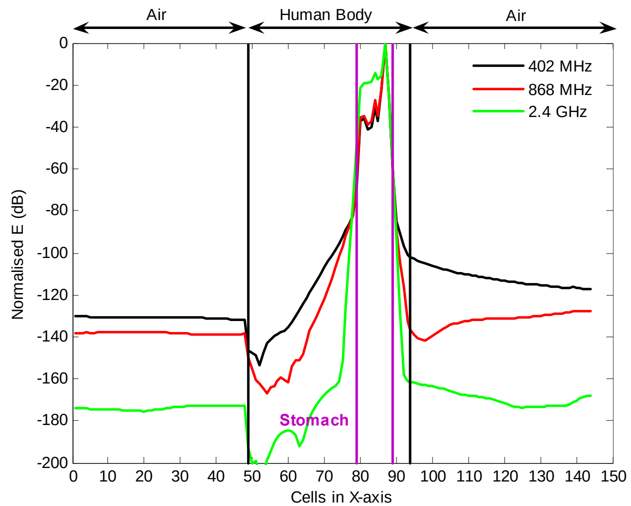
Physical Phantom

402 MHz

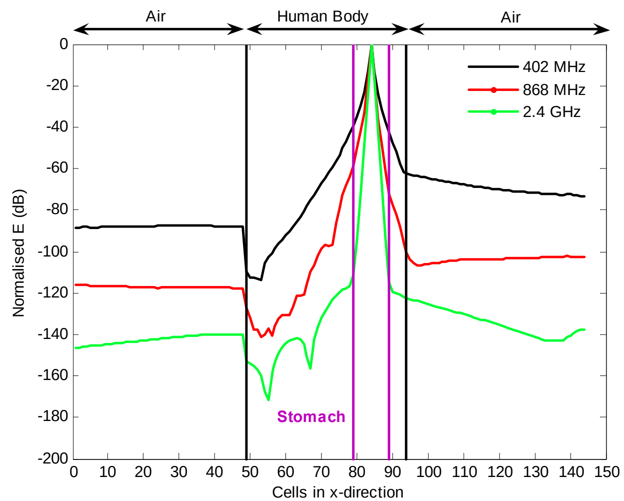


Wave propagation from implants at 402, 868 and 2400 MHz

Queen Mary, University of London and Philips Research East Asia, Shanghai, China



Empty Stomach



Solid Stomach

A. Alomainy and Y. Hao, "Modelling and Characterisation of Biotelemetric Radio Channel from Ingested Implants Considering Organ Contents", IEEE Transactions on Antennas and Propagation, Special Issue on Body-Centric Wireless Networks, 2009, Vol. 57, Issue 4, Part 1, April 2009, pp. 999-1005.

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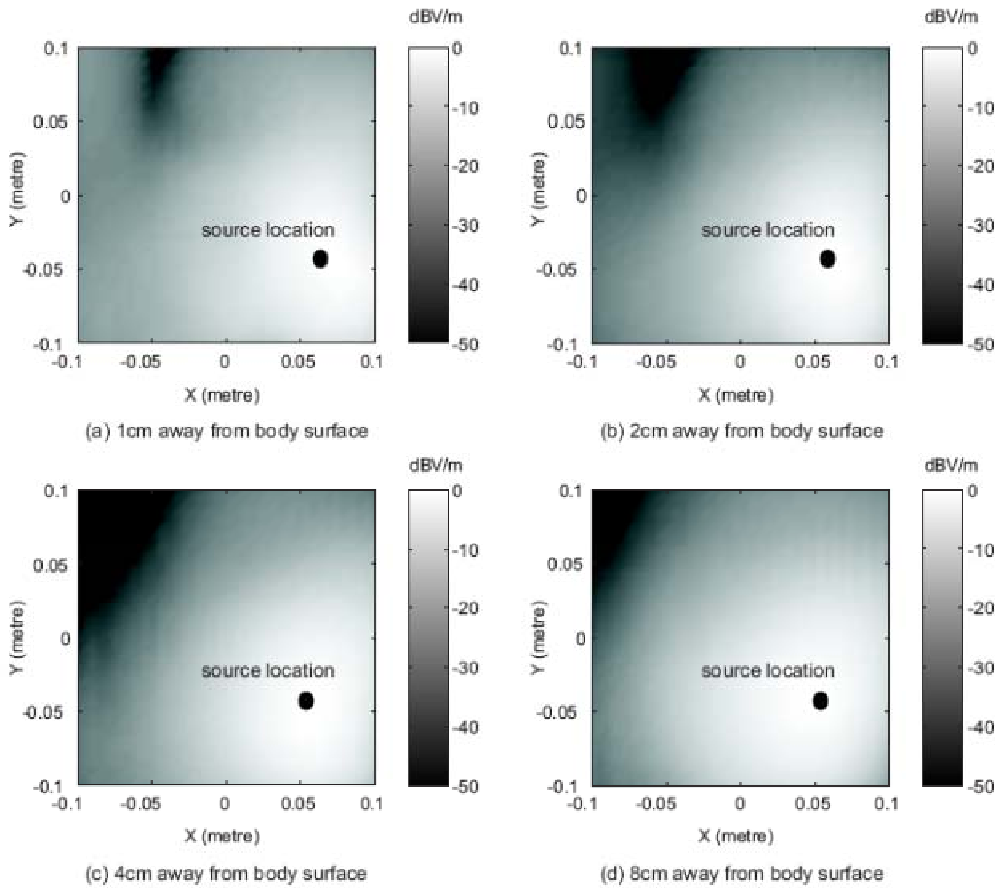
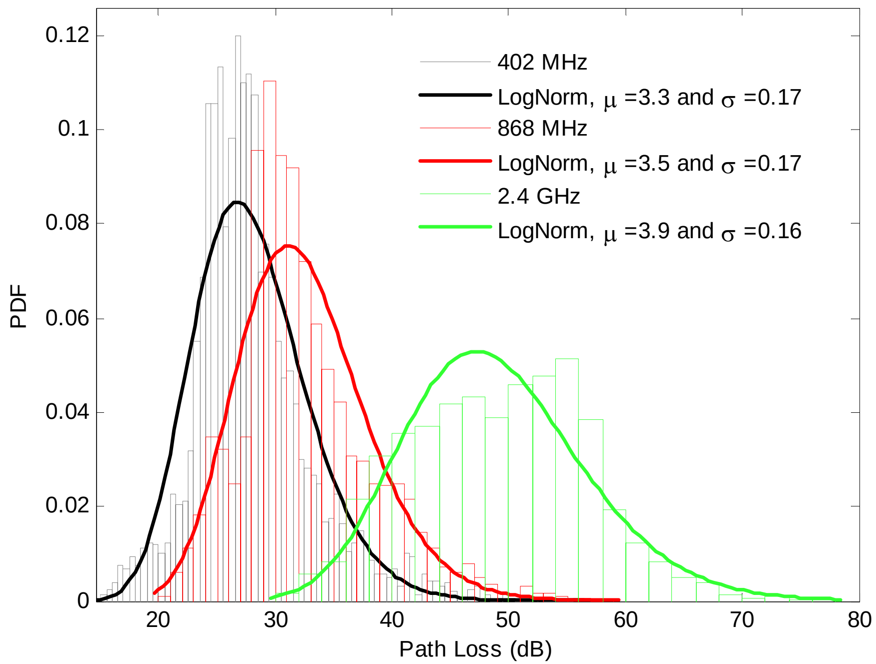
Source Tracking Possibility

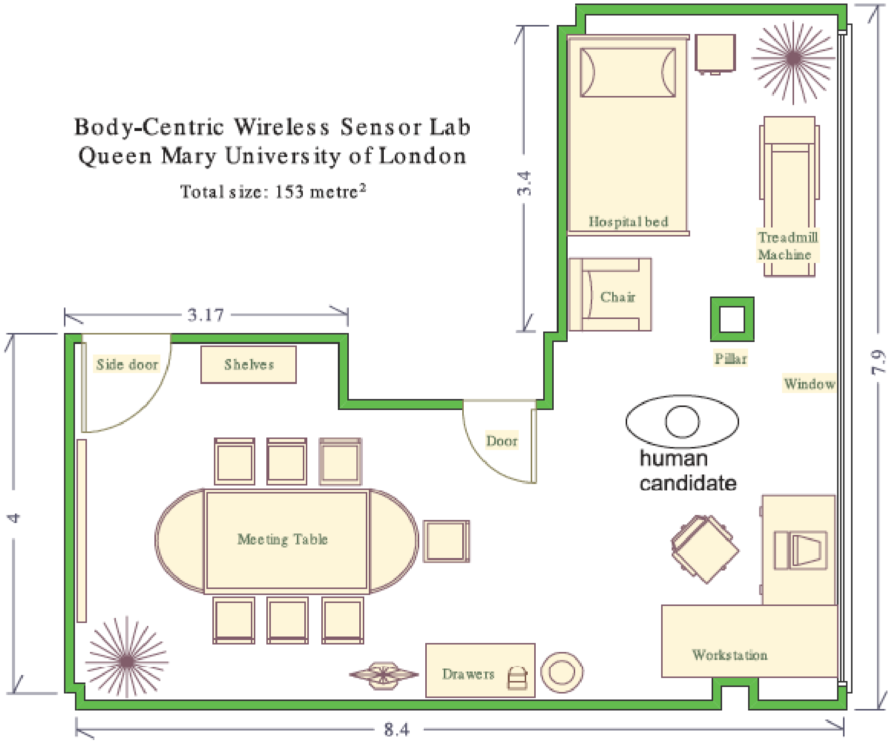
- Locate the wireless implants with a couple of scans
- Needs accurate probes and fast sweep systems





Link budget in an Indoor Environment

- Numerical modelling of radio propagation in the Body-Centric Wireless Sensor Lab at the Antennas Measurement Laboratory in QMUL

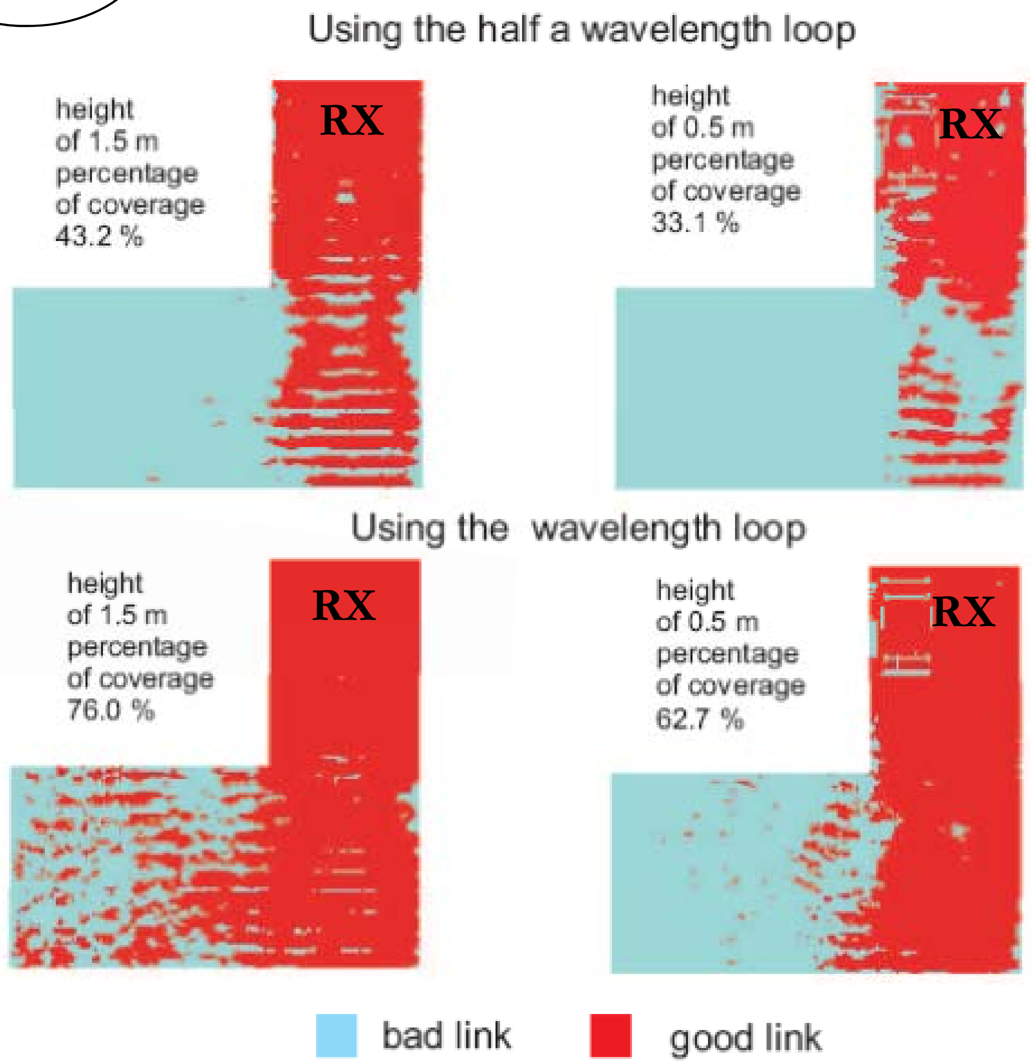


Link budget in an Indoor Environment

$$S[dBm] = Pt[dBm] + G_{imp}[dB] - PL_{dB}(d) + G_r[dB]$$

Full-wave simulation of the path loss in the body-centric lab

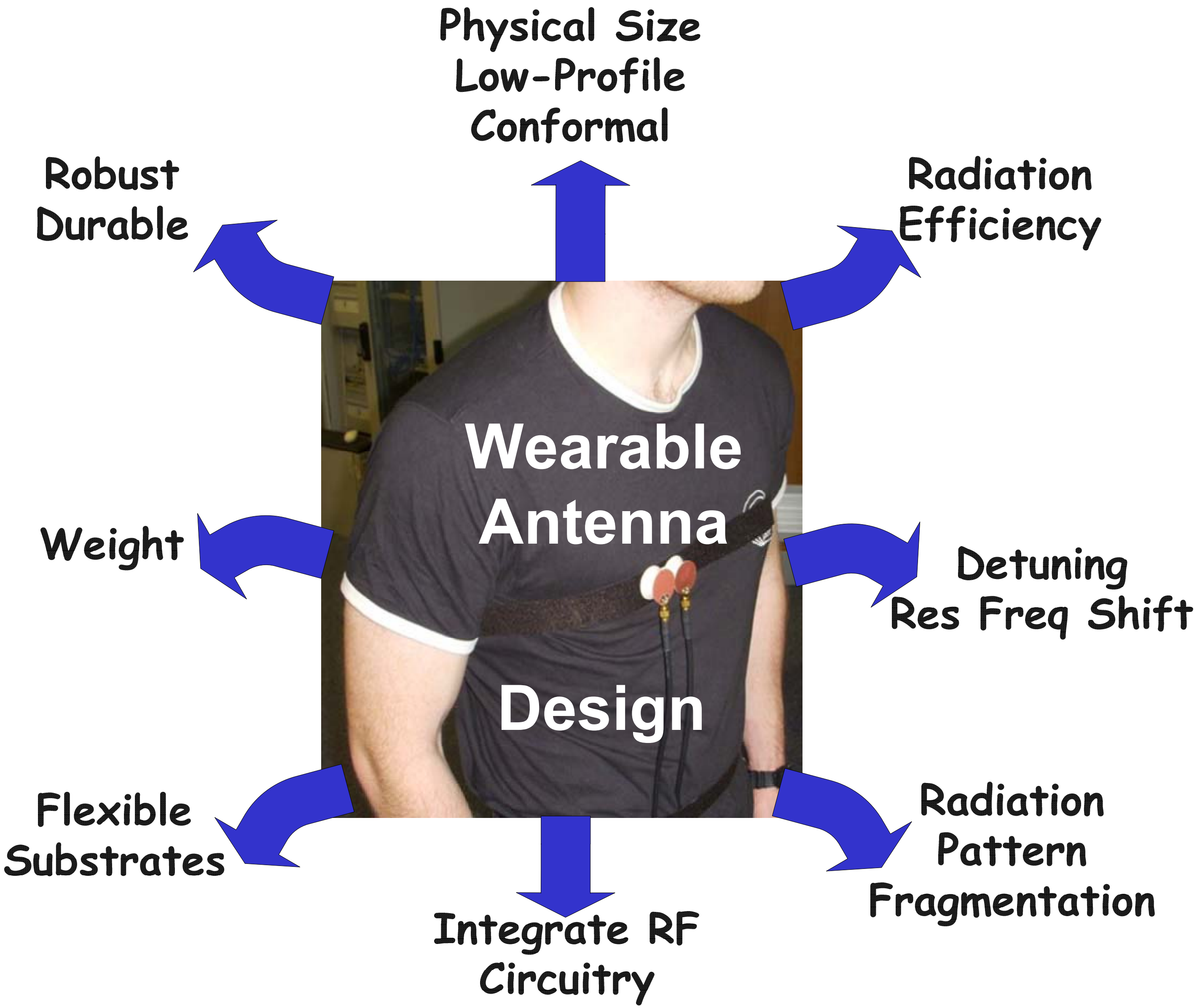
Bit rate of 10 kbps (typical value for the transmission of physiological data)



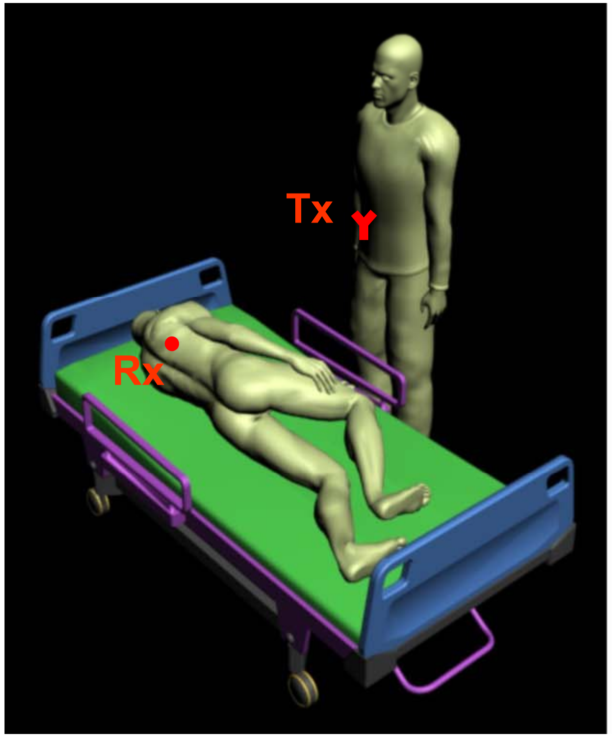
On-Body Communication Channels

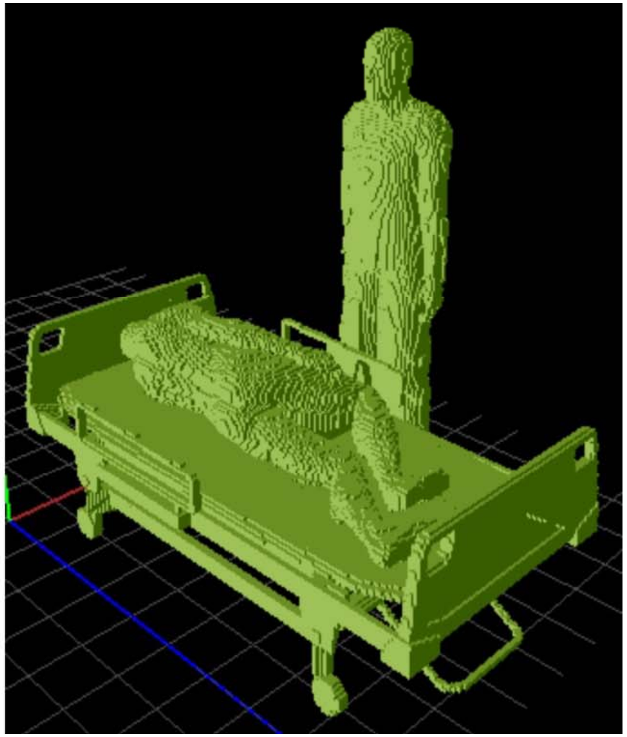
- Measurement of radio propagation channels when both transmitter and receiver placed on the body.
- Investigating different on-body links for different body movements and postures.
- Applying both narrowband signals (2.45 GHz) and UWB measurement.
- Various antenna types to highlight their effects on the radio link
- Statistical channel models for path loss and time delay profiles

Wearable Antenna Considerations



Modelling inter-body radio propagations





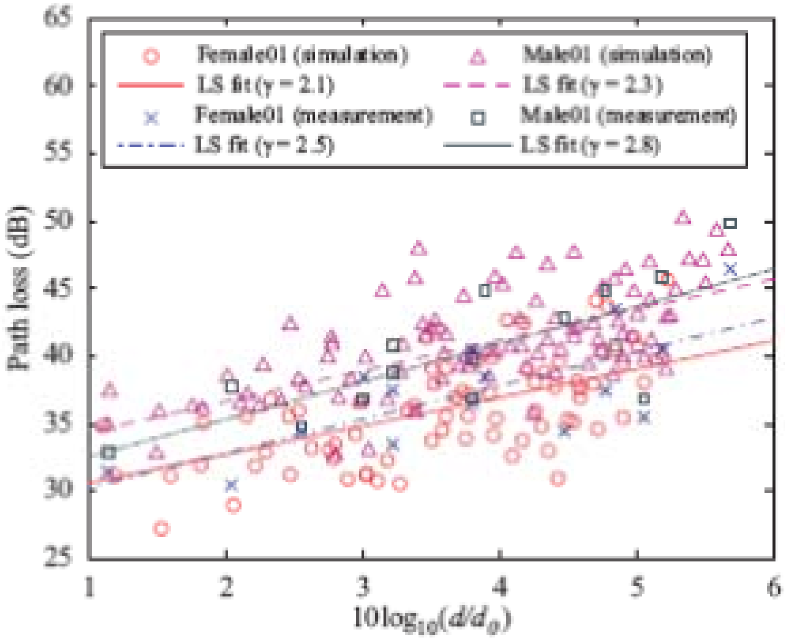
Average path loss [dB]		
	Front	Back
Simul.	46.2	54.8
Meas.	47.5	56.2

Simulations and measurements were performed at 2.4 GHz

	Human muscle	Bed cushion	Bed frame	Walls/floor
Dielectric constant	52.79	1.3	1.0	2.4
Conductivity	1.7	0.01	10^6	0.15

Subject-specific on-body radio channel

- Propagation along the torso $PL_{dB}(d) = 10\gamma \log(d/d_0) + PL_{dB}(d_0) + X_\sigma$



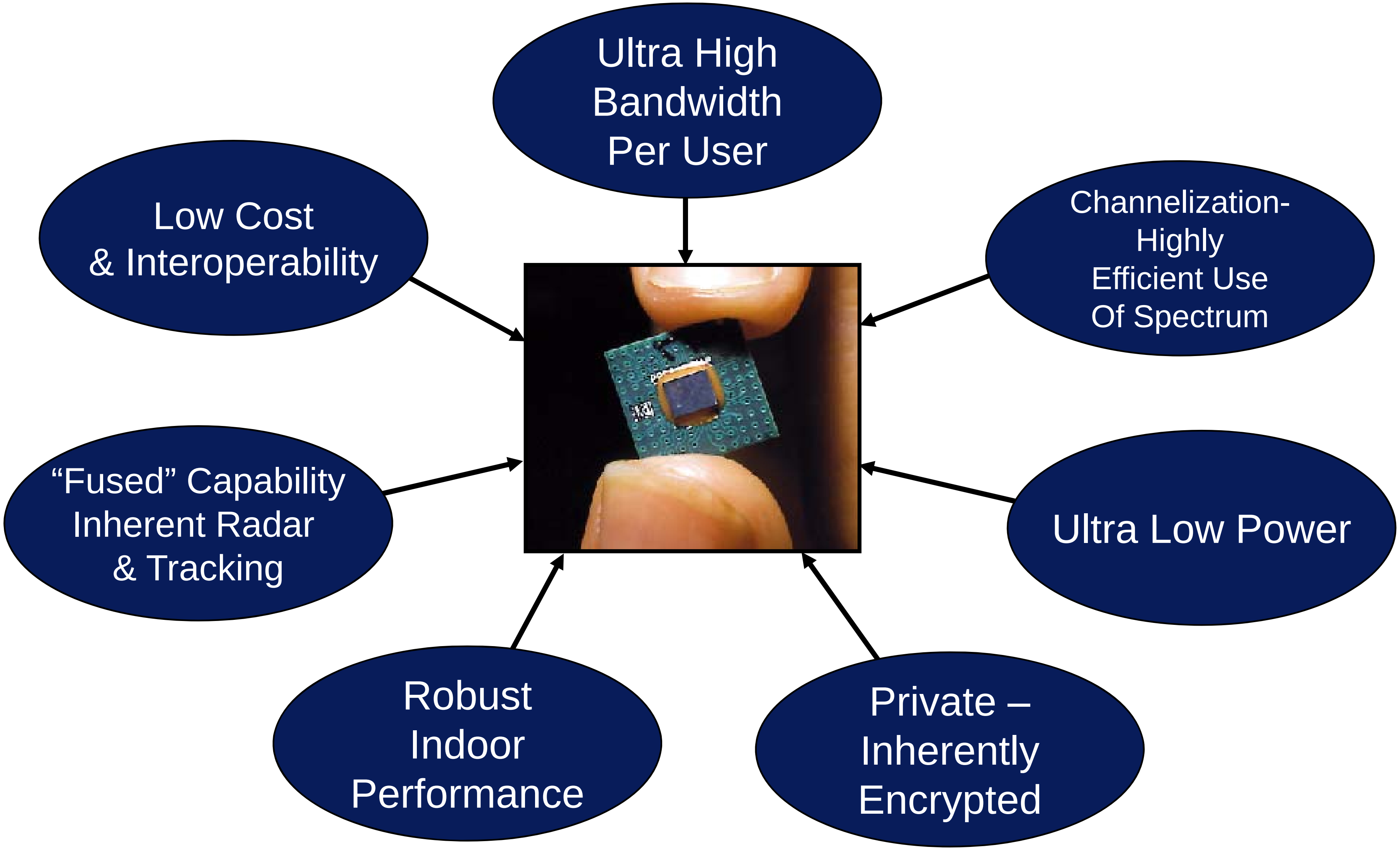
PATH LOSS EXPONENT AND STANDARD DEVIATION OF THE SHADOWING FACTOR FOR THE NINE SUBJECTS (F – FEMALE, M – MALE).

	F01	F02	F03	F04	F05	M01	M02	M03	M04
γ	2.3	2.4	2.3	2.7	2.9	2.5	2.6	3.1	3.0
σ	4.0	3.9	3.8	6.0	4.1	3.9	4.5	4.8	3.8

The transmitter is on the left side of the waist.

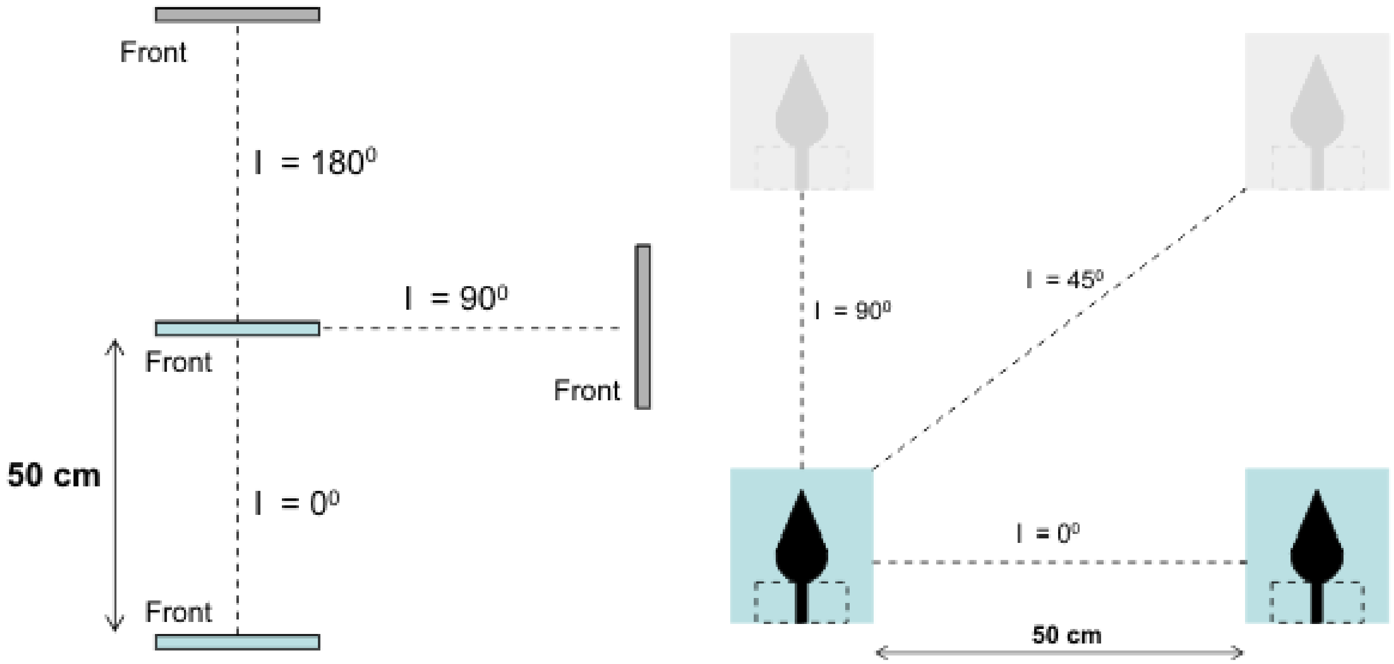
- Good agreement between simulated and measured data.
- Subject with a bigger curvature radius at the trunk (F05, M03, M04) presents higher path loss exponent.→ **the on-body channel is subject specific.**

Why UWB for Body-Centric Communications?



Transient Characteristics in Free Space

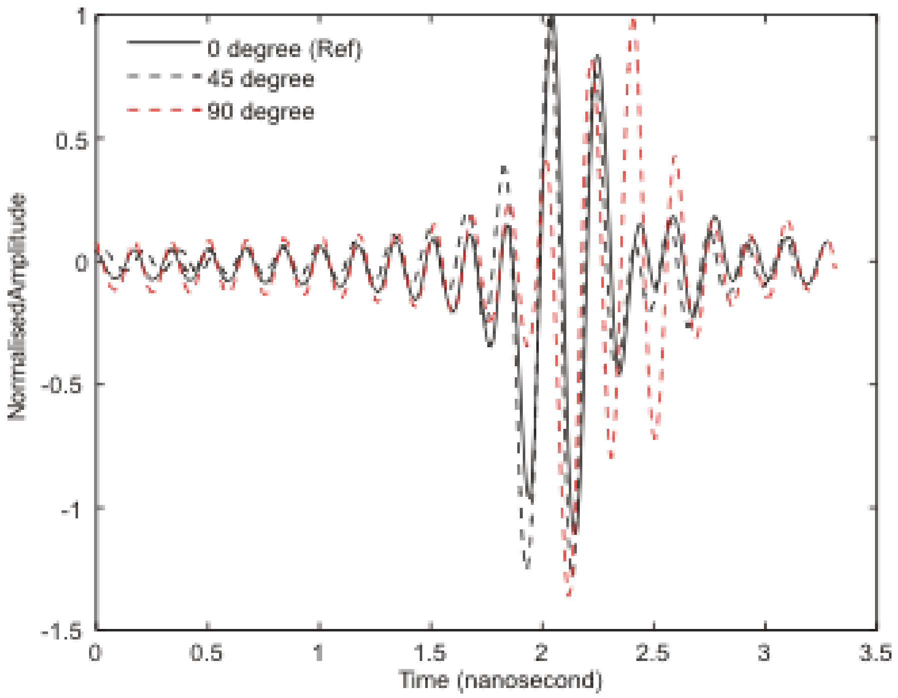
- Performance of the antennas as a spatial filter.
- The two antennas facing each other is the best case and it is used as a reference for the fidelity calculation.



(a) Face-to-Face (b) Side-by-Side

A. Alomainy, A. Sani, A. Rahman, J. Santas and Y. Hao, "Transient Characteristics of Wearable Antennas and Radio Propagation Channels for Ultra Wideband Body-Centric Wireless Communications", IEEE Transactions on Antennas and Propagation, Special Issue on Body-Centric Wireless Networks, Vol. 57, Issue 4, Part 1, April 2009, pp. 875-884.

Transient Characteristics in Free Space



Mean value of pulse fidelity considering different antenna orientations:

PICA: 89.5%

TSA: 85.1%

For the miniaturized TSA antenna results demonstrate slightly higher distortion, however the pulse fidelity values are acceptable for short distance communications.

Experimental Investigations

- Statistical and deterministic modelling of radio channels in various environments.

- Both narrowband and ultra wideband technologies are explored extensively for body-centric networks.

HP8720ES Vector Network Analyser used for on-body frequency domain measurement

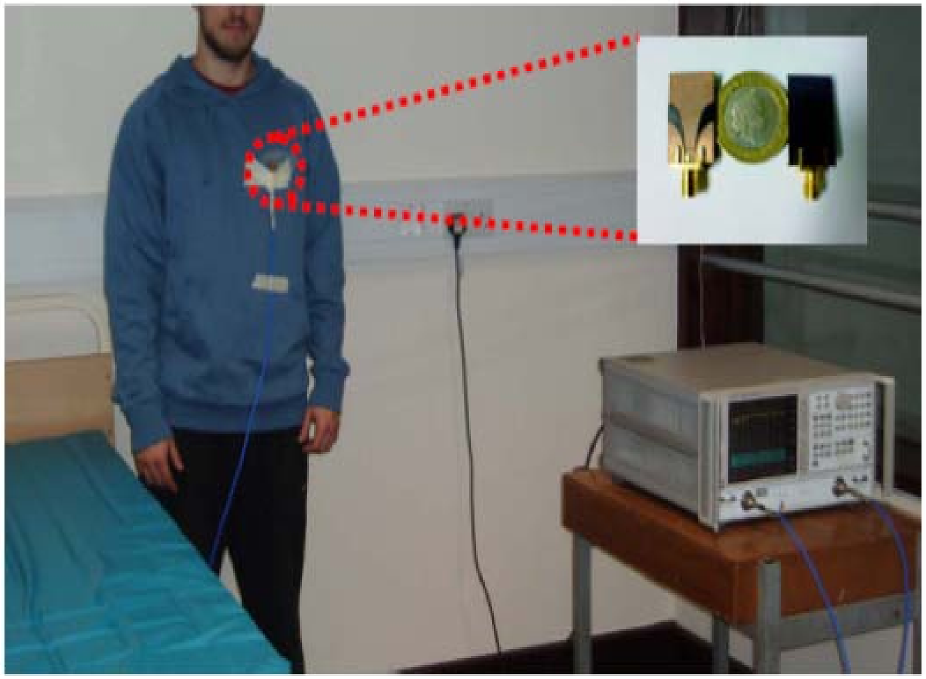
Hollow physical phantom in the Antenna Measurement Laboratory, Queen Mary, University of London, used for measurement protocol settings

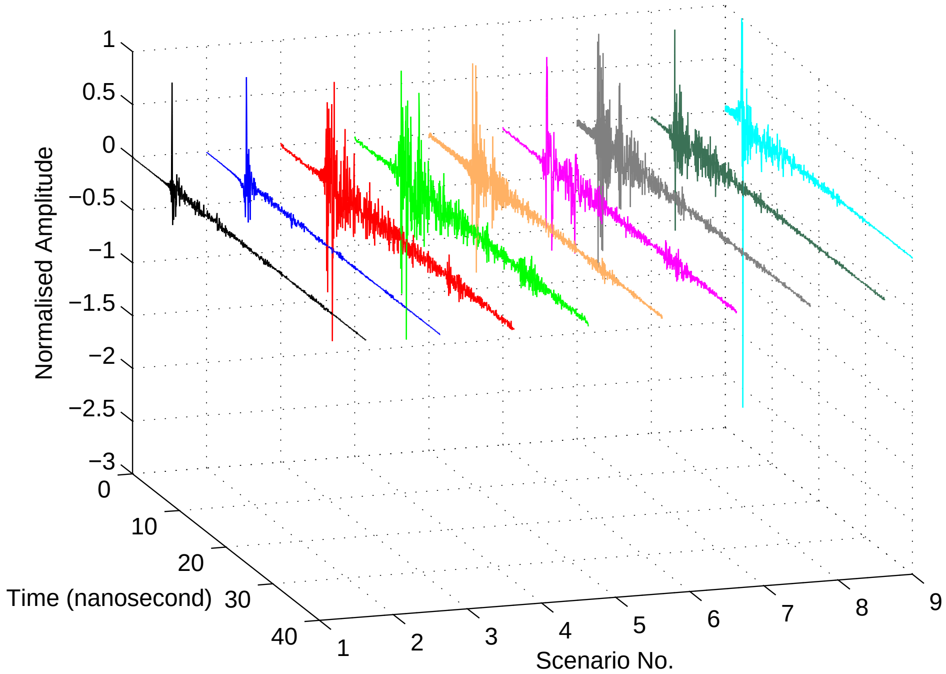
Microstrip patch antennas placed on the left waist (Tx) and right side of the chest (Rx) for 2.4 GHz on-body propagation measurement in the chamber

CPW-fed UWB antennas placed on the left waist and right side of the chest for frequency domain ultra wideband on-body channel measurement

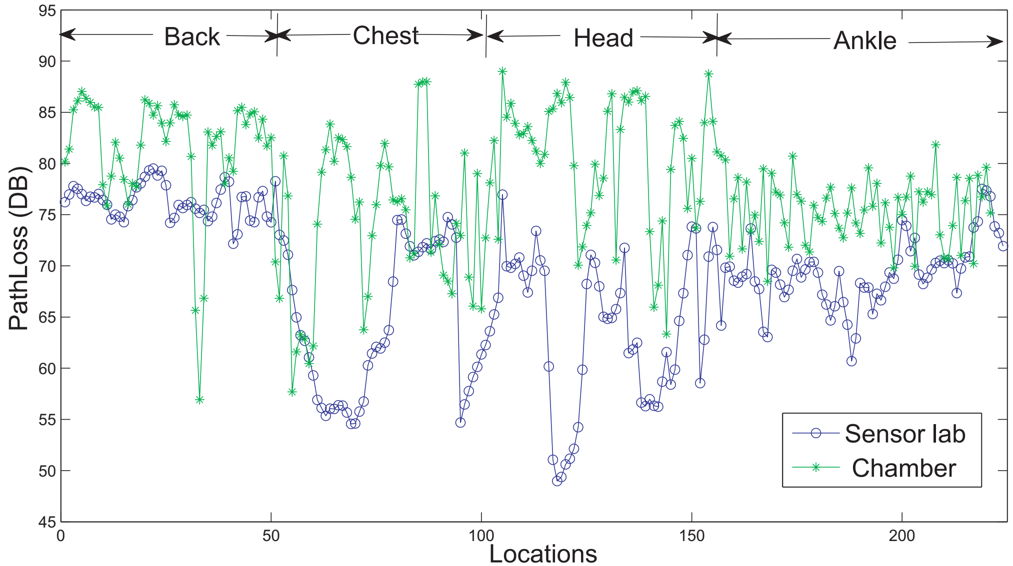
Transient Radio Analysis

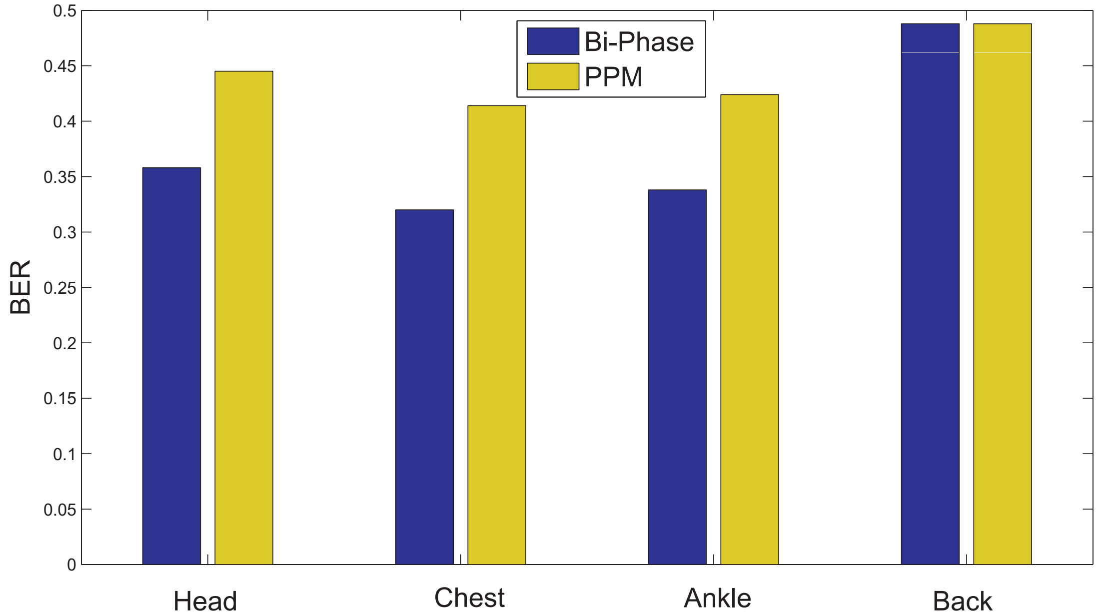
Identifying multipath components and possibly analysing user's behaviour and habits within a healthcare settings.





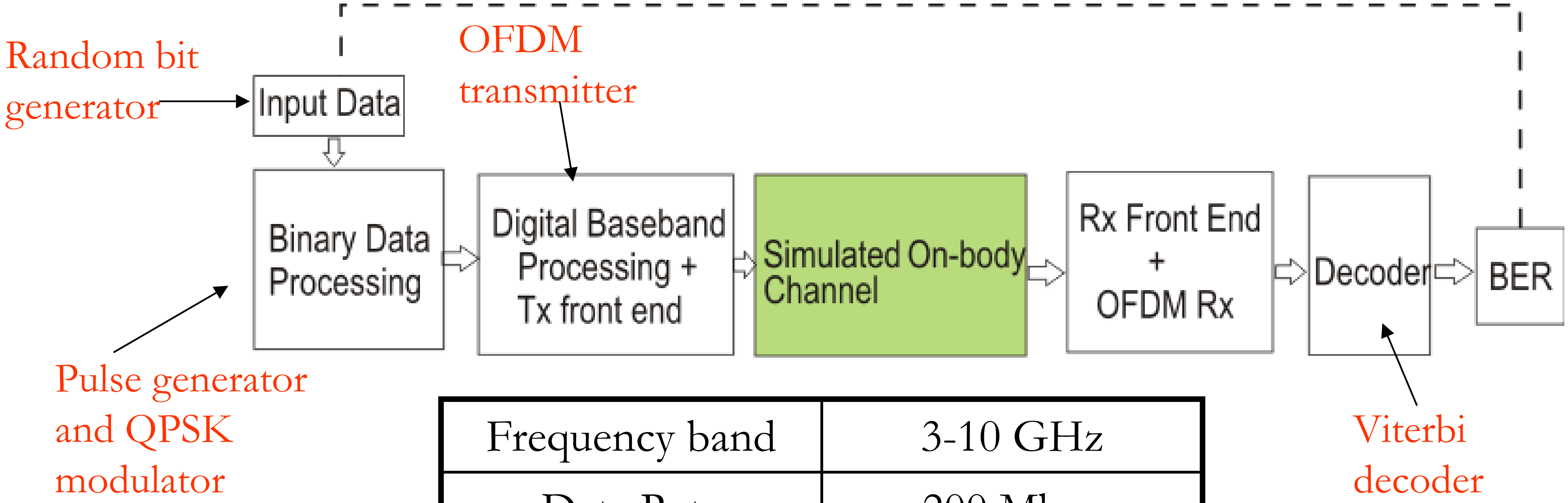
Effect of the body movements





OFDM-based UWB System-Level Modelling

- System performance using Multi-carrier OFDM based UWB for both stationary and dynamic scenarios.

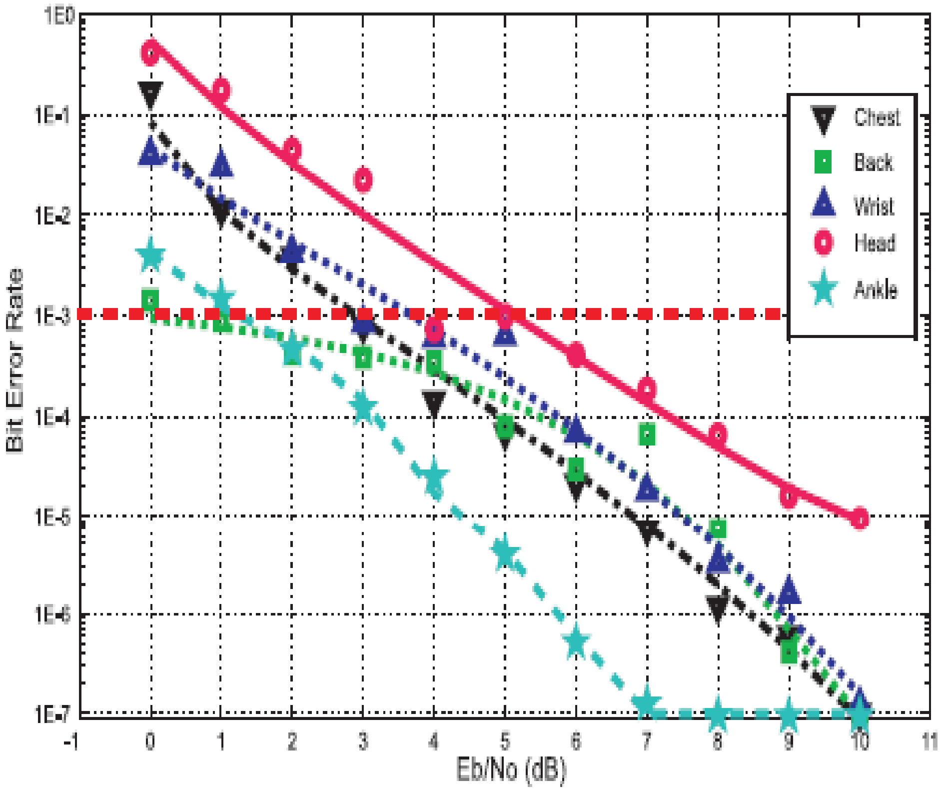


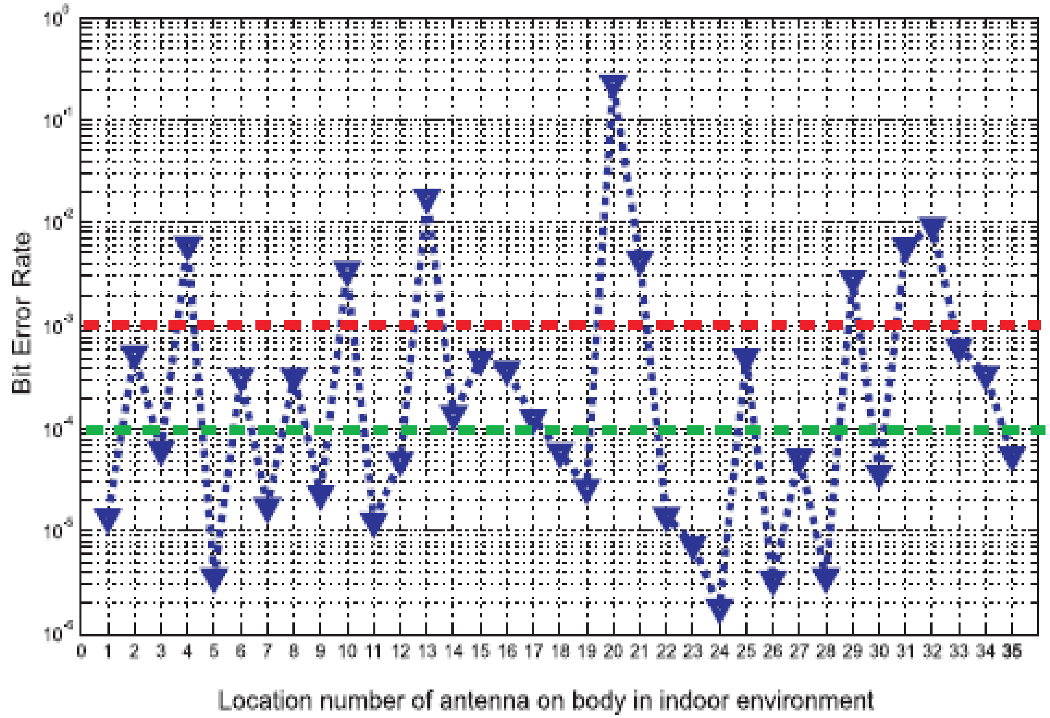
Frequency band	3-10 GHz
Data Rate	200 Mbps
No. of subcarriers	122
Subcarrier spacing	4.125 MHz
Sampling time	0.315 nsec

Q. H. Abbasi, A. Alomainy, Y. Hao, "Characterisation of MB-OFDM based Ultra Wideband Systems for Body-Centric Wireless Communications ", IEEE Antenna and Wireless Propagation letter, Volume 9, pp. 324-327, Dec. 2011

System Performance

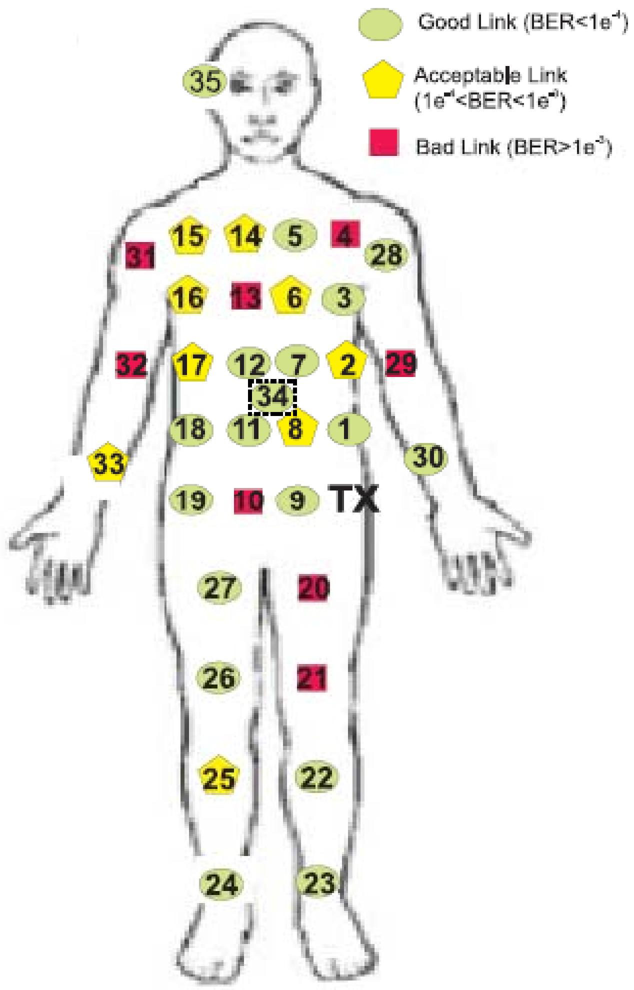
Various Energy-to-Noise ration to determine optimum Eb/No for low-power system





Performance vs. On-body Location

Various Energy-to-Noise ration to determine optimum Eb/No for low-power system

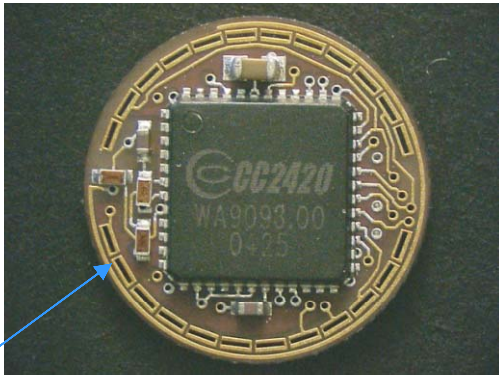


Link Quality	Good	Acceptable	Bad
Torso	50.0	35.0	15.0
Arms	33.3	16.7	50.0
Legs	62.5	12.5	25.0
Head	100.0	-	-

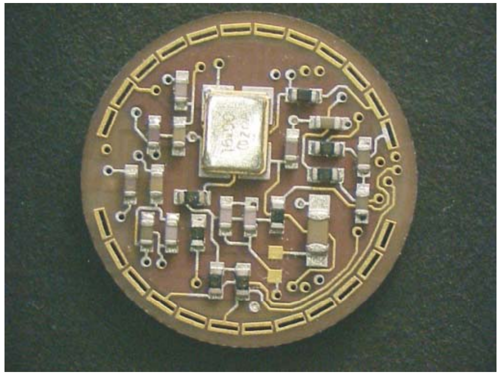
Q. H. Abbasi, A. Sani, A. Alomainy and Y. Hao, "Radio Channel characterization and system-Level Modeling for Multiband OFDM Ultra Wideband Body-Centric wireless networks", IEEE Transactions on Microwave Theory and Techniques, Vol. 58, no. 12, pp. 3485-3492.

Sensor Transceiver Module

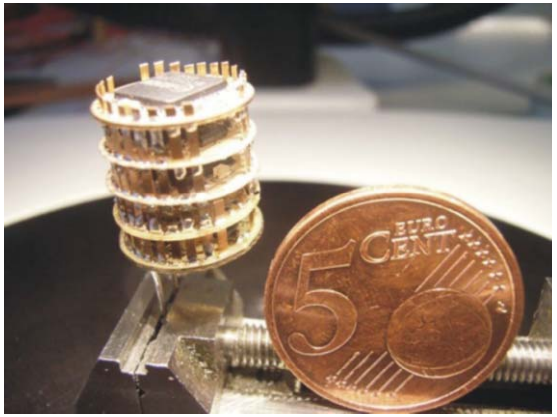
Top Layer - Transceiver



Bottom Layer - Transceiver



Antenna printed around the circumference of the sensor transceiver board



Sensor Prototype

Akram Alomainy, Yang Hao and Frank Pasveer, *Chapter 6: Antennas for Wearable Devices*, in “Antennas for Portable Devices”, Wiley & Sons, Inc., 2007

Applied Sensor Models

- The performance of the sensor antenna is investigated using full wave EM numerical modelling techniques.

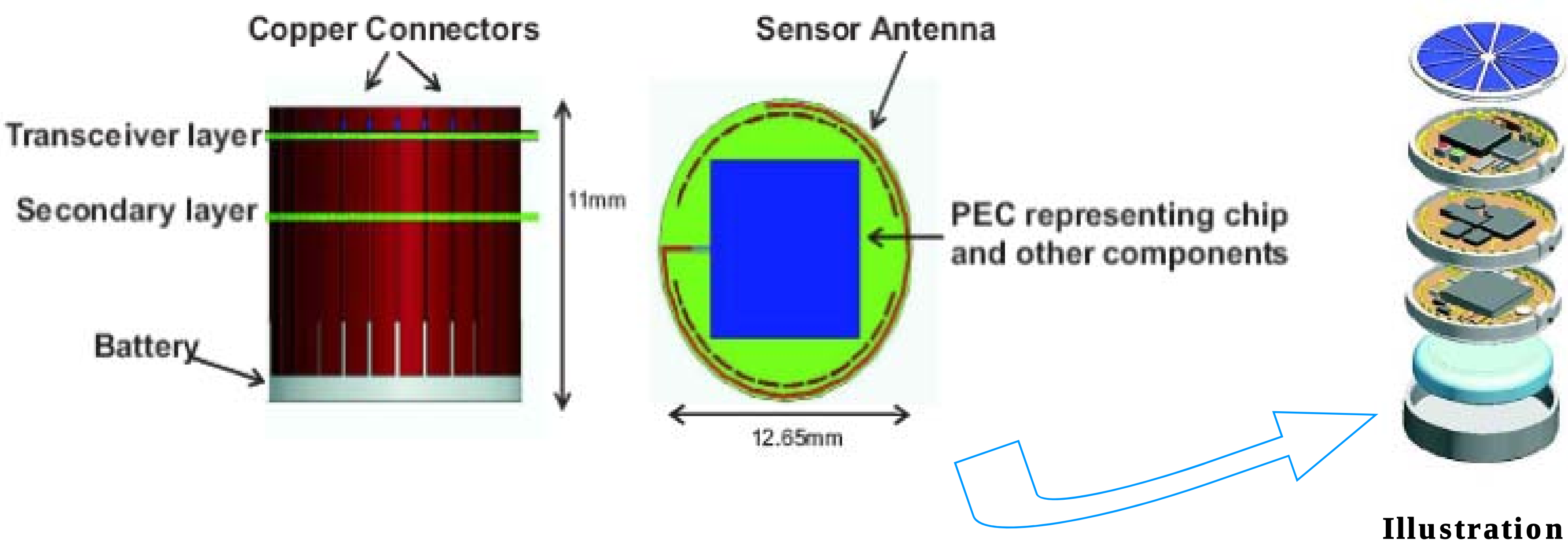
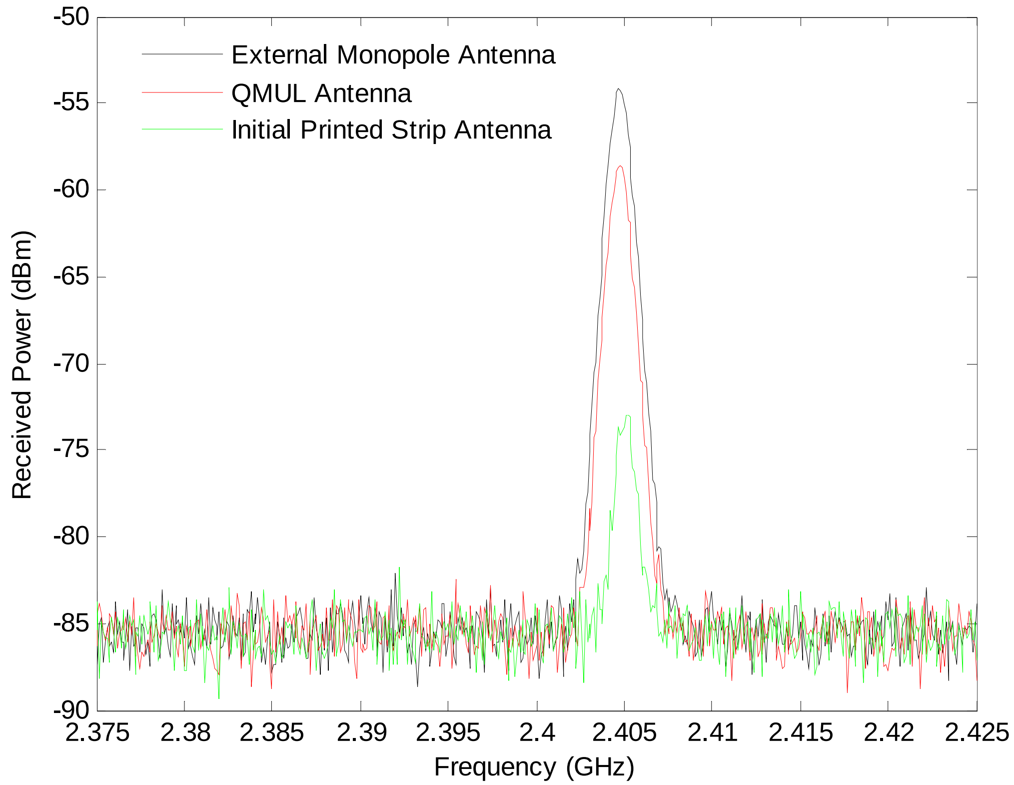


Illustration of production sensor

Improved Antenna Performance

Measurement performed with Microstrip Patch at 2.4 GHz working as the receiver. Output power of 0dBm. Three cases are applied for transmitter:

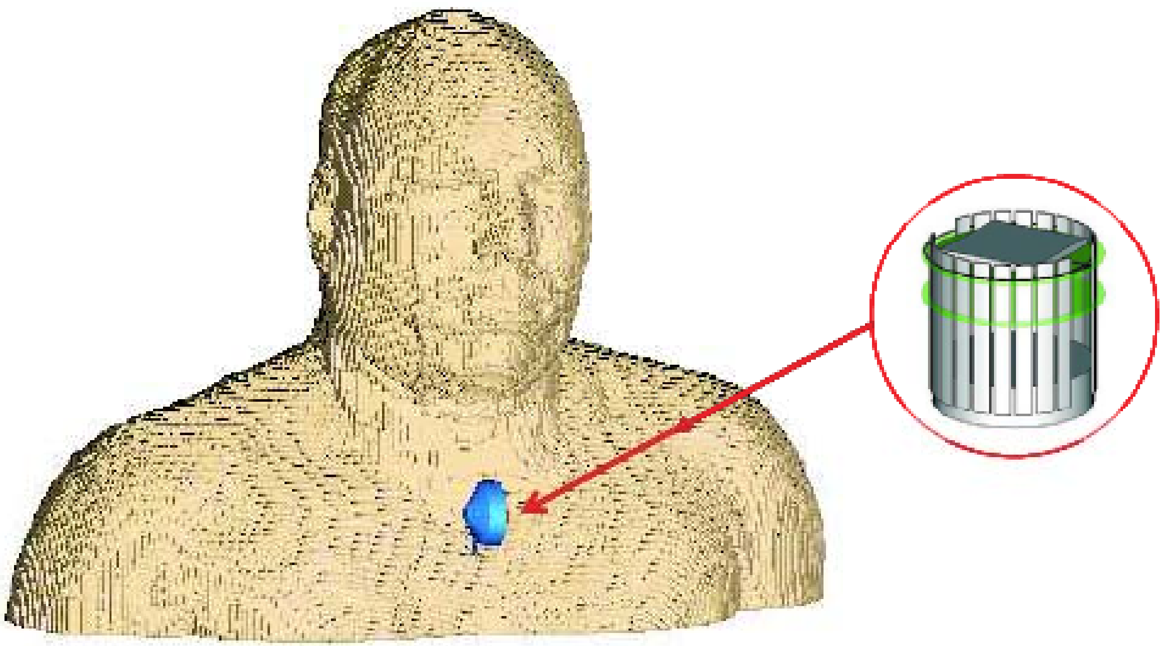
- Transceiver module with external monopole antenna.
- Transceiver module with modified QMUL antenna.
- Initial quarter-wavelength printed strip antenna.



A. Alomainy, Y. Hao and W. F. Pasveer, "Numerical and Experimental Evaluation of a Compact Sensor Antenna Performance for Healthcare Devices", IEEE Transactions on Biomedical Circuits and Systems, Vol. 1 No. 4, December 2008.

Body-Worn Sensor Modelling

- Multi-layer human model (based on US Visible man project).
- Antenna placed on the chest longer sensor dimension parallel to the body at 2 mm away.



Wave Propagation around the Body

Top view

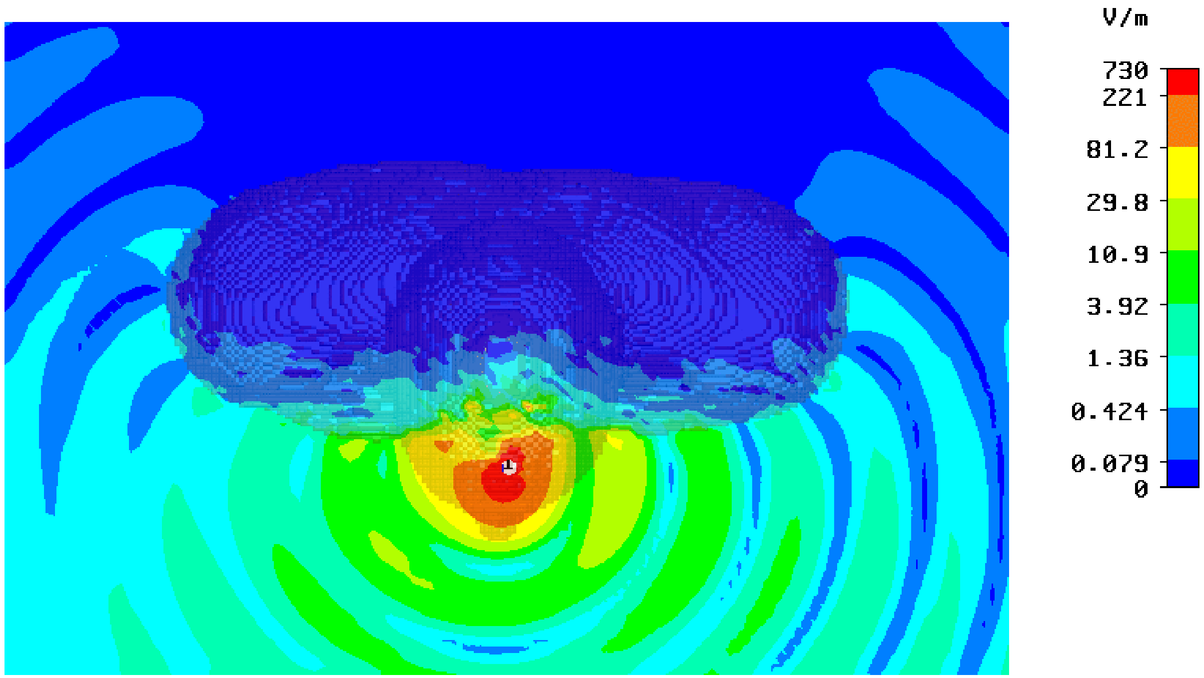


Illustration of electric field distribution at 2.4 GHz when the sensor is placed on the centre of the chest.

Existence of creeping waves caused by diffraction from body curvature.

Outline

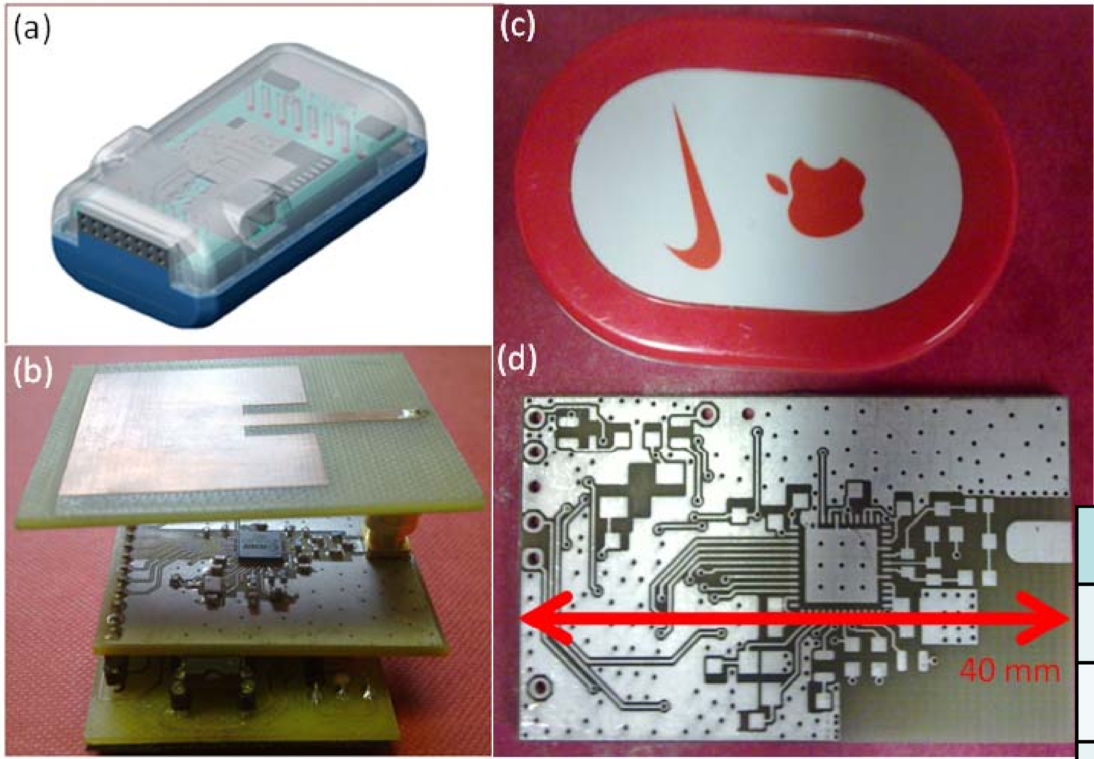
- Introduction
  - Why Body-Centric Communications for healthcare?
  - Applications
  - Challenges
- Domains of Body-Centric Wireless Communications
  - In-Body
  - On-Body
  - Off-Body
- Going Smarter ...
  - The smarter and the greener … the better
  - From Recognition to Cognition!
  - Scaling down to Nano

The need to go cooperative!

- Developing a cooperative Body-Centric Wireless Networks demonstrator for e-health applications.
- Maximize the minimum lifetime of the system and estimate the Network energy saving and
- Achieve various tasks in the cycle of antennas-radio channels-system performance-implementation.
- Comprehensive statistical channel modelling for body-centric wireless communications.
- Evaluation of system performance in various scenarios and providing recommendations.

Example Applications:
BAN for ambulatory monitoring of physiological responses

Wearable Units



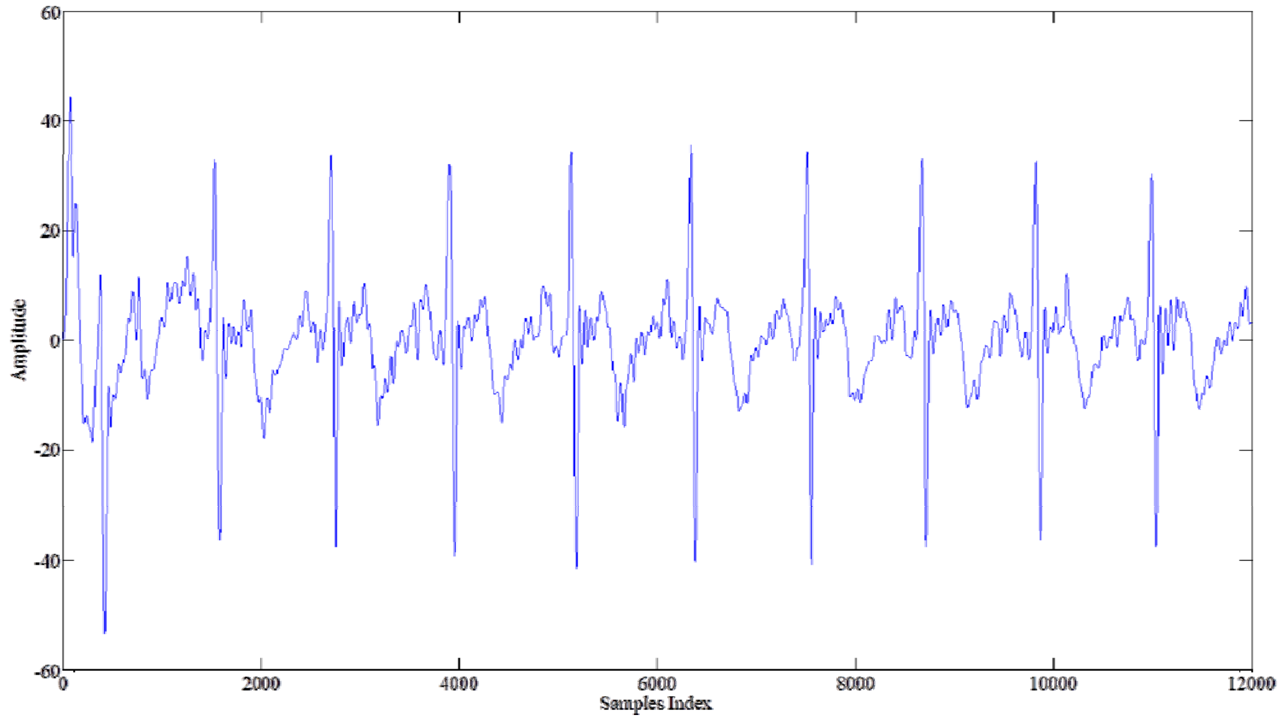
- A market available sensor kit has been used.
- Sensor prototype have been in-house built and ready to work.
- In-house system design allows to test different antennas

Capability	Sensor (Sentilla)
RAM (kB)	512
Flash (kB)	4096
Speed (MHz)	8
Active (mA)	4
Idle (mA)	1
Sleep (uA)	1
Architecture	16-bit

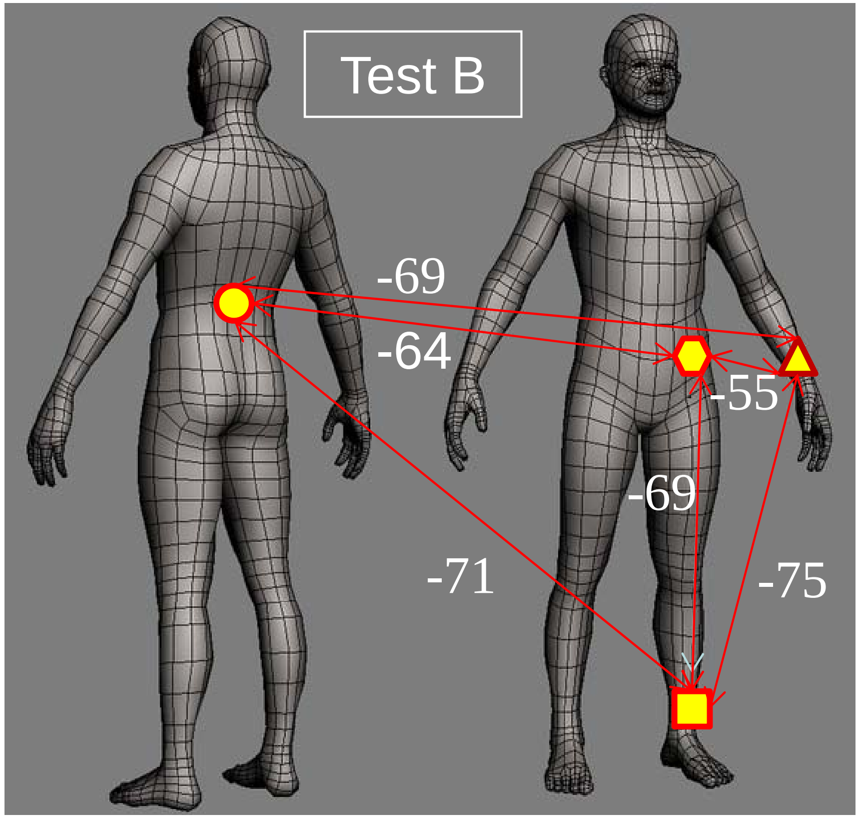
The table shows the Sentilla Motes hardware characteristics. The Motes embeds a CC2420 802.15.4 Radio, MSP430 microcontroller and several analogue sensors, including a 3-axial acceleration sensor.

Sample Payload

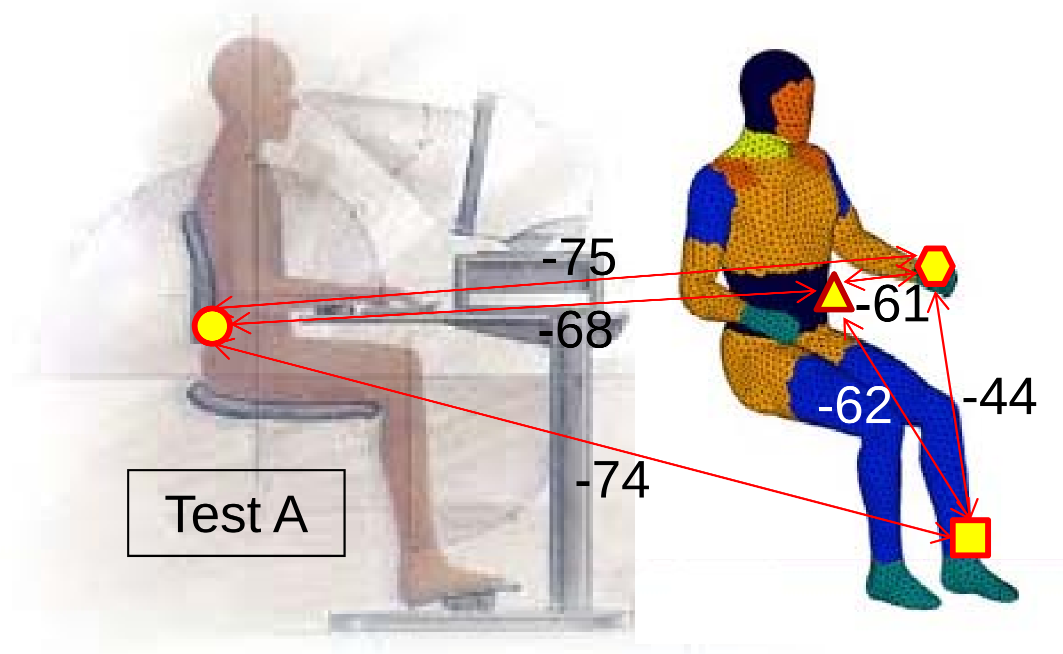
- The network throughput is set to be compatible with the application data rate, e.g. an ECG.
- ECG trace captured from in-house built device, as possible payload to be transmitted through the network. The signal is band-pass filtered. The data rate is 1byte/20ms = 0.05/s



Measured Body-Centric Links

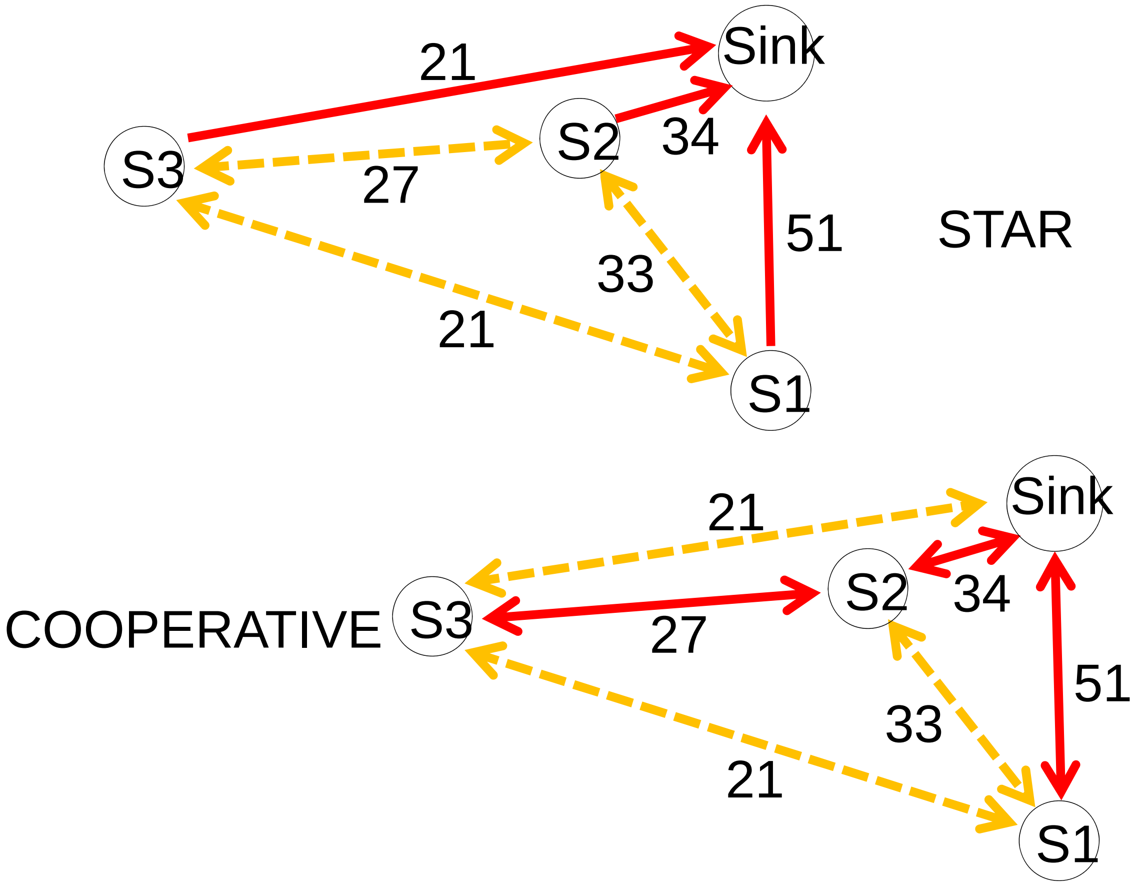


Symbol	Index
⬡	Sink
△	S1
□	S2
○	S3



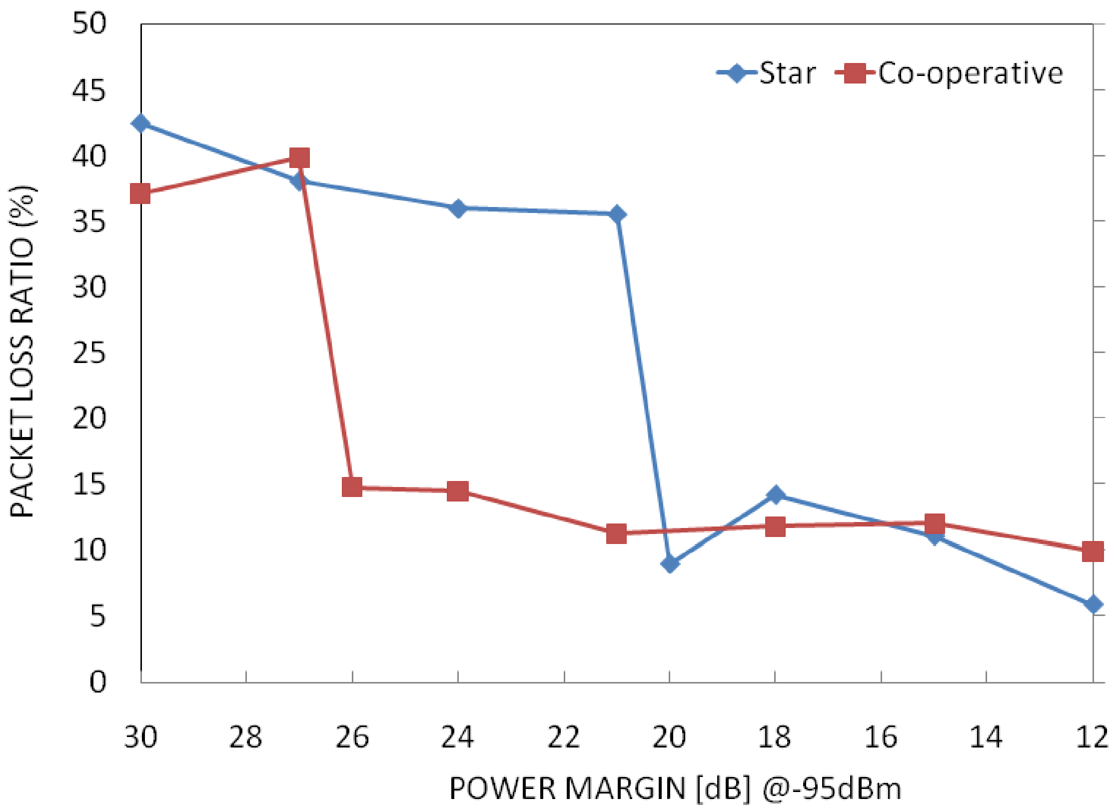
- A sample on-body real case scenario is selected for test evaluation. No movements were allowed.
- The transmitted power (expressed in dBm) is constant and equal to 0 dBm for all motes.

Topologies and Power Margins



- The Network Power Gain (NPG) can be related to the minimum power margins, estimated against the receiver threshold -95dbm.
- Minimum power margins are 20 dB and 26 dB for the star and cooperative topology, respectively.

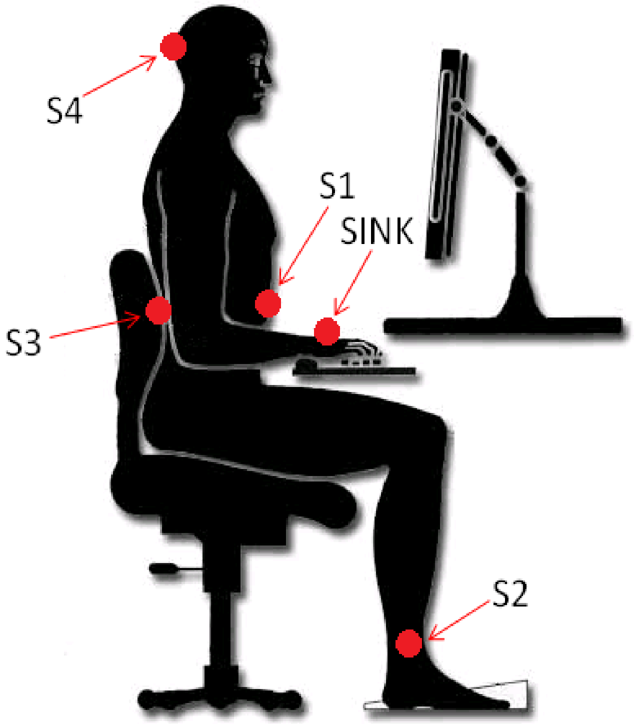
Initial Network Test results



Performances comparison of the two network topology.

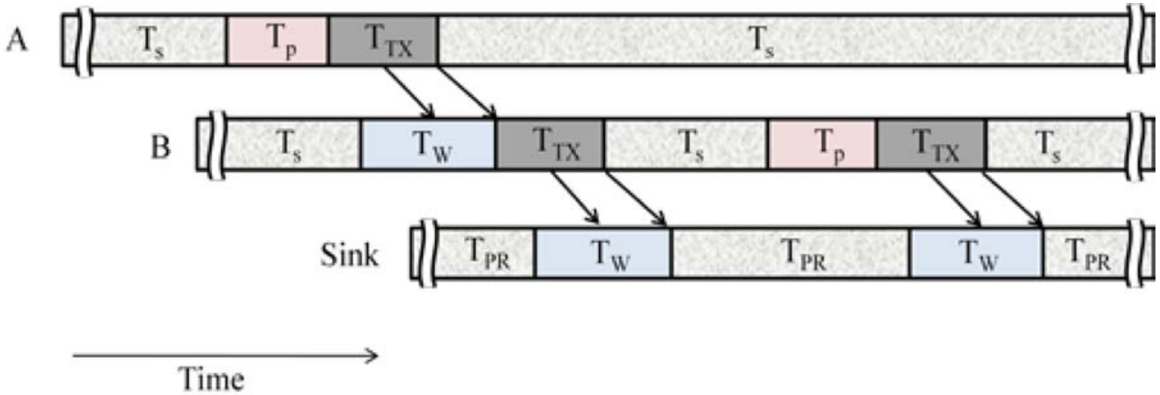
- These values can be translated as 6 dB NPG for the cooperative network.
- The NPG depends on the particular displacements scheme and the number of the sensors on the body.
- The cooperative routing processing overhead does not degrade the sensors performances.

Modified System Set up

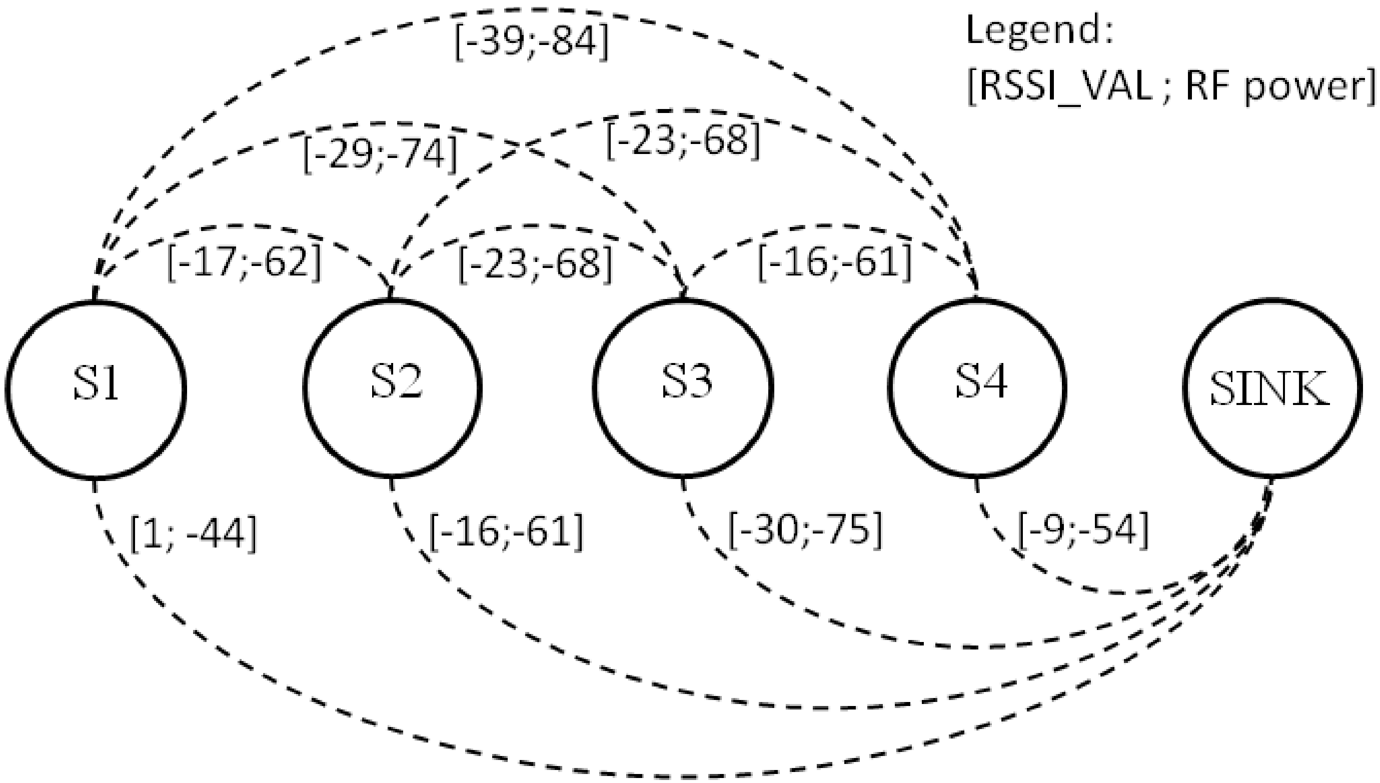


Displacement map of sensor sensors on volunteer body

Sentilla Mote used for this research. The Motes embeds:
-a CC2420 802.15.4 Radio,
-MSP430 microcontroller
-several analogue sensors, including a 3-axial acceleration sensor.

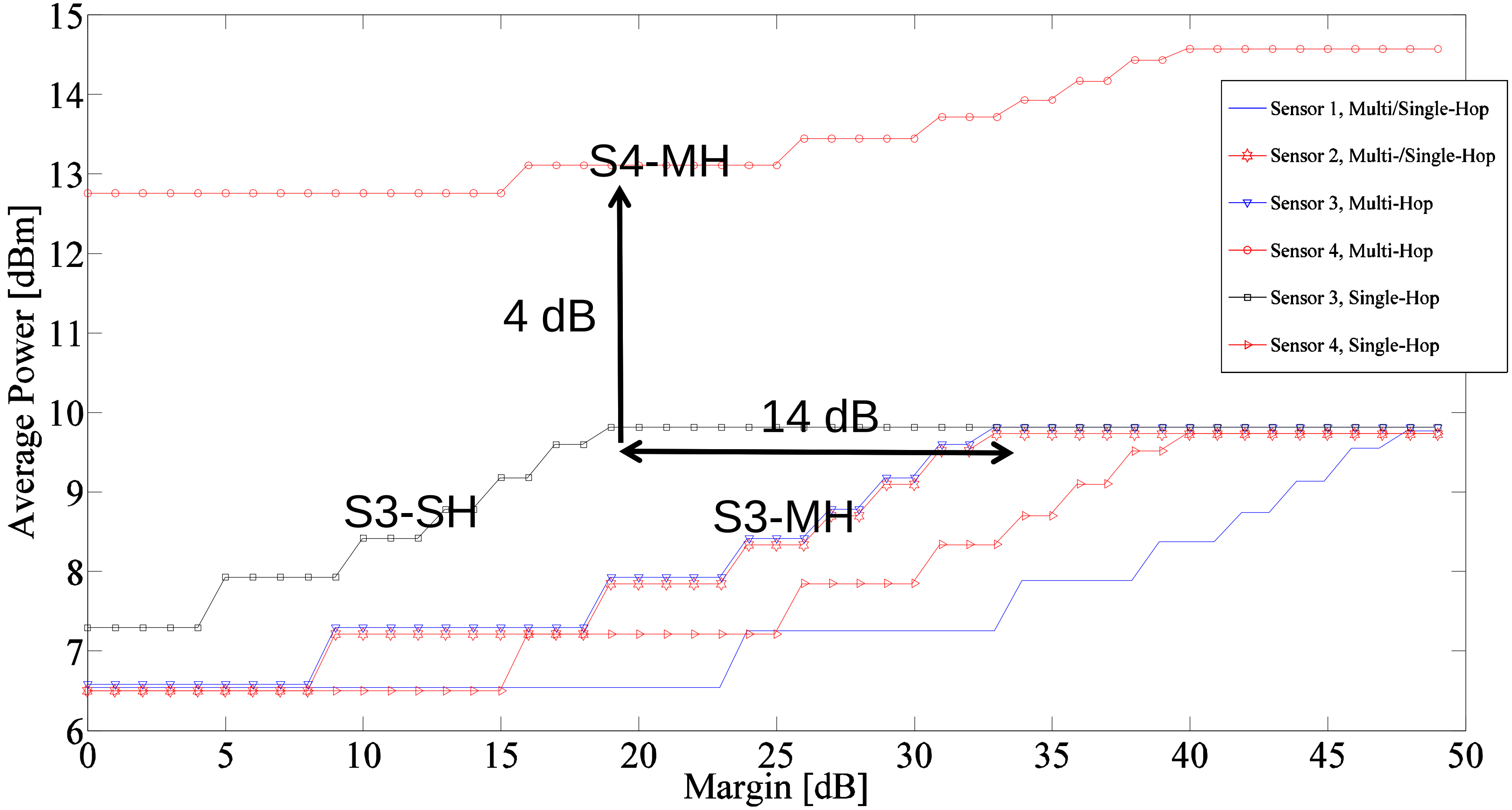


Network Topology Characterisation: Link Cost



Link Costs based on Averages RSSI /RF powers in dBm
for sitting postural set-up

Network Topology Characterisation: Power Consumption

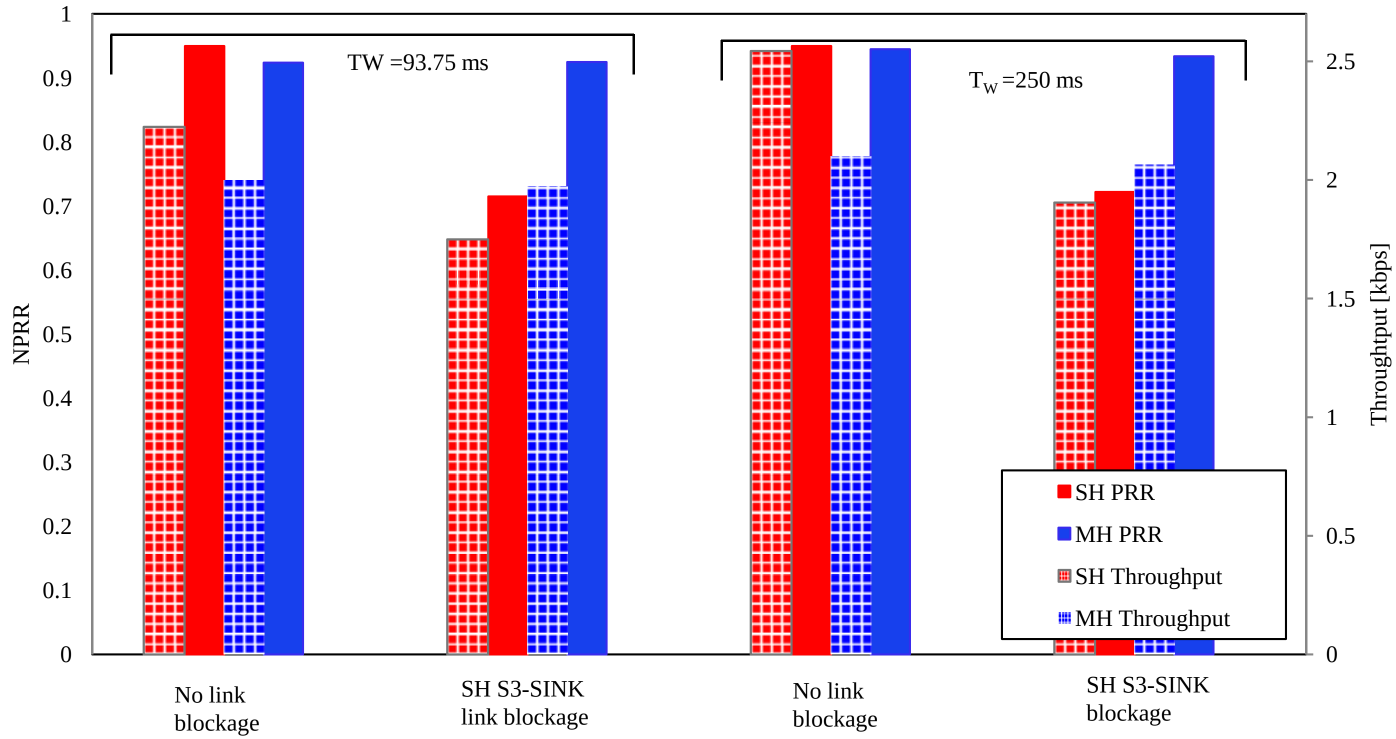


Average power consumption against margins for multi-hop (MH) and single-hop (SH)

centre for intelligent sensing

Queen Mary University of London

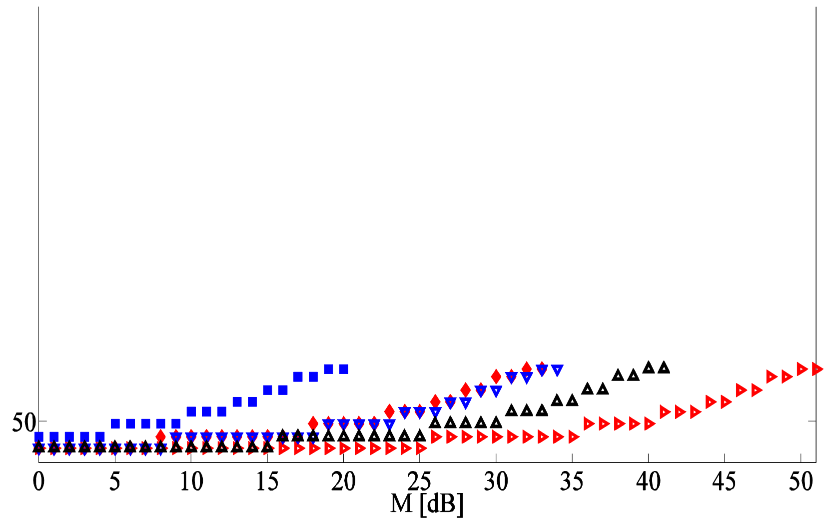
Network Packet Delivery Ratio



- In case of S3-sink link blockage, the SH PDR degrades of about 23% compared to the MH with no link blockage for both T_W cases, while the SH throughput reduction is 21% and 25% for the T_W case of 93.75 ms and 250 ms, respectively.

- This means that the MH topology can be successfully used to overcome SH link blockages.

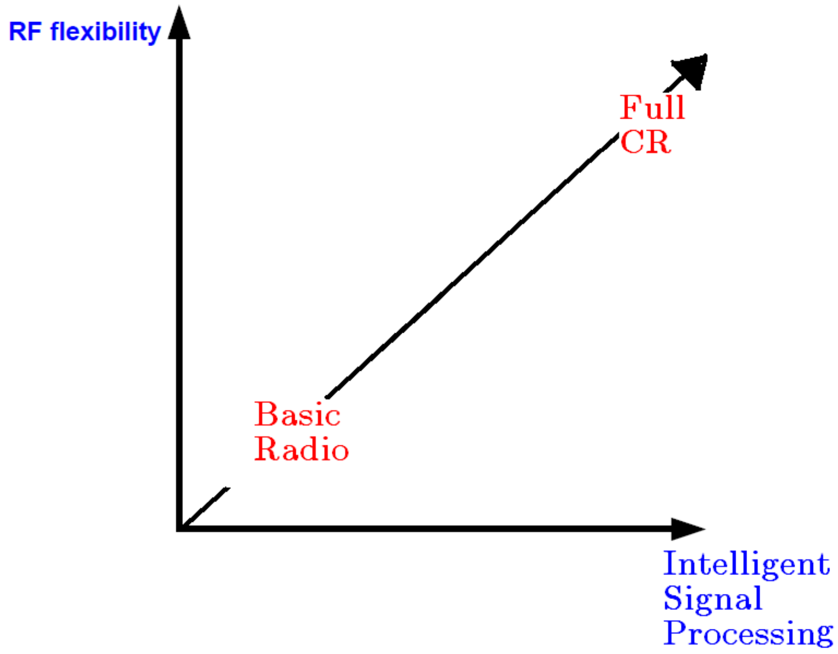
Network Lifetime: Single vs. Multi-Hop



- Network lifetime of the MH network is reduced by 25% to 45% compared to SH.
- T_{net} corresponds to the lifetime of sensors S3 and S4 for SH and MH configurations

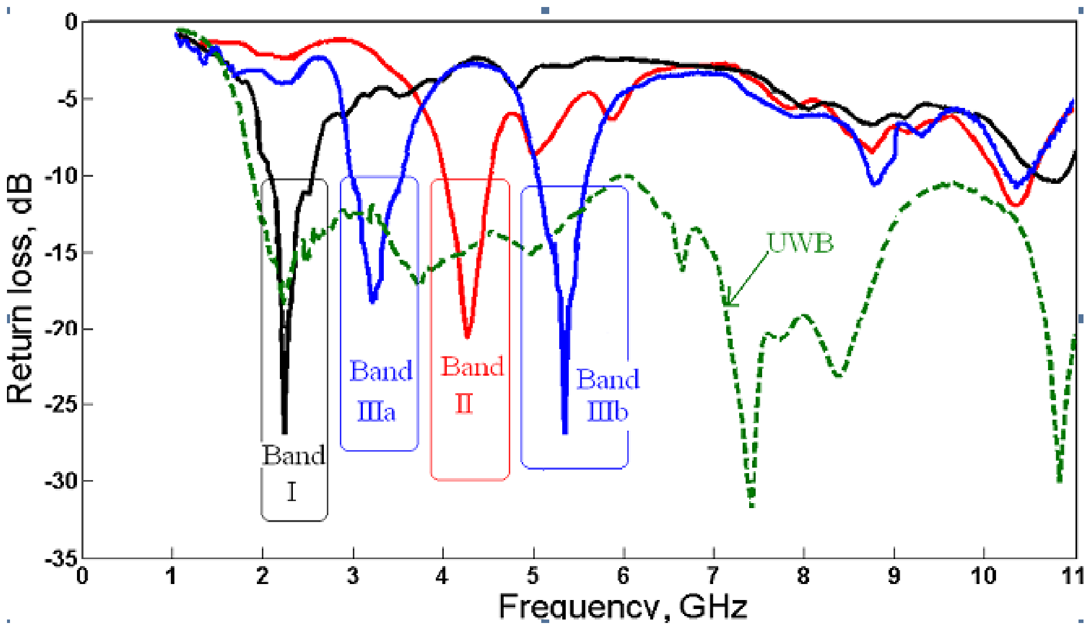
Flexible Radio Front-end is Required … Cognitive Radio

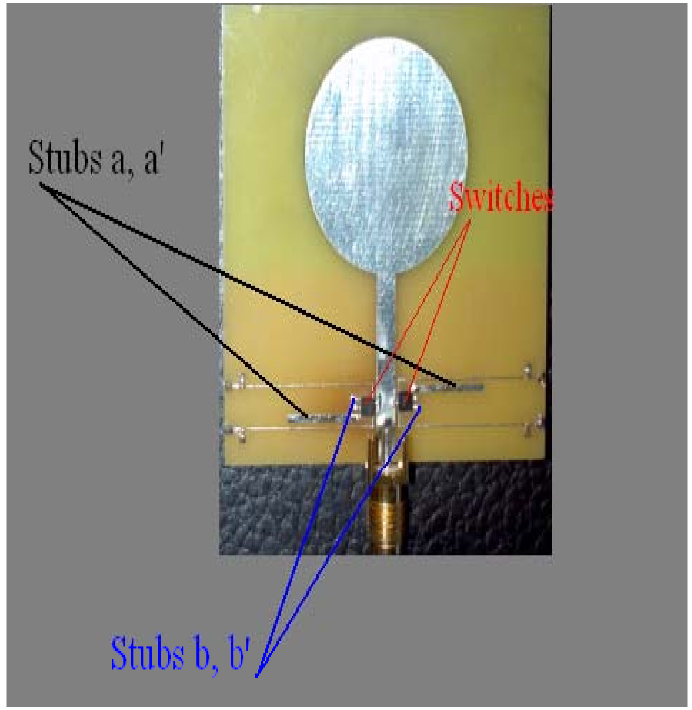
- A device may have intelligence but without the RF flexibility it won’t make correct decisions.
- On the other hand, an extremely flexible device is not worth much if it lacks the intelligence to make use of the information it is receiving.



Reconfigurable Antennas

- Low insertion loss
- Simple biasing with few external components
- Good efficiency
- Very low power consumption





UWB +multiband operation

T. Aboufoul, A. Alomainy, "Reconfigurable UWB Antenna for Cognitive Radio Applications Using GaAs FET Switches", IEEE Antennas and Wireless Propagation Letters, Vol. 11:392-394, 2012.

Realised Gain and Efficiency

Gain improved by 20% with reconfiguration

Total efficiency is at similar performance

Switches consume less than 33µW

Realised gain and efficiency for UWB case

Frequency(GHz)	Gain (dBi)		η_t (%)	
	Simulated	Measured	Simulated	Measured
2.4	2.2	1.8	90	72
4.2	2.7	2.2	91	80
3.3	2.3	2.0	88	77
5.4	3.9	3.6	89	78

Gain for reconfigured bands

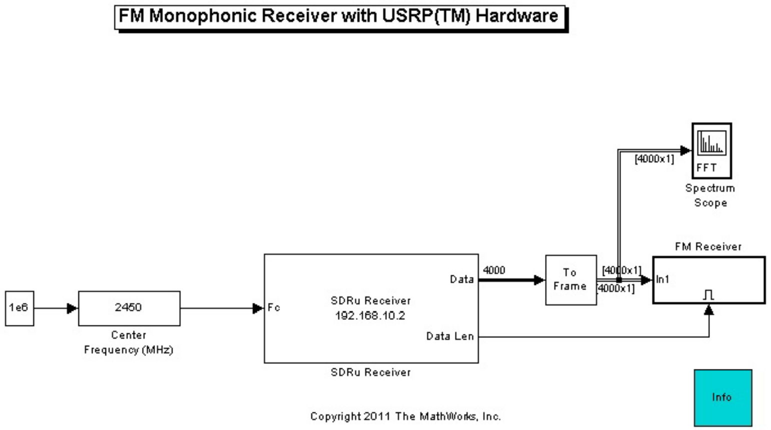
FREQUENCY (GHZ)	Gain(dBi)	
	Simulated	Measured
2.4 (band I)	2.5	2.2
4.2 (band II)	3.3	3.0
3.3 (band IIIa)	3.0	2.7
5.4 (band IIIb)	4.6	4.4

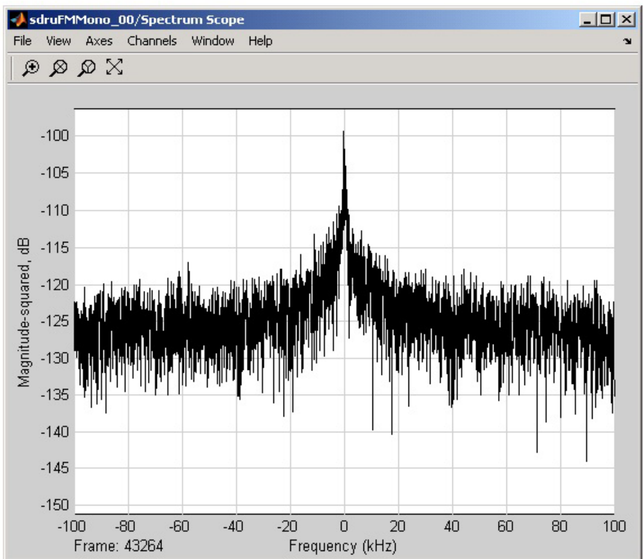
Efficiency for reconfigured bands

FREQUENCY (GHZ)	η_t (%)	
	Simulated	Measured
2.4 (band I)	86	70
4.2 (band II)	90	77
3.3 (band IIIa)	87	73
5.4(band IIIb)	84	75

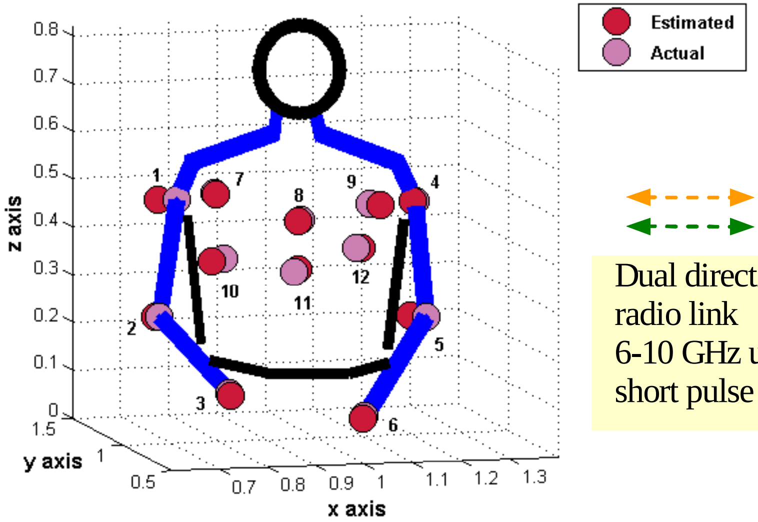
Real-Time Implementation

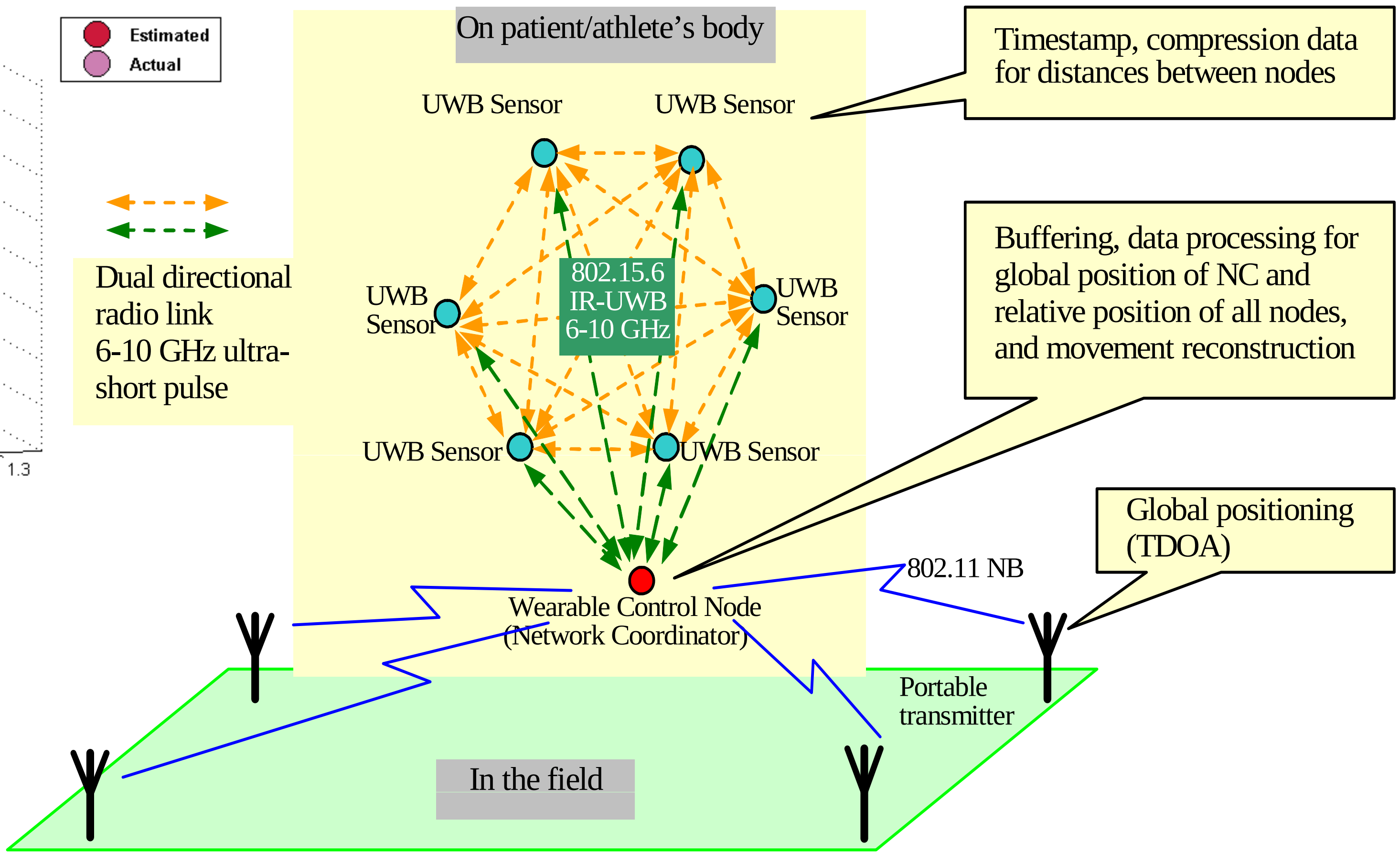
- Using software-defined radio development kit
  - Ettus Research Universal Software Radio Peripheral (USRP) Boards
- Testing of cooperative concept and channel sensing
- Reconfigurable antennas designed and fabricated by PhD student to be integrated with the test platform



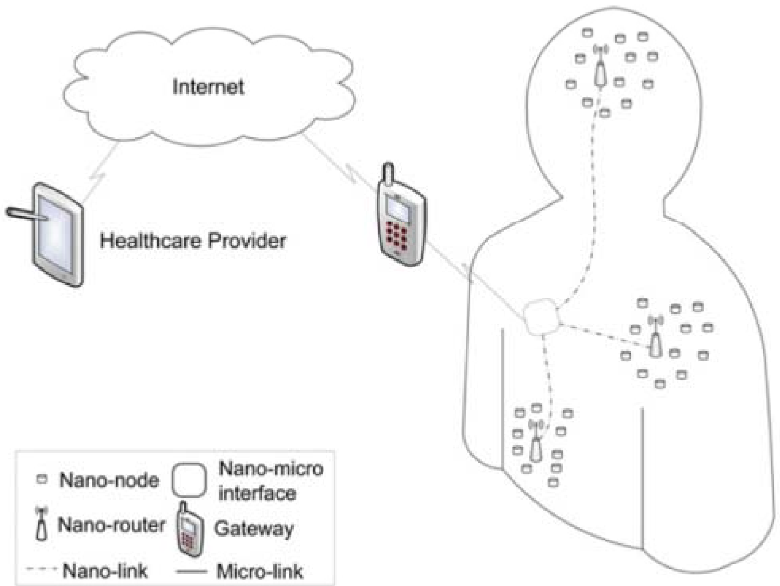


Human Body Motion Capture

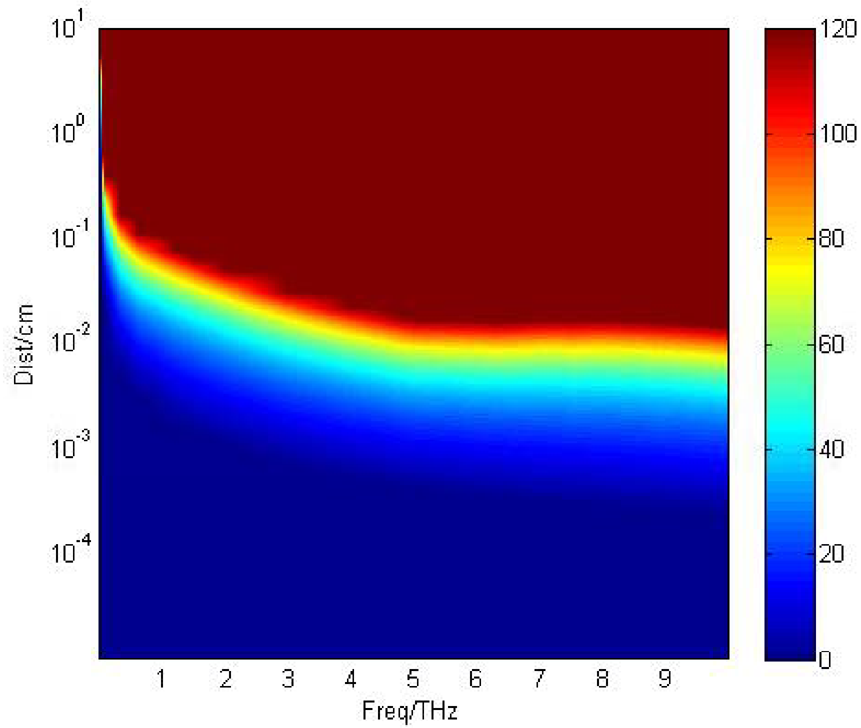




Scaling Down to Nano-networks

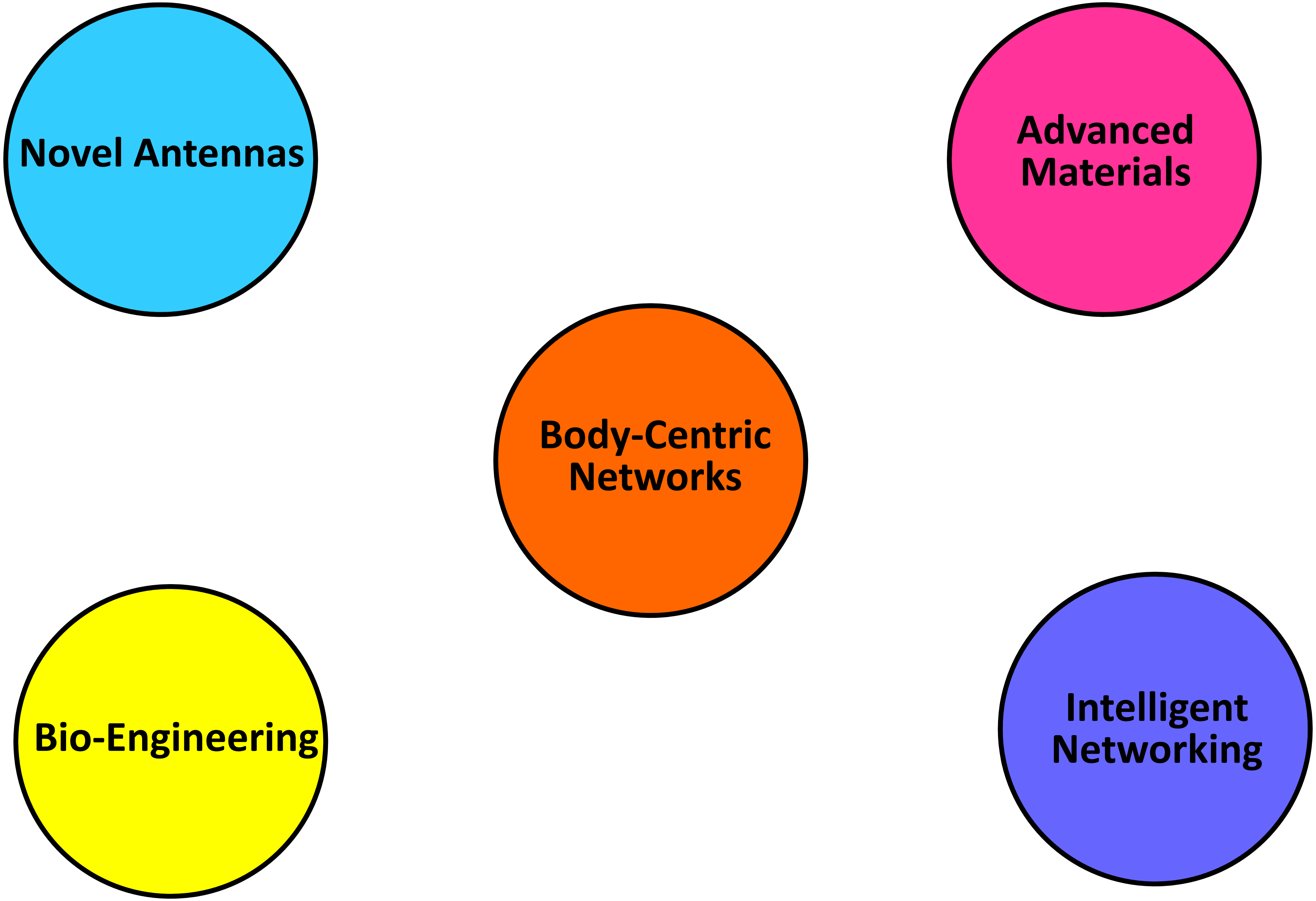


Nano-communication for future healthcare



EM wave attenuation in human blood as a function of frequency in the THz spectrum.

Multidisciplinary Topic



Summary

- Comprehensive antenna and radio channel parameters and models for body-centric wireless networks are essential for future progress.
- Guidelines for radio system designers to be applied in upcoming Medical Body Area Networks.
- Increasing interests in user-centric approaches to wireless personal communications is the main drive for continuous and active research in body-centric networks.
- In addition to academic interests, industrial applications and potential commercialisation will always provide the platform for further funding and collaborations.
- **As long as wireless communication evolves, convenient, easily accessible and efficient means of utilising the available resources will always be in demand.**

THANK YOU

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CIS centre for intelligent sensing

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