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
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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.

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:
  
<table>
<thead>
<tr>
<th></th>
<th>UK</th>
<th>USA</th>
<th>China</th>
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<tbody>
<tr>
<td></td>
<td>24%</td>
<td>20%</td>
<td>13%</td>
</tr>
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*Older People in The United Kingdom – Key facts and statistics, Age Concern’s Policy Unit 2008.
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™ 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**

- Heart rate
- Oxygen level
- Sugar level
- Body temperature
- RFID

**On-body**

- Wireless Biosensor
- Body-worn base unit
- Body Temperature
- Heart rate
- Oxygen level
- Sugar level
- RFID

**Off/on-body**

- Wireless BAN
- Base Unit
- ECG
- EEG
- Oxygen Level
- Blood Pressure
- Motion Sensors

**Surrounding Networks**

**Healthcare & Medical Applications**

**Sport Performance Monitoring**

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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


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

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.
Augmenting Social Interaction

Blue LED indicates RFID reader in reading mode.

Green LED indicates RFID reader done its reading mode.

1. RFID reader

2. RFID tag (wearer’s ID pre-stored)

3. Processor (micro-controller, heat circuit, Bluetooth unit)

4. 

5. 

Kristina

Kristina’s RFID reader recognises Lucie’s ID tag.

Lucie

Lucie’s RFID reader recognises Kristina’s ID tag.

Software in processor calculates social compatibility level between 2 wearers.
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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.

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

Wave propagation from implants at 402, 868 and 2400 MHz

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

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

Wearable Antenna Design

- Physical Size
  - Low-Profile
  - Conformal
- Robust
  - Durable
- Weight
- Flexible Substrates
- Integrate RF Circuitry
- Radiation Efficiency
  - Res Freq Shift
- Detuning
- Radiation Pattern Fragmentation
Modelling inter-body radio propagations

Simulations and measurements were performed at 2.4 GHz

<table>
<thead>
<tr>
<th></th>
<th>Human muscle</th>
<th>Bed cushion</th>
<th>Bed frame</th>
<th>Walls/floor</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Dielectric constant</strong></td>
<td>52.79</td>
<td>1.3</td>
<td>1.0</td>
<td>2.4</td>
</tr>
<tr>
<td><strong>Conductivity</strong></td>
<td>1.7</td>
<td>0.01</td>
<td>$10^6$</td>
<td>0.15</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>Front</th>
<th>Back</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Simul.</strong></td>
<td>46.2</td>
<td>54.8</td>
</tr>
<tr>
<td><strong>Meas.</strong></td>
<td>47.5</td>
<td>56.2</td>
</tr>
</tbody>
</table>
Subject-specific on-body radio channel

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

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?

- Ultra High Bandwidth Per User
- Low Cost & Interoperability
- Channelization - Highly Efficient Use Of Spectrum
- "Fused" Capability Inherent Radar & Tracking
- Ultra Low Power
- Robust Indoor Performance
- Private – Inherently Encrypted

“Fused” Capability
Inherent Radar & Tracking

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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.

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.
Transient Radio Analysis

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

![Diagram](image-url)
Effect of the body movements

![Image showing a person walking on a treadmill with sensors attached]

- **PathLoss (DB)**
  - Sensor lab: Blue line
  - Chamber: Green line

- **Locations**
  - Back
  - Chest
  - Head
  - Ankle

- **BER**
  - Head
  - Chest
  - Ankle
  - Back

**Chamber**
- Bi-Phase
- PPM

**Sensor lab**
- Bi-Phase
- PPM

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OFDM-based UWB System-Level Modelling

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

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency band</td>
<td>3-10 GHz</td>
</tr>
<tr>
<td>Data Rate</td>
<td>200 Mbps</td>
</tr>
<tr>
<td>No. of subcarriers</td>
<td>122</td>
</tr>
<tr>
<td>Subcarrier spacing</td>
<td>4.125 MHz</td>
</tr>
<tr>
<td>Sampling time</td>
<td>0.315 nsec</td>
</tr>
</tbody>
</table>

System Performance

Various Energy-to-Noise ratio 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

Sensor Transceiver Module

Top Layer - Transceiver

Bottom Layer - Transceiver

Antenna printed around the circumference of the sensor transceiver board

Sensor Prototype

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

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

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.
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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.

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 1 byte/20ms = 0.05/s
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

- 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.

Performances comparison of the two network topology.
Modified System Set up

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.

Displacement map of sensor sensors on volunteer body
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)
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


\[ UWB + \text{multiband operation} \]
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

<table>
<thead>
<tr>
<th>Frequency (GHz)</th>
<th>Gain (dBi)</th>
<th>$\eta_t$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Simulated</td>
<td>Measured</td>
</tr>
<tr>
<td>2.4</td>
<td>2.2</td>
<td>1.8</td>
</tr>
<tr>
<td>4.2</td>
<td>2.7</td>
<td>2.2</td>
</tr>
<tr>
<td>3.3</td>
<td>2.3</td>
<td>2.0</td>
</tr>
<tr>
<td>5.4</td>
<td>3.9</td>
<td>3.6</td>
</tr>
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### Frequency (GHz) vs Gain (dBi)

<table>
<thead>
<tr>
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<th>Gain (dBi)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Simulated</td>
</tr>
<tr>
<td>2.4 (band I)</td>
<td>2.5</td>
</tr>
<tr>
<td>4.2 (band II)</td>
<td>3.3</td>
</tr>
<tr>
<td>3.3 (band IIIa)</td>
<td>3.0</td>
</tr>
<tr>
<td>5.4 (band IIIb)</td>
<td>4.6</td>
</tr>
</tbody>
</table>

### Frequency (GHz) vs $\eta_t$ (%)

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<tbody>
<tr>
<td></td>
<td>Simulated</td>
</tr>
<tr>
<td>2.4 (band I)</td>
<td>86</td>
</tr>
<tr>
<td>4.2 (band II)</td>
<td>90</td>
</tr>
<tr>
<td>3.3 (band IIIa)</td>
<td>87</td>
</tr>
<tr>
<td>5.4 (band IIIb)</td>
<td>84</td>
</tr>
</tbody>
</table>

Gain for reconfigured bands

Efficiency for reconfigured bands
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

Timestamp, compression data for distances between nodes

Buffering, data processing for global position of NC and relative position of all nodes, and movement reconstruction

Global positioning (TDOA)

In the field

Wearable Control Node (Network Coordinator)

Dual directional radio link 6-10 GHz ultra-short pulse

UWB Sensor

IR-UWB 6-10 GHz

802.15.6

Portable transmitter

802.11 NB

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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.
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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