Towards Body-Centric Wireless Communications at Millimetre Wave Frequencies

Yang Hao
Antennas and Electromagnetics
Outline

- Overview of Body Centric Wireless Communications
  - History
  - Motivation
  - Applications
- Opportunity and Research Challenges of Body-centric Wireless Communications at Millimeter Waves
- Conclusions and future work
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History of Body-Centric Wireless Communications
Various Antennas Developed at QMUL
Research Income Secured

- Over £10M Research Funding from UK Research Councils, Charity, EU, USA and Industry.

Over £1M research funding from the industry for last three years
Industrial Collaborators

- Over £1M research funding from the industry for last three years
  - Philips Netherlands, Philips Shanghai
  - ONR, US Air Force Research Lab, GE Global Research, USA
  - DSTL, UK
  - BAE Systems, Cobham, Selex, Roke Manor Research Ltd
  - Toumaz Technology, Zimiti Limited
Global population is aging
Body-Centric Wireless Communications

Keep continuous record of patient’s health at all times (including athletes performance monitoring)
Body-Centric Wireless Communications

Stratified Human Digital Phantoms

<table>
<thead>
<tr>
<th></th>
<th>F01</th>
<th>F02</th>
<th>F03</th>
<th>F04</th>
<th>F05</th>
<th>M01</th>
<th>M02</th>
<th>M03</th>
<th>M04</th>
</tr>
</thead>
<tbody>
<tr>
<td>Height (m)</td>
<td>1.60</td>
<td>1.66</td>
<td>1.55</td>
<td>1.65</td>
<td>1.80</td>
<td>1.76</td>
<td>1.67</td>
<td>1.78</td>
<td>1.80</td>
</tr>
<tr>
<td>Weight (kg)</td>
<td>50</td>
<td>55</td>
<td>52</td>
<td>52</td>
<td>75</td>
<td>73</td>
<td>56</td>
<td>87</td>
<td>85</td>
</tr>
<tr>
<td>BMI</td>
<td>19.5</td>
<td>20.6</td>
<td>21.6</td>
<td>19.1</td>
<td>23.1</td>
<td>23.6</td>
<td>20.1</td>
<td>27.5</td>
<td>26.2</td>
</tr>
<tr>
<td>Waist (cm)</td>
<td>67.0</td>
<td>72.7</td>
<td>68.8</td>
<td>66.2</td>
<td>81.9</td>
<td>82.6</td>
<td>67.1</td>
<td>91.0</td>
<td>84.2</td>
</tr>
<tr>
<td>Chest (cm)</td>
<td>79.4</td>
<td>85.6</td>
<td>96.9</td>
<td>80.7</td>
<td>107.9</td>
<td>91.3</td>
<td>82.1</td>
<td>101.1</td>
<td>98.4</td>
</tr>
</tbody>
</table>

Modelling inter-body radio Propagation
Wireless Sensor Node for 2.45 GHz Implementation

Simulations using CST Microwave Studio Model

Current on-body sensors have an average sampling of 14 ms/sample subdivided in three sections: 1) microcontroller module, 2) RF transceiver design, and 3) antenna design.
On-Body Path Loss, \(d_0 = 10\) cm

<table>
<thead>
<tr>
<th></th>
<th>Value</th>
<th>Standard Error</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Antenna Alone</strong></td>
<td>Intercept</td>
<td>33.47825</td>
</tr>
<tr>
<td></td>
<td>Slope</td>
<td>4.86124</td>
</tr>
<tr>
<td><strong>Antenna+System</strong></td>
<td>Intercept</td>
<td>32.09894</td>
</tr>
<tr>
<td></td>
<td>Slope</td>
<td>5.11089</td>
</tr>
<tr>
<td><strong>Embedded System</strong></td>
<td>Intercept</td>
<td>41.60945</td>
</tr>
<tr>
<td></td>
<td>Slope</td>
<td>2.47624</td>
</tr>
</tbody>
</table>
Applications of Wireless Wearable Sensors: Sports and Physiotherapy

- On body channels
  - Belt-back, Belt-wrist, Belt-ankle, Belt-chest
- Wireless sensor module (QMUL prototype)
  - IEEE 802.15.4 Zigbee-Ready transceiver
On-Body Measurements and Results

CDF for different sport Activities

1. Resting Subject
2. Jogging Subject

Two different scenarios:
Weight=80 kg
Height=168 cm

In-house Wireless Sensor Nodes (WSNs operate @ 2.42 GHz)
signal fluctuations of ±15 dB

Motionless Sensor Nodes (On-Body Links)
Gateway Node (Off-Body Link)

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EM Resonators for Biological Tissues
EM Resonators for Biological Tissues

Unloaded Reflection Coefficient of the Spiral Resonator
Patch Resonator for Non-Invasive Glucose Monitoring

<table>
<thead>
<tr>
<th>parameter</th>
<th>(mm)</th>
<th>parameter</th>
<th>(mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$W_s$</td>
<td>29</td>
<td>$L_s$</td>
<td>20</td>
</tr>
<tr>
<td>$W_f$</td>
<td>13.27</td>
<td>$L_c$</td>
<td>3.2</td>
</tr>
<tr>
<td>$W_p$</td>
<td>10.27</td>
<td>$L_d$</td>
<td>1.8</td>
</tr>
<tr>
<td>$W_c$</td>
<td>12.27</td>
<td>$L_f$</td>
<td>3.8</td>
</tr>
<tr>
<td>$W_d$</td>
<td>8.27</td>
<td>$L_h$</td>
<td>1.3</td>
</tr>
<tr>
<td>$W_h$</td>
<td>9.365</td>
<td>$C_{gap}$</td>
<td>0.3</td>
</tr>
<tr>
<td>$L_p$</td>
<td>9.2</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Simulations in air media

Fabricated Resonator
Clinical Trial: Measurements Setup

Soda Test
- Subjects asked to fast at least for eight hours
- We tracked the response of the resonator twice for each subject while they are still fasting.
- A glucose rich drink is given to the subjects.
- Then the response of the resonator is tracked for 110 minutes.

Commercial force sensors [1]

Patch resonator

Wood Block

Comparison of Human Test Results

Female 1

OGT : oral glucose tolerance

Male 1
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High free space loss due to small wavelength

\[ L_f(r) = \left( \frac{4\pi r}{\lambda} \right)^2 \]

Losses due to atmospheric absorption and rain attenuation have to be considered:

\[ L_a(r) = e^{\rho r} \quad L_w(r) = e^{\eta'} \]

Millimetre waves for BANs: Advantages

- Transmission of large amount of data (uncompressed audio and video streaming, entertainment)
- Higher transmission speed
- Data encryption
- Unlicensed frequency bands
- Compact devices
- Energy confinement: reduction of interference and signature (military, medical)
Frequency bands for mm-wave BANs

- Millimetre wave frequency: 30 GHz to 300 GHz (10 mm to 1 mm wavelength)
- Frequencies of interest for commercial use are those around 60, 70, 80 and 90 GHz:

No worldwide agreement on regulations and allocation of these bands. Example:

<table>
<thead>
<tr>
<th>Region</th>
<th>Frequencies (GHz)</th>
<th>Max Tx Power (mW)</th>
<th>Max Antenna Gain (dBi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>USA</td>
<td>57-64</td>
<td>500</td>
<td>NS</td>
</tr>
<tr>
<td>Canada</td>
<td>57-64</td>
<td>500</td>
<td>NS</td>
</tr>
<tr>
<td>Japan</td>
<td>59-66</td>
<td>10</td>
<td>47</td>
</tr>
<tr>
<td>EU</td>
<td>57-66</td>
<td>20</td>
<td>37</td>
</tr>
<tr>
<td>Australia</td>
<td>59.4-62.9</td>
<td>10</td>
<td>47</td>
</tr>
<tr>
<td>South Korea</td>
<td>57-64</td>
<td>10</td>
<td>TBD</td>
</tr>
</tbody>
</table>
MMW70 and MMW80 bands are of interest for point-to-point Gb/s long range communications (fibre optics alternative):

- 10 GHz of total available bandwidth
- Atmospheric absorption only slightly higher than lower frequencies
- As a result, it is possible to obtain a 3 Km link with 1 Gb/s data rate\(^1\).

MMW90 is available for unlicensed use in indoor applications (US only at present), and for licensed outdoor use. The presence of a forbidden band (94 GHz to 94.1 GHz) does not make it interesting as a fibre optics alternative.

MMW60 exhibits a peak in atmospheric absorption (20 dB/Km): also not suitable as fibre optics alternative.

However, atmospheric absorption is not a concern for body-centric communications.

The unlicensed use contributes to cost limitation.

Therefore, MMW60 and MMW90 are the most interesting bands for body-centric communications.

Millimetre waves for BANs: Challenges

- Shared challenges with BANs at lower frequencies (antenna detuning, dynamicity of human body, shadowing from body parts)
- The human body is very large in terms of wavelength:
  - Increased shadowing from body parts (potentially bringing to complete loss of communication link);
  - Numerical investigation by means of full wave methods (mainly FDTD) is difficult to replicate because of the large computational burden;
- Higher propagation losses;
- Atmospheric and rain attenuation have to be taken into account;
- Antennas must be directive enough to compensate losses but not too directive, to avoid misalignment losses.
- Difficulty in experimental characterisation: repeatability of measurements, effects of cables, wearability of measurement set-up (waveguide components).
Propagation characteristics of millimetre waves

- Atmospheric absorption exhibits a local maximum at 60 GHz
- Rain attenuation increases with frequency
- However, these contributions are negligible with respect to free space propagation loss, at distances relevant to on-body communications
- Evaluation of losses:

<table>
<thead>
<tr>
<th>Frequency (GHz)</th>
<th>60</th>
<th>94</th>
</tr>
</thead>
<tbody>
<tr>
<td>Distance (m)</td>
<td>0.3</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>100</td>
</tr>
<tr>
<td></td>
<td>0.3</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>100</td>
</tr>
<tr>
<td>$L_a$ (dB)</td>
<td>6e-3</td>
<td>0.02</td>
</tr>
<tr>
<td></td>
<td>0.1</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>1.5e-4</td>
<td>5e-4</td>
</tr>
<tr>
<td></td>
<td>2.5e-3</td>
<td>5e-3</td>
</tr>
<tr>
<td>$L_w$ (dB)</td>
<td>7.5e-3</td>
<td>0.025</td>
</tr>
<tr>
<td></td>
<td>0.125</td>
<td>2.5</td>
</tr>
<tr>
<td></td>
<td>9e-3</td>
<td>0.03</td>
</tr>
<tr>
<td></td>
<td>0.15</td>
<td>3</td>
</tr>
<tr>
<td>$L_f$ (dB)</td>
<td>58</td>
<td>68</td>
</tr>
<tr>
<td></td>
<td>82</td>
<td>108</td>
</tr>
<tr>
<td></td>
<td>61.4</td>
<td>72</td>
</tr>
<tr>
<td></td>
<td>86</td>
<td>112</td>
</tr>
</tbody>
</table>
Propagation characteristics of millimetre waves

- Very low penetration depth in human tissues.
- Evaluation of penetration depths for dry skin at various frequencies:

<table>
<thead>
<tr>
<th>Frequency [GHz]</th>
<th>Dielectric constant</th>
<th>Electric conductivity [S/m]</th>
<th>Penetration depth [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.45</td>
<td>38.06</td>
<td>1.44</td>
<td>23</td>
</tr>
<tr>
<td>10</td>
<td>31.29</td>
<td>8.01</td>
<td>3.80</td>
</tr>
<tr>
<td>60</td>
<td>7.98</td>
<td>36.40</td>
<td>0.47</td>
</tr>
<tr>
<td>94</td>
<td>5.78</td>
<td>39.18</td>
<td>0.37</td>
</tr>
</tbody>
</table>

- Human body parts have dimensions of several wavelengths;
- Therefore, shadowing from body parts can severely decrease the power available at the receiver, when in NLoS with the transmitter.
- Following the considerations on penetration depth, the body can be modelled as an homogenous object with the properties of skin;
Analysis of upper body links: Measurements

- For waist-torso link, a grid of 143 points was considered, spaced by 3 cm, for a total area of 33cm x 39 cm.

- A planar scanner was used to control the position of the receiver.

- The measurements were repeated with the subjected wearing first a thin cotton t-shirt, then a wool sweater.

- A measurement in absence of the subject was taken, in order to verify that the presence of set-up was not affecting the measurement itself. The obtained path loss exponent was 2.06.
Analysis of upper body links: Measurements

- In the head-shoulder link, the measured path loss was close to the free space one.
- No significant difference between t-shirt and sweater scenarios.
- Waist-torso link:

Path loss versus logarithmic distance

CDF of deviation from estimated path loss

Analysis of upper body links: Measurements

- Comparison of obtained results with similar at lower frequencies

<table>
<thead>
<tr>
<th>Analysed scenario</th>
<th>Frequency (GHz)</th>
<th>n</th>
<th>(\sigma) (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hugo Model(^1)</td>
<td>2.4</td>
<td>3.8</td>
<td>5.2</td>
</tr>
<tr>
<td>Male 02(^2)</td>
<td>2.4</td>
<td>2.8</td>
<td>3.9</td>
</tr>
<tr>
<td>Cotton T-shirt</td>
<td>94</td>
<td>4.4</td>
<td>6.4</td>
</tr>
<tr>
<td>Wool sweater</td>
<td>94</td>
<td>4.5</td>
<td>8.7</td>
</tr>
</tbody>
</table>

- Both path loss exponent and shadowing factor are significantly higher than those obtained at lower frequencies.
- It is possible to notice that the clothes affect mainly the shadowing factor, while just a small increase in path loss was observed.


A scenario similar to the measured one can be simulated by means of ray-based software XGTD (GO/UTD).

A surface digital phantom with dimensions similar to the subject of the measurement has to be imported in the simulation scenario.

Material properties are assigned according to the different simulated scenarios:
Analysis of upper body links: Simulations

- Comparison between measurements and simulations results:

<table>
<thead>
<tr>
<th>Simulated model</th>
<th>Measured n</th>
<th>Simulated n (flat grid)</th>
<th>Simulated n (conformal grid)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dry skin</td>
<td>-</td>
<td>3.7</td>
<td>4.5</td>
</tr>
<tr>
<td>Dry skin + cotton T-shirt</td>
<td>4.4</td>
<td>3.7</td>
<td>4.7</td>
</tr>
<tr>
<td>Dry skin + wool sweater</td>
<td>4.5</td>
<td>4.2</td>
<td>4.8</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Simulated model</th>
<th>Measured $\sigma$</th>
<th>Simulated $\sigma$ (flat grid)</th>
<th>Simulated $\sigma$ (conformal grid)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dry skin</td>
<td>-</td>
<td>8.0</td>
<td>8.9</td>
</tr>
<tr>
<td>Dry skin + cotton T-shirt</td>
<td>6.4</td>
<td>8.8</td>
<td>9.1</td>
</tr>
<tr>
<td>Dry skin + wool sweater</td>
<td>8.7</td>
<td>7.1</td>
<td>8.3</td>
</tr>
</tbody>
</table>

- The results obtained in the case of the conformal grid show a good agreement with the measured values.
Further analysis of clothes effect: shadowing from upper limbs

- Upper limbs are likely to be a major source of shadowing for links based on waist and torso.
- Their effect on 94 GHz signal propagation was investigated by means of both measurements and simulations.
- Two scenarios were considered: bare skin and skin covered by a wool sweater.
Further analysis of clothes effect: shadowing from upper limbs

- The shadowing effect from upper limbs is significantly affected by the presence of a wool layer over the skin.
Further analysis of clothes effect: shadowing from upper limbs

- The shadowing effect from upper limbs is significantly affected by the presence of a wool layer over the skin
Further analysis of clothes effect: shadowing from upper limbs

Normal component of the Electric Field around the wrist @94GHz

At the air-cloth boundary

Inside cloth

Inside air-gap
Perfect Surface Wave Cloaks

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(Received 11 September 2013)

FIG. 1 (color online). A diagram illustrating the orthogonal ray paths that are equated in order to derive the appropriate index distribution to cloak a particular surface, of radius $a$ and height $b$. The blue lines are the radial geometric path lengths ($l_1$ and $l_2$) and the red lines denote the circular geometric paths ($s_1$ and $s_2$), in the curved space and flat space. The green dashed line denotes the length from the origin to the surface, $R(\theta)$.

\[
\frac{n'(\theta)}{n(\theta)} = \frac{\sqrt{R(\theta)^2 + R'(\theta)^2} - R'(\theta)\sin(\theta) - R(\theta)\cos(\theta)}{R(\theta)\sin(\theta)}. 
\]
All Dielectric Realisation of Surface Wave Cloaks

![Graph showing the required dielectric constant vs refractive index](image1)

- Required $\varepsilon_r$ vs Refractive index $n$
  - $\varepsilon_r = 2$
  - $\varepsilon_r = 7$
  - $\varepsilon_r = 11$
  - $\varepsilon_r = 15$

- 0dB to -20dB scale

![Diagram showing different $\varepsilon_r$ values](image2)

- $\varepsilon_r = 9$
- $\varepsilon_r = 10$
- $\varepsilon_r = 11$
- $\varepsilon_r = 12$
- $\varepsilon_r = 13$
- $\varepsilon_r = 14$
- $\varepsilon_r = 15$

(a) - (d) show the simulated wave patterns for different $\varepsilon_r$ values.
Woodpile antennas for mm-Wave BANs

- Based on the resonator antenna concept introduced by Trentini\(^6\), it is composed by an alumina cylindrical woodpile structure fed by a 1 mm coaxial cable.

- The woodpile EBG structure, made of alumina filaments by means of an extrusion free-forming process, is designed to behave as a partially reflecting sheet at the desired frequency.


Woodpile antennas for mm-Wave BANs

- Both flat and cylindrical resonator antennas can be realised
The cylindrical antenna exhibits an azimuthally omnidirectional radiation with a moderate gain (~7-8dB), while the planar antenna has a directive pattern with a high gain (~18-20dB).
Metamaterial Antennas: Woodpile Spatial Angular Filter for Beam Shaping of Conical Horn Array

- Dual-layer woodpile cavity provides very sensitive angular discrimination for off-normal transmission through the structure.

$$d_1 = 1\text{mm}$$

$$d_2 = 1.4 - 1.7\text{mm}$$
Metamaterial Antennas: Performance Enhancement from Transformation Electromagnetics

Aim – Use the transformation lens as a super-strate to compensate the phase difference of the rays ($\theta > 0$) radiated by the source.
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New Devices, Materials Arising from Body-Centric Wireless Communications

Research activity been extended to high frequencies, with applications already available.
Thank you very much for your attention

And

Look forward to collaboration opportunities