Exploring the Potentials of EM Technologies from Body- to Nano-Scale for Healthcare Applications

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Abstract

With the advent of commercial products, such as Google Glass, Samsung Galaxy Gear and the expected iWatch, body-centric communication has increasingly garnered the public attention and smoothly translated state-of-the-art research work into reality. With the development of nanotechnology, the idea of connecting nano-devices to conduct complicated tasks and communicate the information collected by these sensors was a natural progression in order to complete the overall picture of a new generation of body-centric wireless networks. Connecting these nano-machines (or nano-devices) together in order for them to execute a useful function and deliver information between nano-nodes and ultimately interfacing to users or the outside world, the birth of nano-communication and networking was a necessity. Nano-scale communication is referred to the exchange of information at the nanoscale and it is the basis of any wired/wireless interconnection of nano-devices in a nano-network. The way the nano-devices communicate with each other has strong dependence on the way in which they are realised. In addition, the specific application of the nano-network determines the deployment of the nano-networks, thus constraining the choice on the particular type of nano-communication.

The talk will present development of reliable and comprehensive channel modelling, human tissue electric properties in the THz band and networking technologies to address the major challenges of the nano-scale electromagnetic channels needed for body-centric wireless nano-networks deployed in future healthcare applications. With the advancement of nano-scale machine fabrication and the deep understanding of molecular behaviour within the human body, future healthcare monitoring and feedback systems are expected to be comprehensive, efficient and ubiquitous hence coupling existing wireless wearable sensors and implantable units with nano-machines and networks.

Index terms: Wearable, Antennas, Nano-scale, Terahertz, Biomedical
Talk Context

- This talk was delivered as a keynote speech at the URSI Turkey Congress that took place in Konya on 6 to 8 September 2018.

- The talk was part of the Electromagnetics in Biology and Medicine section to highlight recent advances in healthcare application of EM technologies at low frequencies for wearable application up to THz at the nano-scale.
Biography of Presenter

Akram Alomainy received the M.Eng. degree in communication engineering and the Ph.D. degree in electrical and electronic engineering (specialized in antennas and radio propagation) from Queen Mary University of London (QMUL), U.K., in July 2003 and July 2007, respectively. He joined the School of Electronic Engineering and Computer Science, QMUL, in 2007, where he is a Reader in Antennas and Applied EM. He is a member of the Institute of Bioengineering and Centre for Intelligent Sensing at QMUL. His current research interests include small and compact antennas for wireless body area networks, radio propagation characterisation and modelling, antenna interactions with human body, computational electromagnetic, advanced antenna enhancement techniques for mobile and personal wireless communications, nano-scale networks and communications, THz material characterisation and communication links and advanced algorithm for smart and intelligent antenna and cognitive radio system. He has managed to secure various research projects funded by research councils, charities and industrial partners on projects ranging from fundamental electromagnetic to nano-scale wearable and in-vivo technologies. He is the lead of Wearable Creativity research at Queen Mary University of London and has been invited to participate at the Wearable Technology Show 2015, Innovate UK 2015 and also in the recent Wearable Challenge organised by Innovate UK IC Tomorrow as a leading challenge partner to support SMEs and industrial innovation. He has authored and co-authored two books, 6 book chapters and more than 250 technical papers (4700+ citations and H-index 33) in leading journals and peer-reviewed conferences.

Dr. Alomainy won the Isambard Brunel Kingdom Award, in 2011, for being an outstanding young science and engineering communicator. He was selected to deliver a TEDx talk about the science of electromagnetic and also participated in many public engagement initiatives and festivals. He is a Chartered Engineer, member of the IET, senior member of IEEE, fellow of the Higher Education Academy (UK) and also a College Member for Engineering and Physical Sciences Research (EPSRC, UK) and its ICT prioritisation panels. He is also a reviewer for many funding agencies around the world including Expert Swiss National Science Foundation (SNSF) Research, the Engineering and Physical Sciences Research Council (EPSRC), United Kingdom and the Medical Research Council (MRC), UK. He is an elected member of UK URSI (International Union of Radio Science) panel to represent the UK interests of URSI Commission B (1 Sept 2014 until 31 Aug 2017).
The Mile End campus is historically the home of Queen Mary College, which began life in 1887 as the People's Palace, a philanthropic centre to provide east Londoners with educational, cultural and social activities.
Electrical Engineering was first taught at East London College in October 1888.

In 1936 the High Voltage Laboratory opened and this state of the art research facility was unique to London.
Contribution & Acknowledgement

- External & Industrial collaborators
  - Intrinsique Materials Ltd
  - Philips Research
  - Defence Science and Technology Lab (DSTL)
  - GE Healthcare, USA
  - Engineering and Physical Sciences Research Council (EPSRC), UK
  - Toumaz Technologies, UK
  - Onzo Ltd., UK
  - Acute Technology Ltd.
  - Trimble Ltd., New Zealand
  - The Shadow Robot Company
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
Measuring Oneself

Some individuals’ increasing interest in measuring their daily activities, steps taken, calorie intake, sleep quality, body temperature, heart rate, glucose level, etc.
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 Communication

Radio channel characterisation and modelling

In-house conformal FDTD

System-level modelling

Data In → GFSK Modulator → VCO → PA → Radio Channel

Measured on-body channel results

Statistical Analysis → IDFT

Channel Characterisation → Post-Processing

Initial Model

Data Collection → Analysis Software → Measured on-body channel results


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/

Digital Human Phantom for Wireless Implants

Localisation of Wireless Endoscope

Sensor receivers

Measured RSSI

RSSI Reader

Localization and Simulation platform

Capsule Traveling through small intestine
Numerical & Experimental Analysis

- Radio Propagation from Implants

Wave propagation from implants at 402, 868 and 2400 MHz

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

Sensor Transceiver Module

Top Layer - Transceiver

Bottom Layer - Transceiver

Antenna printed around the circumference of the sensor transceiver board

Sensor Prototype

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.
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.

Final Design and Production

- Real scenarios sensor performance evaluation (e.g. Hospital environment) applying new designs and more compact production.

≈1.25 cm
Textile Radio Interfaces
Antennas for Future Communications (e.g. 5G)

Fabricated on various textile substrates with advanced embroidery techniques

Next → Inkjet printing for bias line inclusion
Different stubs connected to feedline → Different frequency Band operations

Simulated and measured return loss curves when antenna is configured in: a) Band I at 2.4 GHz, b) Band II: 3.3 to 4.4 GHz, c) Band III: 4.1 to 5.4 GHz, d) Band IV: 5 GHz, e) Dual band: 2.4, 5 GHz, and f) Band V: 6.5 to 7.5 GHz.
Advanced EM Textile Concepts

(a) Laser-engraved silver cotton (b) Copper vacuum deposition, with a screen-printed latex stencil peeled-off (c)- (d) Cotton samples chemically etched.

(a) Screen-printed polyester cotton (b) Laser engraved silver cotton (c) Embroidered polyester cotton. All samples pleated and assembled manually.
Augmenting Social Interaction

Icebreaker Jacket v0.2: features diagram

Social indicator badge – heat sensitive paints change colours from black to purple, blue, green, yellow and/or orange (depending on compatibility levels between 2 wearers).

Hidden camera with 5cm adjustable position for recording point of view, facial expression and conversation.

Feedback LED – green light blinks twice to notify when the exchange of information has completed.

Hidden RFID system - tag and antenna used to sense handshaking gesture.

Hidden control board and power pack placed inside pocket.
Scaling Down to Nano-networks

Nano-communication for future healthcare

- Collaborative work with Texas A&M University at Qatar (Khalid Qaraqe and Qammer Abbasi) on QNRF NPRP funding
- Joint publications on theoretical and analytical work with Khalifa University (Raed Shubair) and UAE University (Najah AbuAli)

EM wave attenuation in human blood as a function of frequency in the THz spectrum.
Nanosensor Device (Nano-Antenna)


Terahertz (THz)
Methodology – Biological Modeling & THz-TDS

- **Culturing Collagen**
  - Constitutes for the second layer of the skin – DERMIS
  - Scaffolding for various important entities such as capillaries, sweat ducts and hair shaft.
  - Protein Matrix

- **THz spectroscopy of Collagen**
  - Retrieve valuable information on phase and amplitude of sample.
  - Working band is 0.5 – 2 THz
  - Data Analysis: working on Transfer equation based algorithm to retrieve refractive index and absorption coefficient.
Schematic of THz-Time Domain Spectroscopy
Experimental Setup

Laser source – Ti:Sa femtosecond pulsed laser

Electro-optic detector – ZnTe crystal

Delay stage – maximum traveled distance is 15 cm

THz emitter – biased LT-GaAs photoconductive antenna
Culturing Artificial Skin – Biological Modeling

(a) Collagen         (b) Fibroblast cells

a) Artificially synthesized collagen layer at the Blizard Institute, QMUL & (b) Fibroblasts cells assisting the growth of collagen samples.

**THz Signal Transmission – Time Domain**

**THz Time Domain Analysis of TPX & Collagen**

- Main peak - reference
- Main peak - Collagen
- Satellite peaks

Expected high attenuation for collagen from main to satellite peak between 0.1 – 2 THz
THz Spectrum – Frequency Domain

![THz Spectrum graph](image)

- **Frequency Domain (Log)**
- **Spectrum Magnitude (arb)**
- **Frequency (Hz)**

- **Dynamic range**
- **Noise Floor**

THz Spectrum graph showing the frequency domain with logarithmic scale for spectrum magnitude and frequency. The graph includes two lines representing Collagen and TPX with markers indicating the noise floor and dynamic range.
Refractive Index ranging from 0.5-1.3 THz illustrates that with increasing frequency the value decreases. The sample was embedded with 100k, 300k, and 500k fibroblast cells.
## Fibroblast Cell Number Density Variation

<table>
<thead>
<tr>
<th>Sample</th>
<th>Cell no. (k=1000)</th>
<th>1 week old Diameter (cm)</th>
<th>2 weeks old Diameter (cm)</th>
<th>Contraction (approx.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coll1</td>
<td>100k</td>
<td>2.5</td>
<td>2</td>
<td>~0.5,</td>
</tr>
<tr>
<td>Coll3</td>
<td>300k</td>
<td>1.8</td>
<td>1.6</td>
<td>0.2,</td>
</tr>
<tr>
<td>Coll5</td>
<td>500k</td>
<td>1.6</td>
<td>1.5</td>
<td>0.1</td>
</tr>
</tbody>
</table>
Microscopic Imaging Verification

Microscopic image of real human skin presenting the two defined layers: Epidermis and Dermis.

Cross-section of skin sample (A): Longitudinal section of the hair follicle attached to a sweat duct in the dermis layer, (B). Cross-section of oval shaped hair follicle structure.
Skin Tissue Electric Properties – Refractive Index

![Graph](image)

- **Refractive Index**
- **Polynomial Fitting**
Skin Tissue Electrical Properties – Absorption Coefficient

Absorption Coefficient

Alpha - Polynomial Fitting

Absorption Coefficient (alpha, cm⁻¹)

Frequency (THz)

-50  0  50  100  150  200

1  1.5  2  2.5
Path Loss Modelling for Various Tissue Types

Modified Friis Equation

\[ PL_{total} [dB] = PL_{spr}(f, d)[dB] + PL_{abs}(f, d)[dB] \]

\[ PL_{spr}(f, d) = \left( \frac{4\pi d}{\lambda_g} \right)^2 \]

\[ PL_{abs} = \frac{1}{\tau(f, d)} = e^{\alpha(f)d} \]

where \( \lambda_g = \lambda_0/n_r \) stands for the wavelength in medium with free-space wavelength \( \lambda_0 \); \( d \) is the travelling distance of the wave; \( f \) is the frequency; \( \alpha \) is the absorption coefficient.

Total path loss as a function of the distance and frequency for different human tissues

blood

skin

fat
Molecular Noise Inclusion

\[ T_{mol}(f, d) = T_0 \xi(f, d) \]

\[ \xi(f, d) = 1 - \tau(f, d) \]

where, \( \tau(f, d) = e^{-\alpha(f)d} \) is the transmissivity of the medium; \( f \) is the frequency of the EM wave; \( d \) stands for the path length.

Noise temperature as a function of the distance and frequency for different human tissues

blood  skin  fat
Complexity of Human Skin

Optical coherent tomography image of the human skin

Stratified skin model with sweat duct

Stratified skin model with capillary

1. P.-L. Hsiung, Y. Chen, T. Ko, J. Fujimoto, C. de Matos, S. Popov, J. Taylor, and V. Gapontsev, "Optical coherence tomography using a continuous-wave, high-power, Raman continuum light source," Optics Express
Numerical Analysis of the Human Skin

Sweat ducts will be conductive when sweating. Form the right figure, it can be seen that it will affect the field distribution in skin.

On other occasions, their effect can be neglected as shown from the field distribution on the right!
Intelligent Decision Making

- PAMBAYESIAN: PAtient Managed decision-support using Bayesian networks
  - Multidisciplinary project including computer scientists, electronic engineers, human computer interaction designer and clinicians
- Patients with chronic diseases must take day-to-day decisions about their care and rely on advice from medical staff to do this.
- Remote monitoring of patients relies too much on clinical staff to interpret the sensor readings; patients may become more dependent on health professionals; remote sensor use may then lead to an increase in medical assistance, rather than reduction.
Summary

- Covering the human body inside/out to provide more comprehensive look into health oriented aspects.
- Flexible and textile solutions are the way forward specially with advances in inkjet and embroidered electronics.
- Moving down to the nano-scale and exploring the internal structure of the human body through natural communication routes and EM ones.
- Multi-disciplinary approach towards user-centric health and well-being monitoring feedback by utilising wearable technology (existing and novel solutions).
- Importantly we need to understand the data and how we can use it for reverse engineering better wearables!
Related Readings


References

THANK YOU

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