Wireless and Battery-less Bio-integrated Sensors for Bodycentric Internet of Things

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Wireless bodycentric system

“The Internet of the Body”

800 million body-worn sensors are expected to be worldwide connected to the backbone of the Internet by 2020.

The augmented human bodies outfitted with imperceptible sensors is the vehicle for a mine of pertinent health information.

These data are accessible from anywhere at anytime, making the human beings a inherently integrated parts of IoT Architectures.
The fundamental mismatch

Conventional Electronics Systems
Rigid, stiff, Hard Planner, and wired

Intimately Bio-integrated Interface
Flexible, stretchable, tattoo-like, Seamless

Our Body – Biological systems
Soft, Curvilinear, Continuously evolving

Epidermal Electronics, Science, 2011

prof. J.A. Rogers

http://medicmobile.ru/_pu/0/44347604.jp
Epidermal Electronics & EM community

2013, Where we were...

Background:
Material Science
Applied physics
Micro-assembly techniques

• Hard-wired connections
• Bulky electronics
• Local batteries

• Near-Contacting Interfaces (coils, NFC)
• UHF RFID reading only for Identification

prof. J.K. Batchelor
The **Radio Lab-on-skin**

- Sensing the skin
- Remote reading (> 1m)
- No battery
- Flexible
- Low-profile
- Bio-compatible membranes

**RFID UHF Telemetry**

- 860-960 MHz

**Antenna**

**Coated electrodes** (bio-potentials, pH...)

**Sensor**

**Microchip**

**Bio-compatible transpiring membrane**

**Absorption of Body Fluids** (sweat, exudates...)

**Local temperature measurement**

**CHALLENGES UHF-RFID Tags:**

- Antenna has to play as sensor: radiator very close to high-loss body
- **Human Variability**: broadband and/or possible on-body retuning
- not interfere with local skin metabolism: **Bio-compatibility** and **transpiration**
Fundamental Limitations and Optimal Performance
Gain vs. antenna length

free space

Gain vs. antenna length on skin

Trade-off between two counteracting phenomena for increasing length

1. Improvement of the radiation resistance, proportional to the overall length of the antenna

2. More intense power dissipation into the surrounding tissues

Optimal size of antennas over the skin

\[ \varepsilon = 49 \]
\[ \sigma = 0.9 \text{ S/m} \]
Optimal UHF skin antennas

Which is the best layout for the antenna?
- gain
- size
- amount of conductor
- trace conductivity

Optimal performance practically independent on the antenna shape
Performance vs. trace conductivity

Optimized size radiator
50 × 1 mm dipole
30 × 1 mm loop
f=870 MHz

Antenna conductivity is a second-order parameter !!

→ Attractive performance expected by low-cost inkjet printing

- No variation in the radiation performance for $\sigma>10^4$ S/m

- even by reducing the conductivity down to $\sigma=1000$ S/m, the gain drops by less than 2 dB
Experimentations

System Gain

\[ g = \frac{P_{out,av}}{P_{in}} = \frac{|S_{21}|^2}{(1 - |S_{11}|^2)(1 - |S_{22}|^2)} \]
Skin Antennas

- Miniaturization of the “un-useful” traces
- Additional meandering to achieve stretching
- Halved sized, Performance unchanged
- Battery integration for logging capabilities

Simulated frequency-dependent Realized Gain

Upper Bound $G_{T_{\text{Max}}} \approx -12.5 \, \text{dB}$

 Radiation like two C-dipoles

S. Amendola, S. Milici, and G. Marrocco
"Performance of Epidermal RFID Dual-loop Tag and On-Skin Retuning", IEEE Trans. on Antennas and Propagation, August 2015.
Human Body Variability

Human tissues challenging to be EM modeled (different body parts, different body size...)

No grounded Layout!
- Strong sensitivity to different body placements

Read Range can reduce by more than 50%

Performance vs. body position

10 dB

→ need to readapt the same antenna to different body placements
On-skin Retuning

- Tuning at a given position
- Change of the UHF band - inter-operable device

- post-fabrication
- post-placement
Manufacturing technologies

- Carved adhesive copper
- Coated micro-wires
- Microfabrication
- Low cost inkjet printing
Copper-based Techniques

**Carved Adhesive Copper**

- Two-axis digital-controlled cutting plotter
- 35 μm adhesive-backed foil

**Coated Microwires**

- Nails driven in the Styrofoam
- 120 μm radius copper wire

- Eco-friendly, shape and substrate versatility
- Minimum conductor large-scale production;

- In-plaster

- ✓ Cheap, versatility of bio-substrates.
- ✓ Low Resolution (0.5 - 1 mm);
- ✓ Fragility of thin traces

- MECSTAR

- ✓ Smoothed corners;
- ✓ Connections with QFNs
Microfabrication

Flexible Photolithography

- high-resolution; ultra-thin substrates (<20 μm);
- monolithic fabrication (radiator + microsensor)
- High costs (cleanroom facilities, photo masks, chemicals, manpower)
Low-Cost Inkjet Printing

Desktop printer  100 €
Self Sintering Ag-ink  185 €
PVA-coated PET substrates

Instantly conductive at ambient temperature!
RF conductivity $\sigma \approx 10^4$ S/m

Resistance vs Bending & Body Fluids
Communication Performance

Carved Copper

Copper Micro wire

Gold Photolithography

Silver Inkjet-Printed

On Body Measurements

0.7 m < $D_{max}$ (EIRP 3.2 W) < 5 m

Sensing
Pchip=-4 dBm

Labeling
Pchip=-22 dBm
Epidermal Antennas + Sensors
Body temperature monitoring

Why?

• Fever rush
  - control and localization of epidemics
    (SARS, EBOLA, ZIKA, ..?)

• Infection around wounds and lesions

• Brain activity and particular psychological states

• Circadian system activity
In-Plaster Encapsulation

Sterile and eco-compatible

Two detachable components:
1. Disposable medical-grade dressings
2. Reusable inner transponder hosting functional electronics

Sensor-skin adhesion ensured, while avoiding direct skin contact (ultra-thin separating film)
Thermal Accuracy & Time Response

EM-4325 IC

Stationary Multi-Point measurements

Post-calibration Accuracy: ±0.18°C

$T \approx a_1 + a_2 \cdot e^{-t/\tau}$

Power Pulse

Time constant: 4 sec
Manual Temperature reading

- **Abdominal temperature** does not correlate with the core one because of time-variant ambient conditions.

- After 3 °C offset compensation, data non-invasively measured over the forehead provide an acceptable estimate of the central temperature.

25 years old female down with the flu

- **Antipyretic**
- **Covering**
- **Uncovering**
- **Leaving**
Overnight temperature monitoring

Reliability of the wireless link

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<td>10%</td>
<td>8%</td>
<td>4%</td>
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<td>15%</td>
<td>14%</td>
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<td>9%</td>
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<td>20%</td>
<td>14%</td>
<td>8%</td>
<td>4%</td>
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Interruptions longer than 30 min occurred in average for less than the 3 % of the total observation time.

artifacts due to subject’s movement
<table>
<thead>
<tr>
<th><strong>“MORETEC”</strong> approved by Ethics Committee on July 2016</th>
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<td><strong>Type</strong></td>
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<td><strong>Single Centre</strong></td>
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On-flight screening across gates

Identification & Temperature Sensing of moving people

Epidemic control at airport and hospital

In-house automatic screening on crossing door

Since the outbreak of recent epidemics public health authorities have been looking for a fast, easy, non-invasive, and reliable method to early detect and isolate suspected cases of infection in high-risk groups...
On-flight screening across gates

Cyclic gate crossing with a controlled gait cadence

1.2 m

**Moderate** (80 steps/min)  
security check

**Natural** (100-120 steps/min)  
normal walking at home or hospital

**Fast** (140 steps/min)  
rushed motion, emergency environment

Identity + temperature

Identity + temperature

Slow → Moderate → Natural → Fast
Benchmark guidelines for the optimal design, fabrication and experimentation of real RFID epidermal transponders

**UHF epidermal transponders** ready to become the building block of new-generation distributed assisting systems connected to the IoT infrastructure

**Boundary of skin-mounted technology pushed forward**

The best has still to come: Beyond Temperature.... Hydration, strain, biopotentials sensor **Multivariate sensing!**

Critical mass inside the AP community around a very new and fascinating topic