A HOLISTIC ANTENNA DESIGN PARADIGM FOR THE 5G WIRELESS COMMUNICATION SYSTEM

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OUTLINE:

- 5G Networks and The Internet-of-Things:
  - Opportunities and challenges

- Holistic Stochastic Design Paradigm

- Representative Design Examples
  - Autonomous wearable RFID-based sensing platform
  - Downlink photonic-enabled remote antenna unit for analog radio-over-fiber

- Conclusions and future work
INTRODUCTION
5G NETWORKS AND THE INTERNET-OF-THINGS

- Unprecedented data rate
- Ultra-low latency
- User density
- Multiple usage scenarios
"Integration of functionality and intelligence in common things/surfaces that originally had other goals"
Stable antenna performance requires taking into account adverse conditions during design phase:

- effect of varying environmental conditions
- effect of fabrication tolerances
- effect of bending/compression/layers covering antenna
- effect of equipment in near-field

Antenna design constraints:

- Cost-effective
- Compact
- Low-profile
- Flexible
- Breathable
- Wideband
- High efficiency

→ Invisible/unobtrusive integration
→ Comfortable to wear
→ High-data-rate communication
→ Prolonged system autonomy
IOT ANTENNA SYSTEM DESIGN CHALLENGES

High data rate and reliable link performance in harsh multipath environment:
• Wideband/multi-band performance
• Multi-antenna system

Holistic stochastic design strategy is requisite!
HOLISTIC STOCHASTIC DESIGN PARADIGM
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Full-wave/Circuit Computer-Aided Co-Optimization Procedure with Integrated Stochastic Analysis

First Time Right Stable and High-performance Wireless systems

Design Requirements
- Selection of Materials and Fabrication Technology
  - Preliminary Design of Building Blocks
    - Antenna System
    - Active Circuits
    - Power Supply
  - Stochastic-Framework-Based Circuit/Full-Wave Co-Optimization
  - Validation in Realistic Conditions

High-Performance Wireless System According to Requirements

(AIR-FILLED) SUBSTRATE-INTEGRATED WAVEGUIDE TECHNOLOGY

Substrate-integrated-waveguide technology

+ E- and H-fields are confined in waveguide
+ High isolation from integration platform
+ High power handling capability
+ Planar
+ Compact arrays with low mutual coupling

- Substrate losses

Air-filled substrate-integrated-waveguide technology

+ Standard PCB/Silicon/3D-printing technology
+ Low fabrication cost
+ High efficiency
+ Simple integration of additional electronics
+ Facilitates step-by-step validation
Substrate-integrated-waveguide technology

Smart textile integration

Smart floor integration

Smart desk integration

Air-filled substrate-integrated-waveguide technology

Standard PCB fabrication technology

Standard silicon process technology

Standard 3-D printing technology


STOCHASTIC ANTENNA DESIGN FRAMEWORK

Accounting for random variations

Design strategies accounting for randomness

1. Overspecifying design requirements
   → enlarging bandwidth, applying stricter specs
     - out-of-band interference
     - cost

2. Quantifying random effects on antenna performance
   → applying Monte Carlo analysis
     - very accurate
     - time-consuming

→ a more effective stochastic formalism is needed!
STOCHASTIC ANTENNA DESIGN FRAMEWORK

Case study: effect of fabrication tolerances on dual-polarized probe-fed textile antenna

Geometry variations: input PDF

1) Variations in patch width $W$: largest influence on $Z_{in}$

- measurements on 100 patches, manually cut

  • mean value $\bar{W} = 45.385 \text{ mm}$
  
  • standard deviation $\sigma = 0.127$

  • variation interval $[44.9 - 45.9] \text{ mm}$

nominal input impedance $Z_{in} = 50 \Omega$ at 2.45GHz

E-textile

protective foam substrate ($\varepsilon_r=1.53$, $h=3.94 \text{ mm}$)

STOCHASTIC ANTENNA DESIGN FRAMEWORK

Case study: input impedance $Z_{in}$ of dual-polarized probe-fed textile antenna

<table>
<thead>
<tr>
<th>L</th>
<th>44.46 mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>W</td>
<td>45.32 mm</td>
</tr>
<tr>
<td>$(x_f,y_f)$</td>
<td>$(\pm 5.7, 5.7)$ mm</td>
</tr>
<tr>
<td>$W_s$</td>
<td>1 mm</td>
</tr>
<tr>
<td>$L_s$</td>
<td>14.88 mm</td>
</tr>
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nominal input impedance $Z_{in} = 50 \, \Omega$ at 2.45GHz

Polynomial chaos expansion

- relates patch width $W$ to $Z_{in}$
  - convergence for polynomial order $P = 2$
  - $V = 3$ quadrature points

simulation time: 18 s  (Intel Core i7-2600, 3.40 GHz, 16 GB RAM)

STOCHASTIC ANTENNA DESIGN FRAMEWORK

Case study: input impedance $Z_{in}$ of dual-polarized probe-fed textile antenna

<table>
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<tr>
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<th>Value</th>
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protective foam substrate $(\epsilon_r=1.53, h=3.94 \, \text{mm})$

Polynomial chaos expansion

- Output PDF of $Z_{in}$ generated with 10000 realizations
  - Monte-Carlo based on polynomial expansion (PC) (CPU-time 18s) versus based on full-wave simulations (MC) (CPU-time 16h 40min)

REPRESENTATIVE DESIGN EXAMPLES
Holistic Design Approach and System Architecture

- Flexible photovoltaic (PV) module
  - Integrated on the antenna's patch
- Textile circular patch antenna, serving as an integration platform
  - Integrated on the antenna's ground plane
- Power management
- Energy storage
- Power management hardware
- Memory
- Transceiver
- MCU
- analog sensor
- digital sensor
- Sensing, computational and transceiver hardware

Flexible Lithium Ceramic Battery (FLCB)

Photovoltaic (PV) cell

3D view

Photovoltaic (PV) cell

Antenna feed

Antenna patch

DC+ connection

Insulator

DC- connection

Antenna substrate

Antenna/circuit ground plane

Cross-section

Solar cell cathode

Antenna feed

Flexible Circuit Board

Prologium's FLCB

Electronic components

Tafetta e-textile patch

Substrate

Adhesive sheet

Hollow tubelet

DC+ connection island

Conductive adhesive sheet

Flexible Circuit Board

Prototype

Temperature and humidity sensor
(HDC1000 by Texas Instruments)

Block Diagram Flexible Circuit Board

PV-cell terminal

Antenna feed

Power management
(BQ2570)

4 MB Memory

Transceiver

MCU (C8051F921)

Energy storage
(Prologium066113)

analog sensors
digital sensors

Sensing, computational and transceiver hardware

a-Si:H photovoltaic cell

Solar cell anode

DC+ Connection island

System Deployment

Measured Antenna Performance

Reflection coefficient

XZ-plane

\( \eta_{\text{rad}} > 65 \% \)
Max gain = 2.7 dBi

YZ-plane

Stable, high performance

AUTONOMOUS WEARABLE RFID-BASED SENSING PLATFORM

Measured Read Range

• Minimum received signal strength for successful decoding = -95 dBm

• Received signal level for different reader locations:

<table>
<thead>
<tr>
<th>Transmitter location</th>
<th>Received signal level (dBm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>*LoS 1 m</td>
<td>-39.4</td>
</tr>
<tr>
<td>LoS 2 m</td>
<td>-41.2</td>
</tr>
<tr>
<td>**NLoS 5 m</td>
<td>-55.5</td>
</tr>
<tr>
<td>NLoS 13 m</td>
<td>-70.4</td>
</tr>
<tr>
<td>NLoS 23 m</td>
<td>-85.8</td>
</tr>
<tr>
<td>NLoS 1 floor up, overhead</td>
<td>-64.2</td>
</tr>
<tr>
<td>NLoS 1 floor up, 10 m off</td>
<td>-75.5</td>
</tr>
</tbody>
</table>

* LoS: Line-of-Sight
** NLoS: Non Line-of-Sight

Measured System Autonomy

<table>
<thead>
<tr>
<th>Sleep Time (s)</th>
<th>Average Supply Current (μA)</th>
<th>System autonomy (days)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>186</td>
<td>31</td>
</tr>
<tr>
<td>2</td>
<td>97</td>
<td>51</td>
</tr>
<tr>
<td>5</td>
<td>44</td>
<td>84</td>
</tr>
<tr>
<td>10</td>
<td>26</td>
<td>107</td>
</tr>
<tr>
<td>60</td>
<td>11</td>
<td>138</td>
</tr>
</tbody>
</table>

Read Range > 23 m

Autonomy > 100 days

Fiber-like connectivity to robots in a factory-of-the-future scenario

- High robot density
- Large bandwidth
- Low latency
- High reliability

Solution

- Large number of ATTO-cells
- Floor-integrated photonic-enabled RAUs
- Radio-over-Fiber (RoF) interconnection

⇒ Extreme low cost and power

ANALOG RADIO-OVER-FIBER (ARoF) INTERCONNECTION

- Central Office (CO) and multiple Remote Antenna Units (RAUs)
- RF signals modulated on optical carrier
  + Wideband and low-loss
  + No EMI/EMC issues
  + Low complexity, cost-effective and flexible
  + Tight synchronization amongst RAUs
    - High-speed photodetectors and optical sources required

Focus on downlink direction

Architecture

1. AFSIW Cavity-Backed Slot Antenna
   - Air-filled Coupled half-mode sub-cavities
   - -10-dB-Impedance bandwidth w.r.t. 50Ω:
   - Capacitively-coupled probe feed

2. Photodetector & Matching Network
   - Zero-volt bias
   - Mixed lumped/distributed implementation
   - Maximum power transfer in 3.30 – 3.70 GHz band

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> 10 x extracted power as compared to direct loading

Prototype measurements (normalized w.r.t. laser)

- Directive linearly polarized antenna
- Boresight gain of 10.8 dBi at 3.5 GHz
- Cross polarization < -25 dB
- -3 dB gain bandwidth of ± 500 MHz (13.7 %)
- Good performance prediction by model

DL-RAU prototype in anechoic chamber

Far-field radiation patterns at 3.50 GHz:
E-plane (red) and H-plane (blue)
Measurement (solid) and simulation (dashed)

Radiation performance

DL-RAU prototype in anechoic chamber

Link performance

Constellation diagram:
- 64-QAM
- symbol rate of 80 MBd
- rms EVM = 2.2%

CONCLUSION AND FUTURE WORK

- Antenna systems for 5G/IoT applications should fulfill a challenging set of techno-economical design requirements

- Holistic stochastic design strategy is required
  - First Time Right stable and high-performance wireless systems
    - Exploiting materials that are readily available
    - Dedicated antenna topology for excellent antenna to IoT platform isolation
    - High performance through full-wave/circuit co-optimization
    - Reusing the antenna as integration platform for active (opto-)electronic hardware
    - Accounting for random variations in IoT/5G antenna systems
      - Fabrication tolerances
      - Uncertainty in deployment conditions

- Representative design examples
  - Autonomous wearable RFID-based sensing platform
  - Downlink photonic-enabled remote antenna unit for analog radio-over-fiber
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