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FACULTY OF ENGINEERING AND ARCHITECTURE

DEPARTMENT OF INFORMATION TECHNOLOGY
ELECTROMAGNETICS GROUP

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

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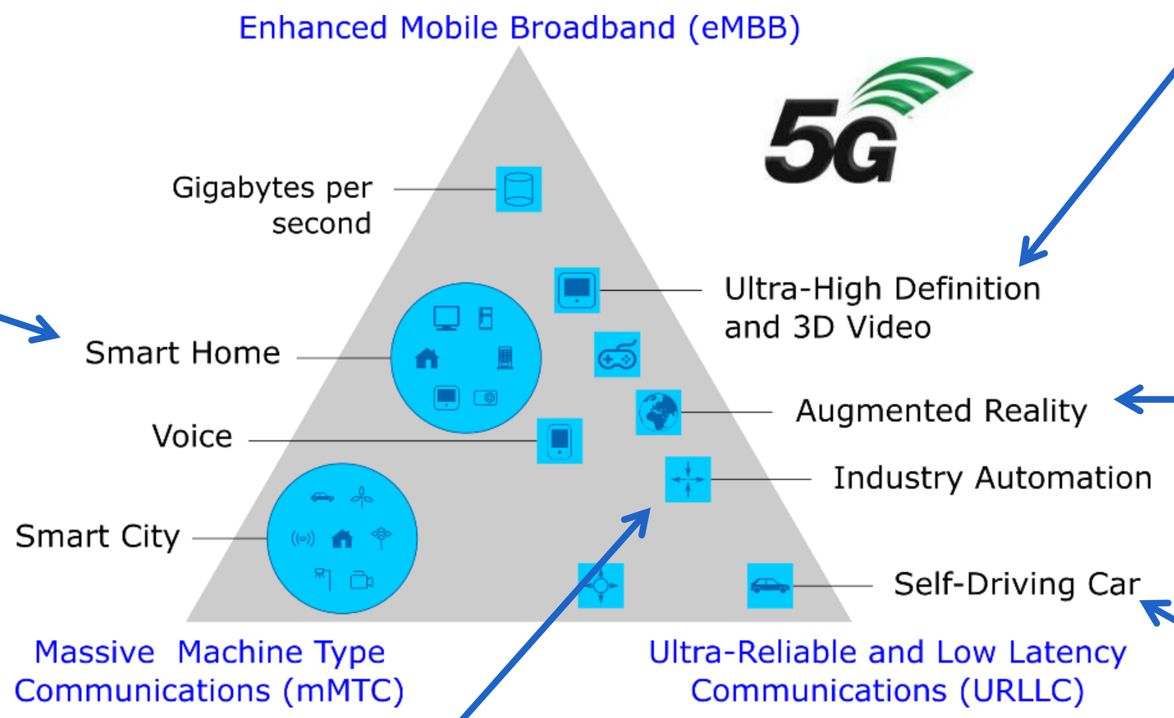
OUTLINE:

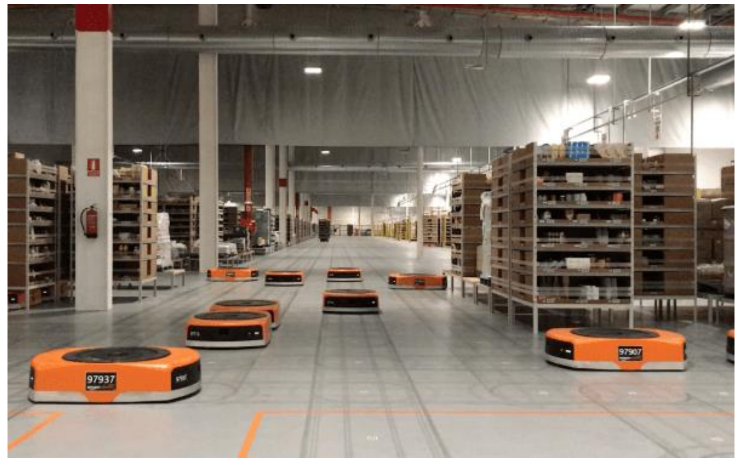
- **5G Networks and The Internet-of-Things:**
  - Opportunities and challenges
- **Holistic Stochastic Design Paradigm**
- **Representative Design Examples**
  - Autonomous wearable RFID-based sensing platform
  - Downlink photonic-enabled remote antenna unit for analog radio-over-fiber
- **Conclusions and future work**

INTRODUCTION

5G NETWORKS AND THE INTERNET-OF-THINGS

- Unprecedented data rate
- Ultra-low latency
- User density
- Multiple usage scenarios





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THE INTERNET-OF-THINGS

"Integration of functionality and intelligence in common things/surfaces that originally had other goals"

Smart Textiles

Smart Surfaces/Things

Functionality

- Vital Sign Monitoring
- Environmental Monitoring
- Localization & Detection
- Wireless Communication

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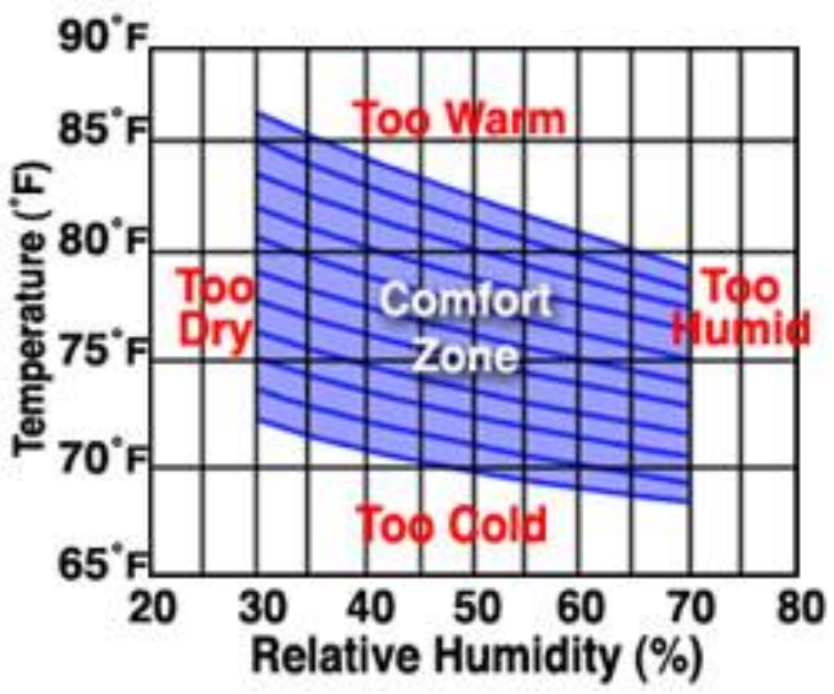
IOT ANTENNA SYSTEM DESIGN CHALLENGES



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 → Invisible/unobtrusive integration
- Flexible
- Breathable → Comfortable to wear
- Wideband → High-data-rate communication
- High efficiency → Prolonged system autonomy

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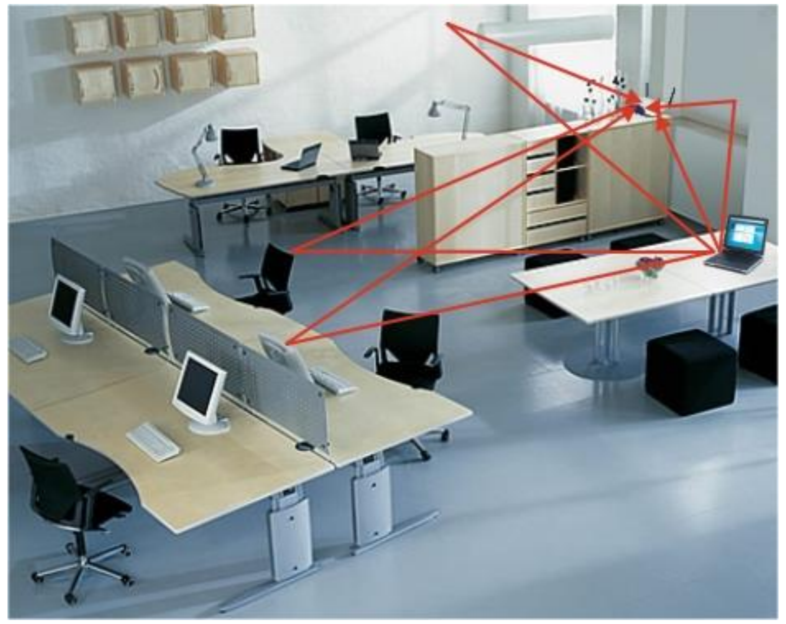
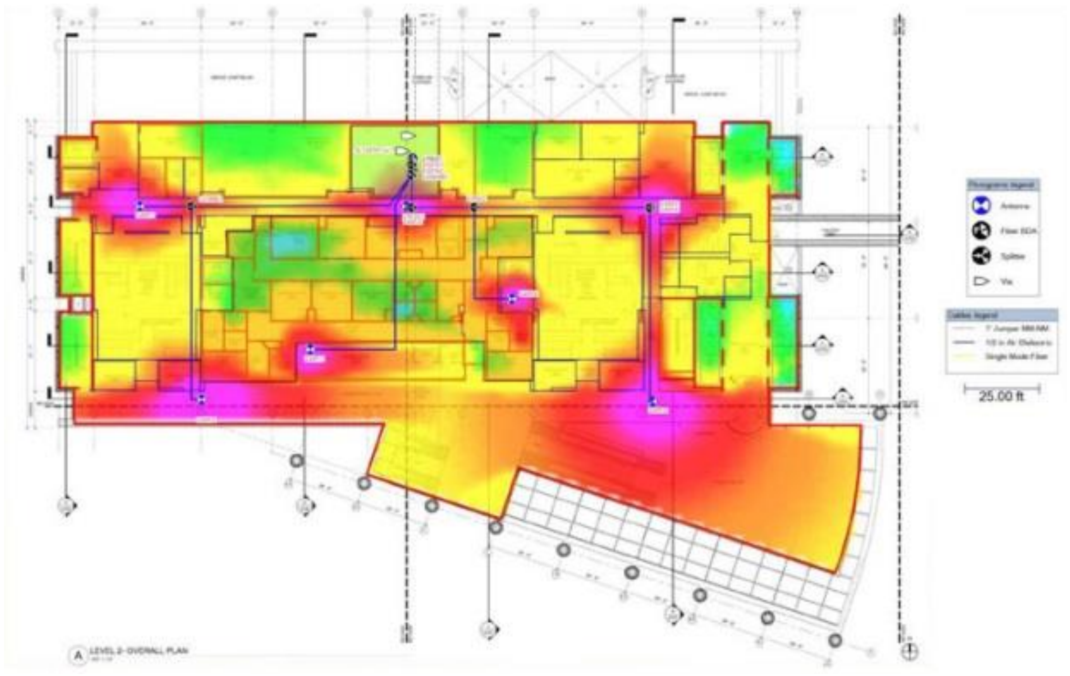
IOT ANTENNA SYSTEM DESIGN CHALLENGES

High data rate and reliable link performance in harsh multipath environment:

- Wideband/multi-band performance
- Multi-antenna system





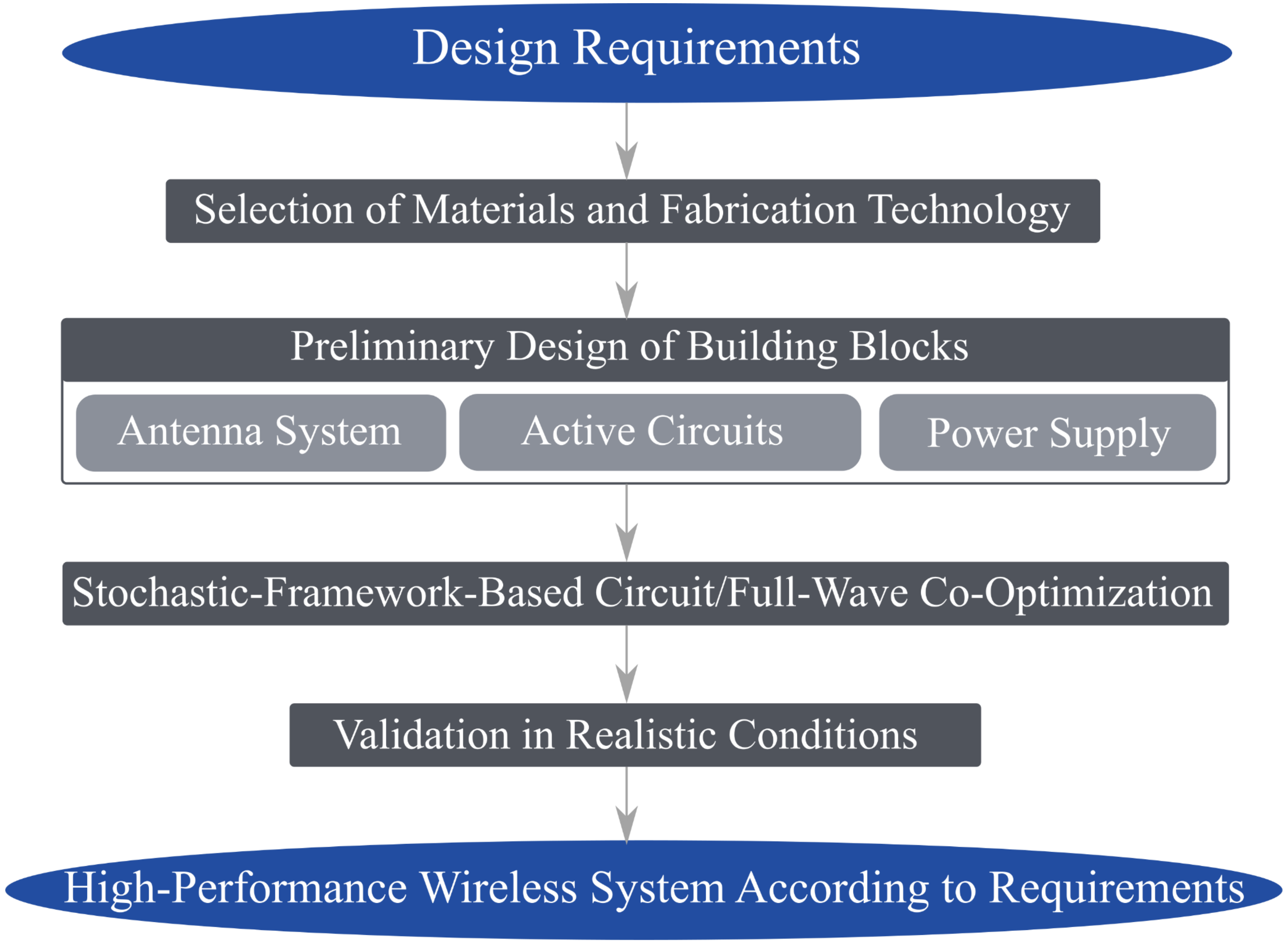
!Holistic stochastic design strategy is requisite!

HOLISTIC STOCHASTIC DESIGN PARADIGM

HOLISTIC STOCHASTIC DESIGN PARADIGM

Full-wave/Circuit Computer-Aided Co-Optimization Procedure with Integrated Stochastic Analysis

First Time Right Stable and High-performance Wireless systems



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S. Lemey, S. Agneessens, and H. Rogier, “Wearable Smart Objects,” *IEEE MICROWAVE MAGAZINE*, vol. 19, no. 6, pp. 83–100, 2018.

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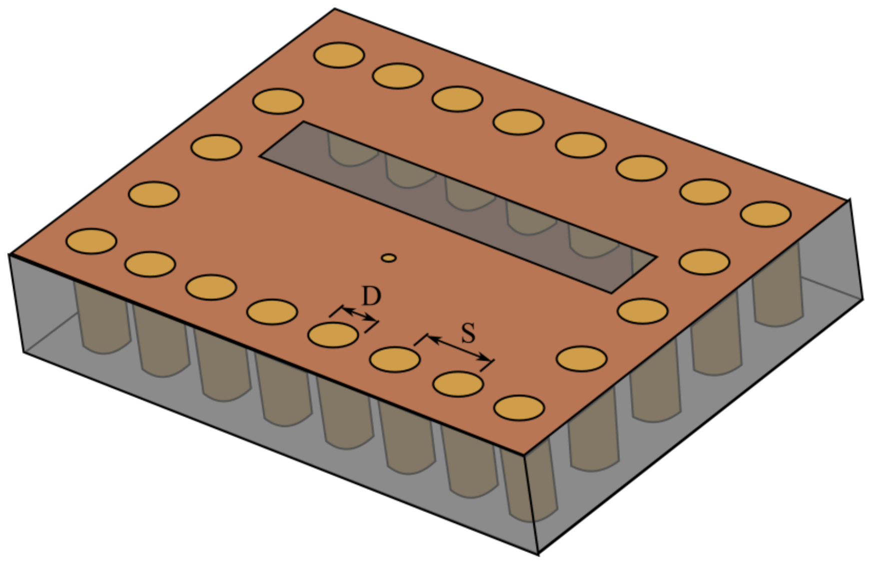
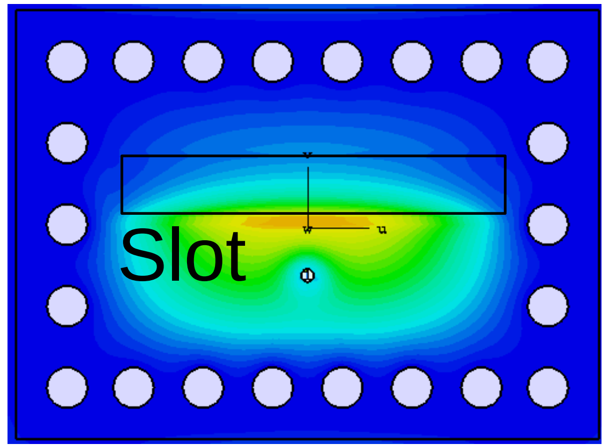
(AIR-FILLED) SUBSTRATE-INTEGRATED WAVEGUIDE TECHNOLOGY

Substrate-integrated-waveguide technology



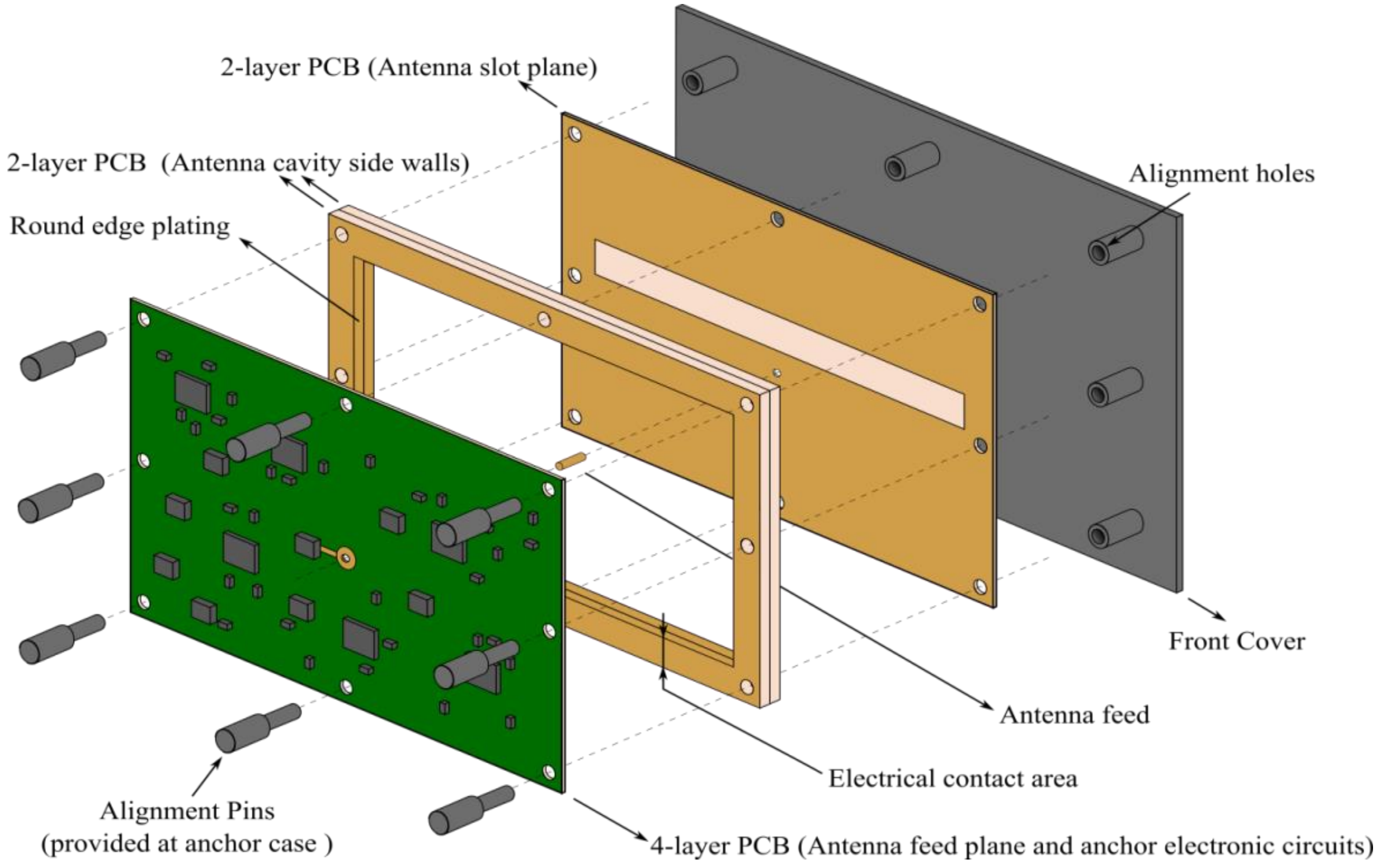
Front view



+ 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

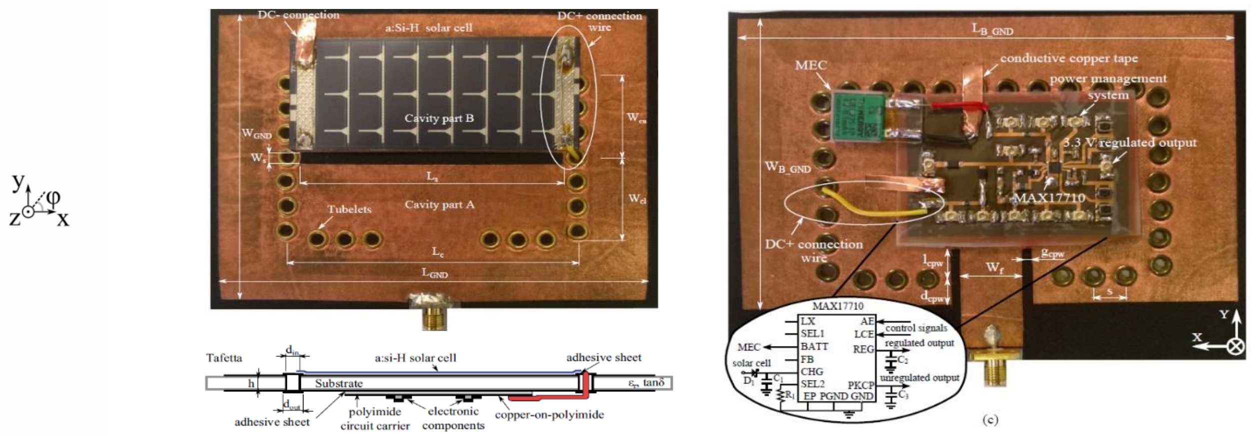


+ Standard PCB/Silicon/3D-printing technology
+ Low fabrication cost
+ High efficiency
+ Simple integration of additional electronics
+ Facilitates step-by-step validation

(AIR-FILLED) SUBSTRATE-INTEGRATED WAVEGUIDE TECHNOLOGY

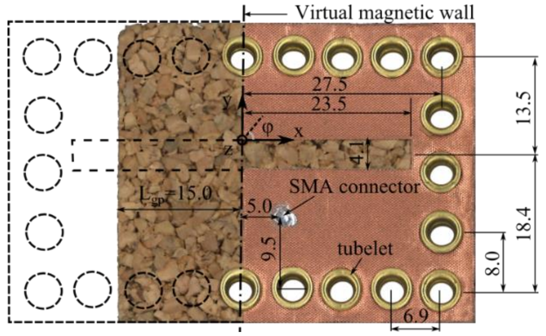
Substrate-integrated-waveguide technology

Smart textile integration



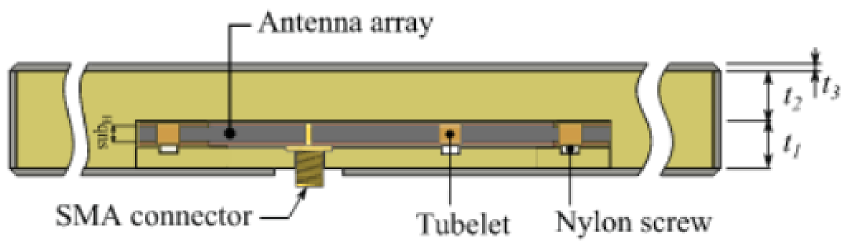
S. Lemey, F. Declercq, and H. Rogier, "Textile antennas as hybrid energy-harvesting platforms," PROCEEDINGS OF THE IEEE, vol. 102, no. 11, pp. 1833–1857, 2014.

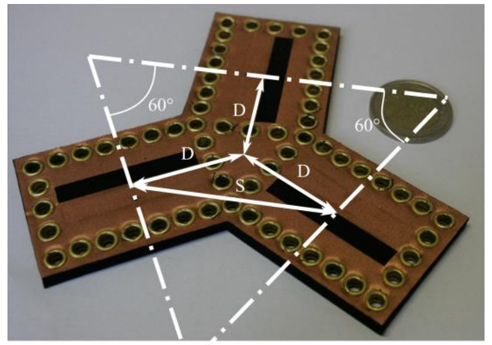
Smart floor integration



O. Caytan et al., "Half-mode substrate-integrated-waveguide cavity-backed slot antenna on cork substrate," IEEE ANTENNAS AND WIRELESS PROPAGATION LETTERS, vol. 15, pp. 162–165, 2016.

Smart desk integration

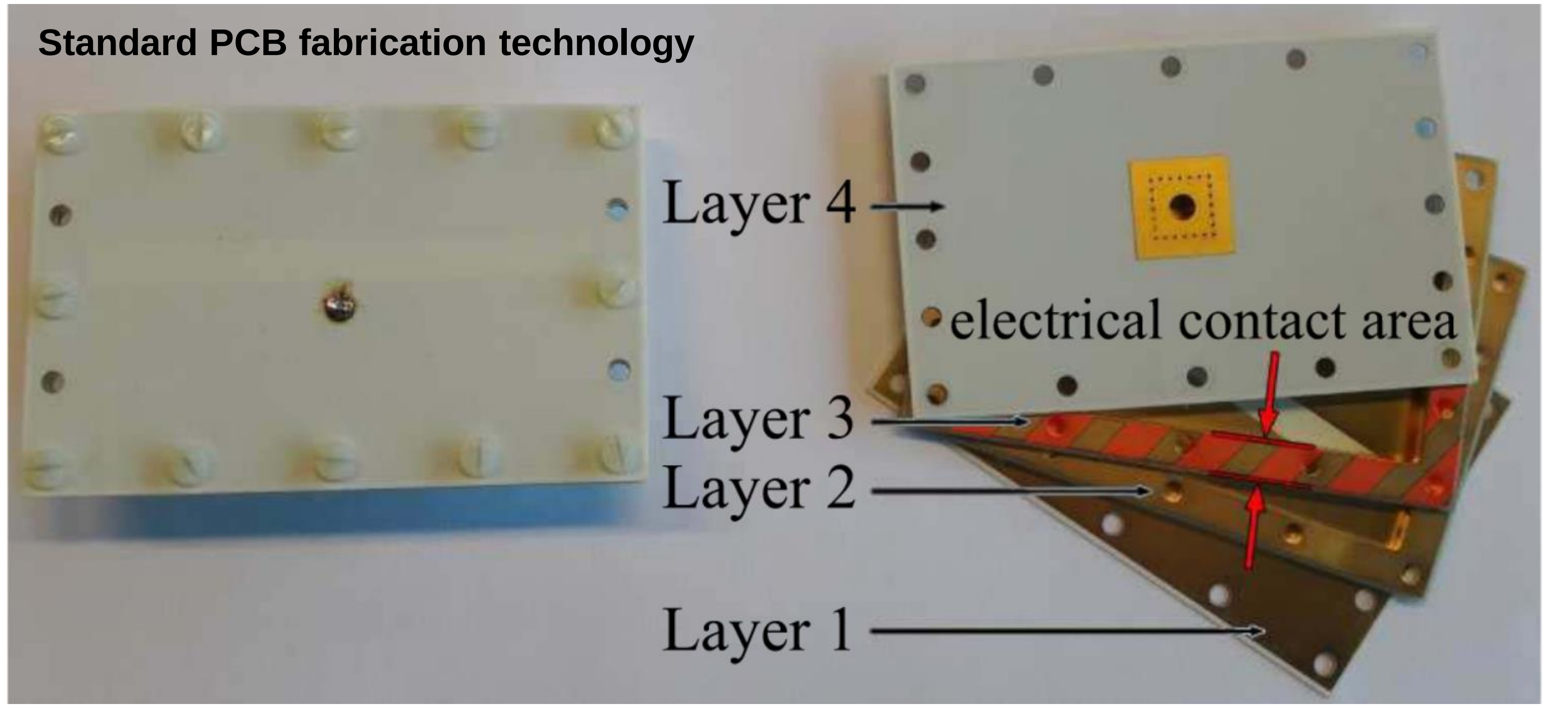




S. Lemey et al., "Threefold rotationally symmetric SIW antenna array for ultra-short-range MIMO communication," IEEE TRANSACTIONS ON ANTENNAS AND PROPAGATION, vol. 64, no. 5, pp. 1689–1699, 2016

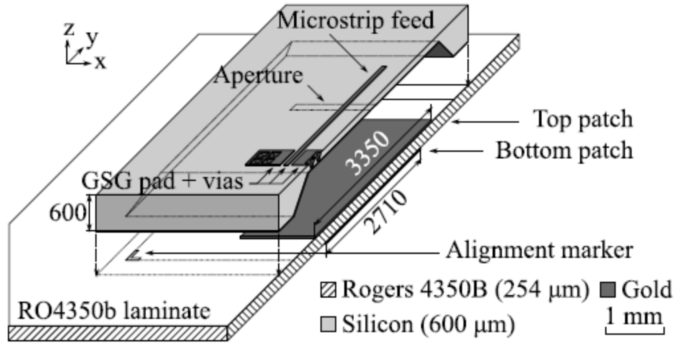
Air-filled substrate-integrated-waveguide technology

Standard PCB fabrication technology



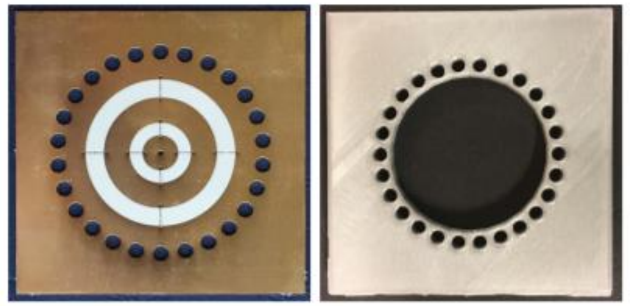
Q. Van den Brande et al. , "Highly-Efficient Impulse-Radio Ultra-Wideband Cavity-Backed Slot Antenna in Stacked Air-Filled Substrate-Integrated-Waveguide Technology," in IEEE Trans. Antennas Propag., 2018.

Standard silicon process technology



Q. Van den Brande et al., "A Hybrid Integration Strategy for Compact, Broadband and Highly Efficient Millimeter-Wave On-Chip Antennas," in IEEE Antennas Wirel. Propag. Lett., 2019.

Standard 3-D printing technology



K. Y. Kapusuz et al., "Polarization reconfigurable air-filled substrate integrated waveguide cavity-backed slot antenna," *IEEE ACCESS*, 2019.

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

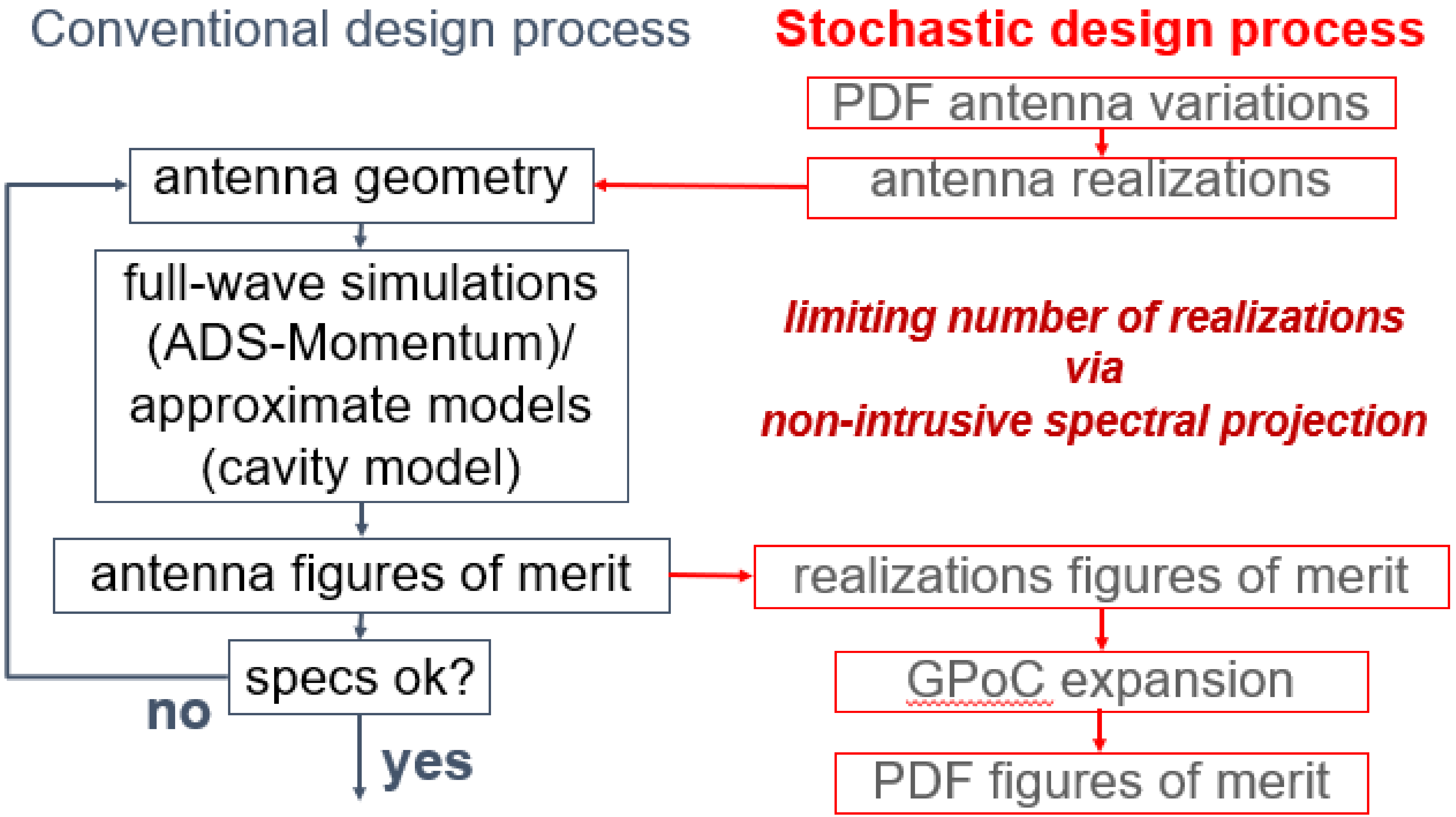
→ applying Monte Carlo analysis

☑**very accurate**

☒**time-consuming**

→ **a more effective stochastic formalism is needed!**

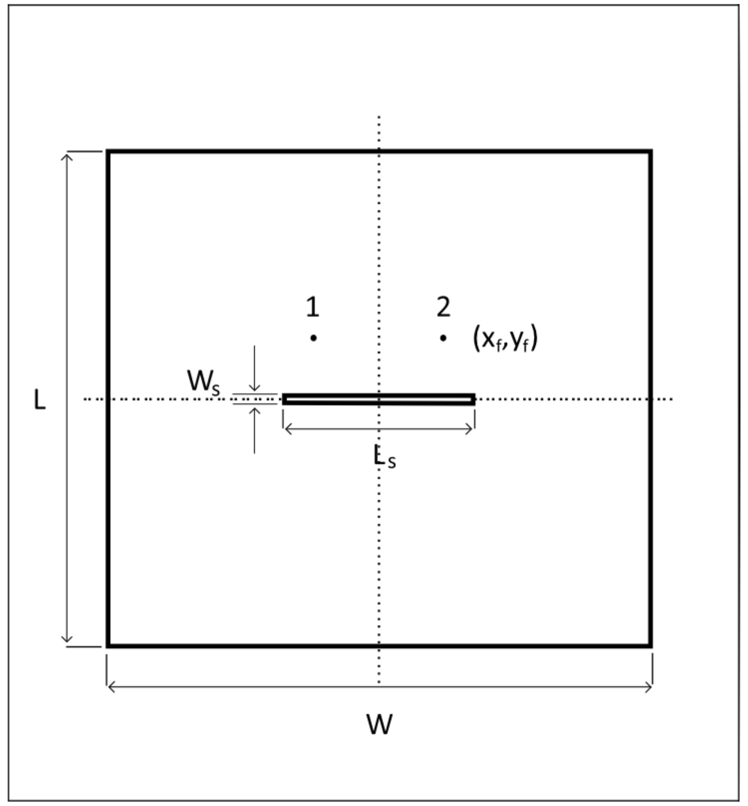
STOCHASTIC ANTENNA DESIGN FRAMEWORK



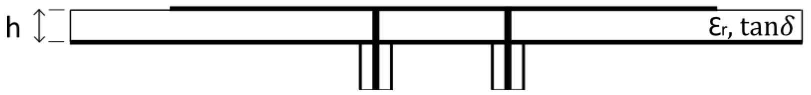
H. Rogier, M. Rossi, S. Agneessens, and D. Vande Ginste, "Overview of stochastic design strategies for wearable antennas," in 2017 IEEE MTT-S INTERNATIONAL CONFERENCE ON NUMERICAL ELECTROMAGNETIC AND MULTIPHYSICS MODELING AND OPTIMIZATION FOR RF, MICROWAVE, AND TERAHERTZ APPLICATIONS (NEMO), Seville, Spain, 2017, pp. 326–328.

STOCHASTIC ANTENNA DESIGN FRAMEWORK

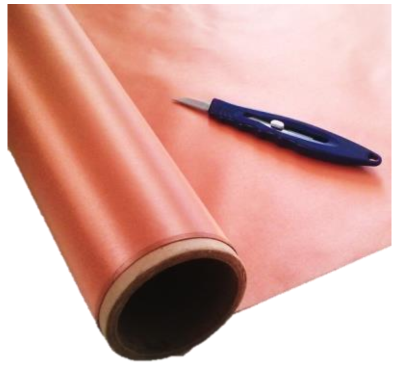
Case study: effect of fabrication tolerances on dual-polarized probe-fed textile antenna



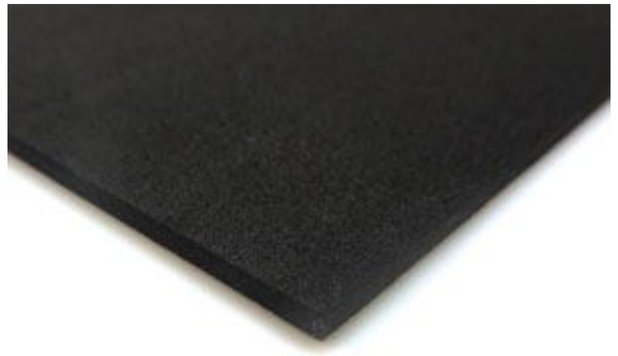
L	44.46 mm
W	45.32 mm
(x_f, y_f)	(±5.7,5.7) mm
W_s	1 mm
L_s	14.88 mm



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



E-textile



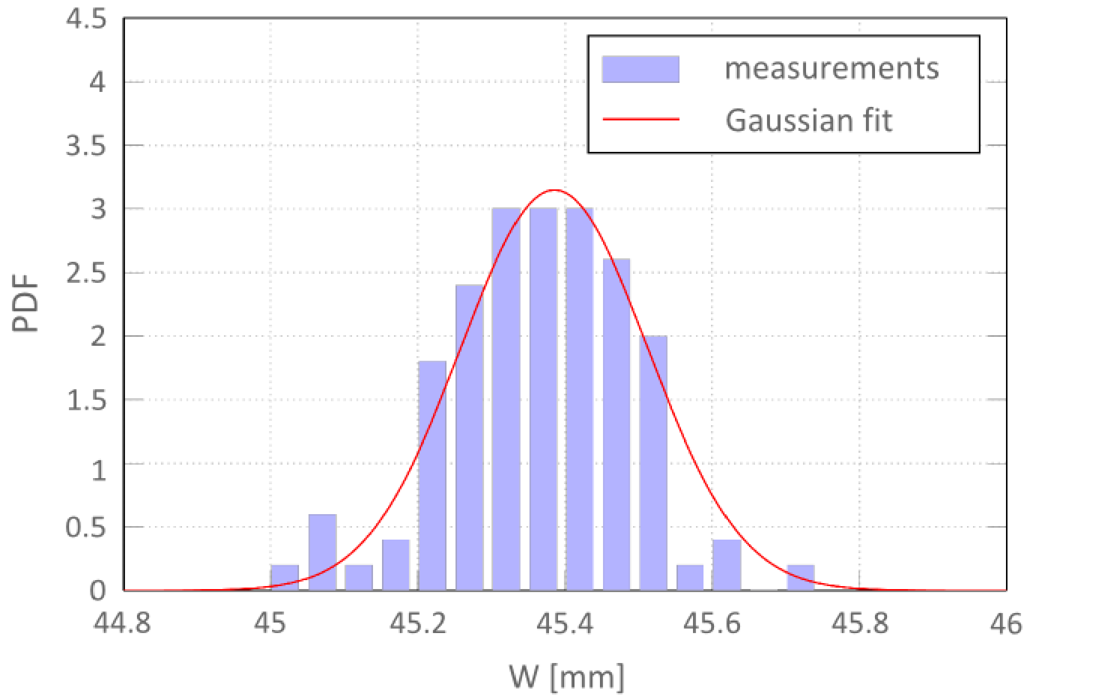
protective foam substrate (ε_r=1.53, h=3.94 mm)

Geometry variations: input PDF

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

– measurements on 100 patches, manually cut

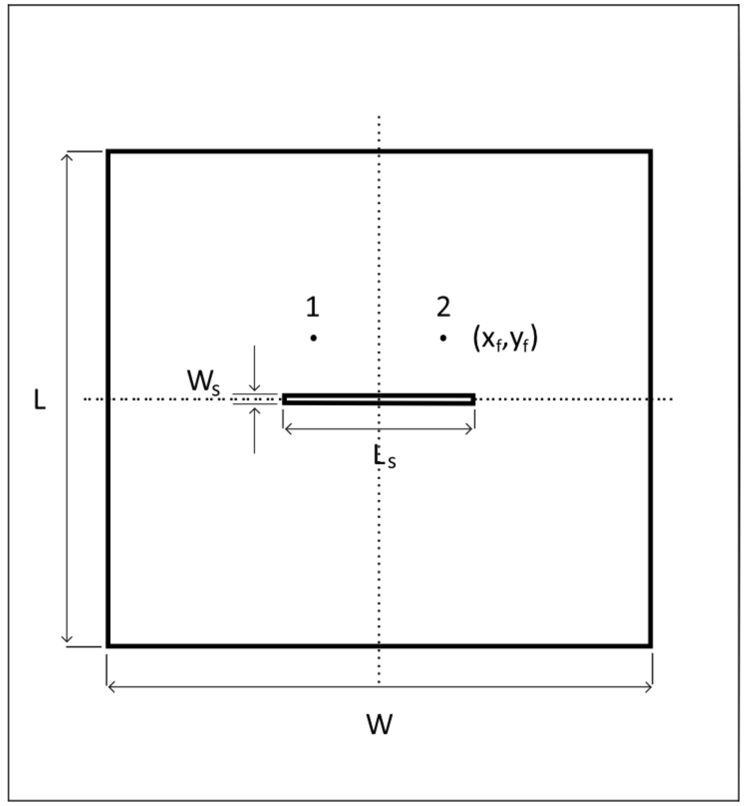
- mean value $\overline{W} = 45.385\ mm$
- standard deviation $\sigma = 0.127$
- variation interval $[44.9 - 45.9]\ mm$



M. Rossi, A. Dierck, H. Rogier, and D. Vande Ginste, "A stochastic framework for the variability analysis of textile antennas," IEEE TRANSACTIONS ON ANTENNAS AND PROPAGATION, vol. 62, no. 12, pp. 6510–6514, 2014.

STOCHASTIC ANTENNA DESIGN FRAMEWORK

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



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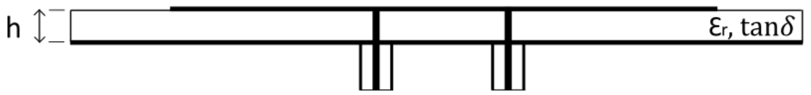

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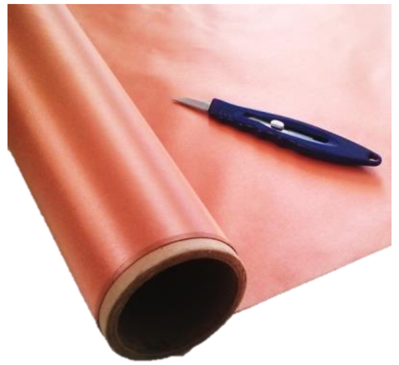

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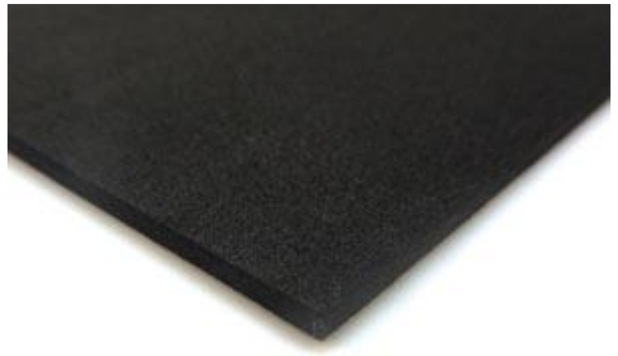
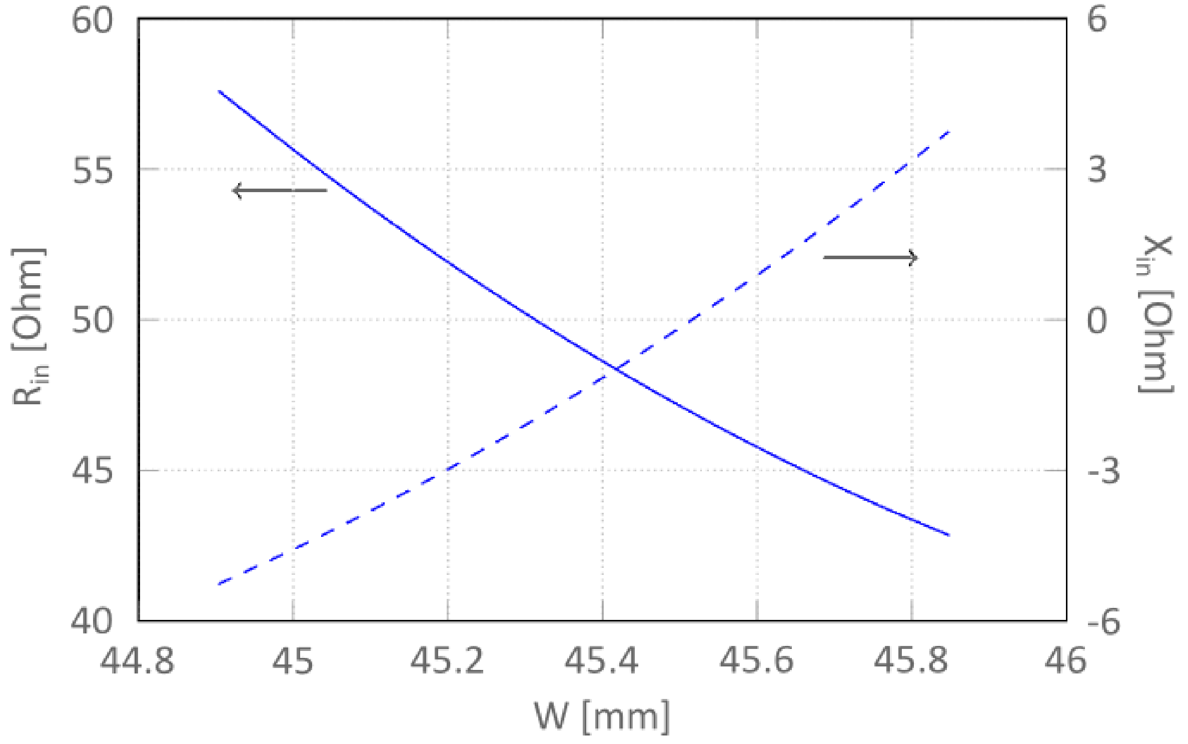


protective foam substrate
(ε_r=1.53, h=3.94 mm)

Polynomial chaos expansion

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

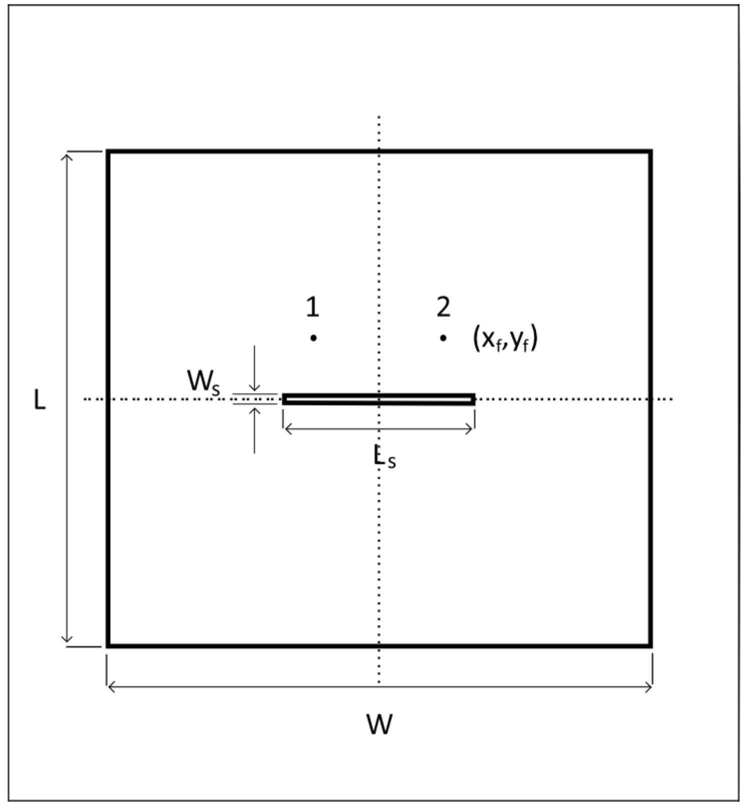


simulation time: **18 s** (Intel Core i7-2600, 3.40 GHz, 16 GB RAM)

M. Rossi, A. Dierck, H. Rogier, and D. Vande Ginste, "A stochastic framework for the variability analysis of textile antennas," IEEE TRANSACTIONS ON ANTENNAS AND PROPAGATION, vol. 62, no. 12, pp. 6510–6514, 2014.

STOCHASTIC ANTENNA DESIGN FRAMEWORK

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



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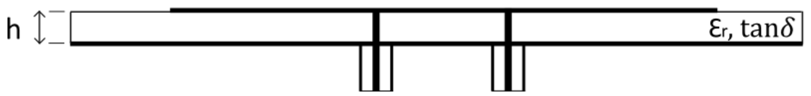

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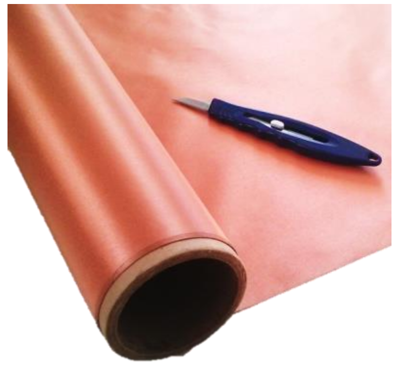
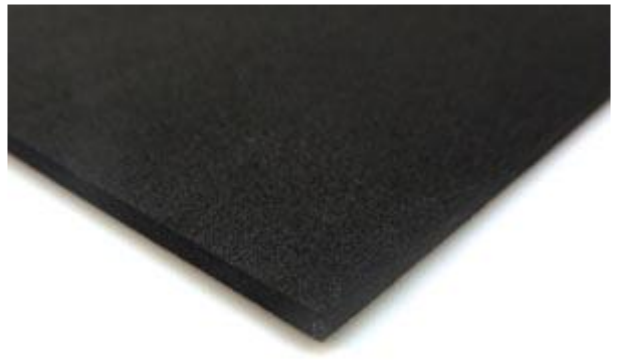


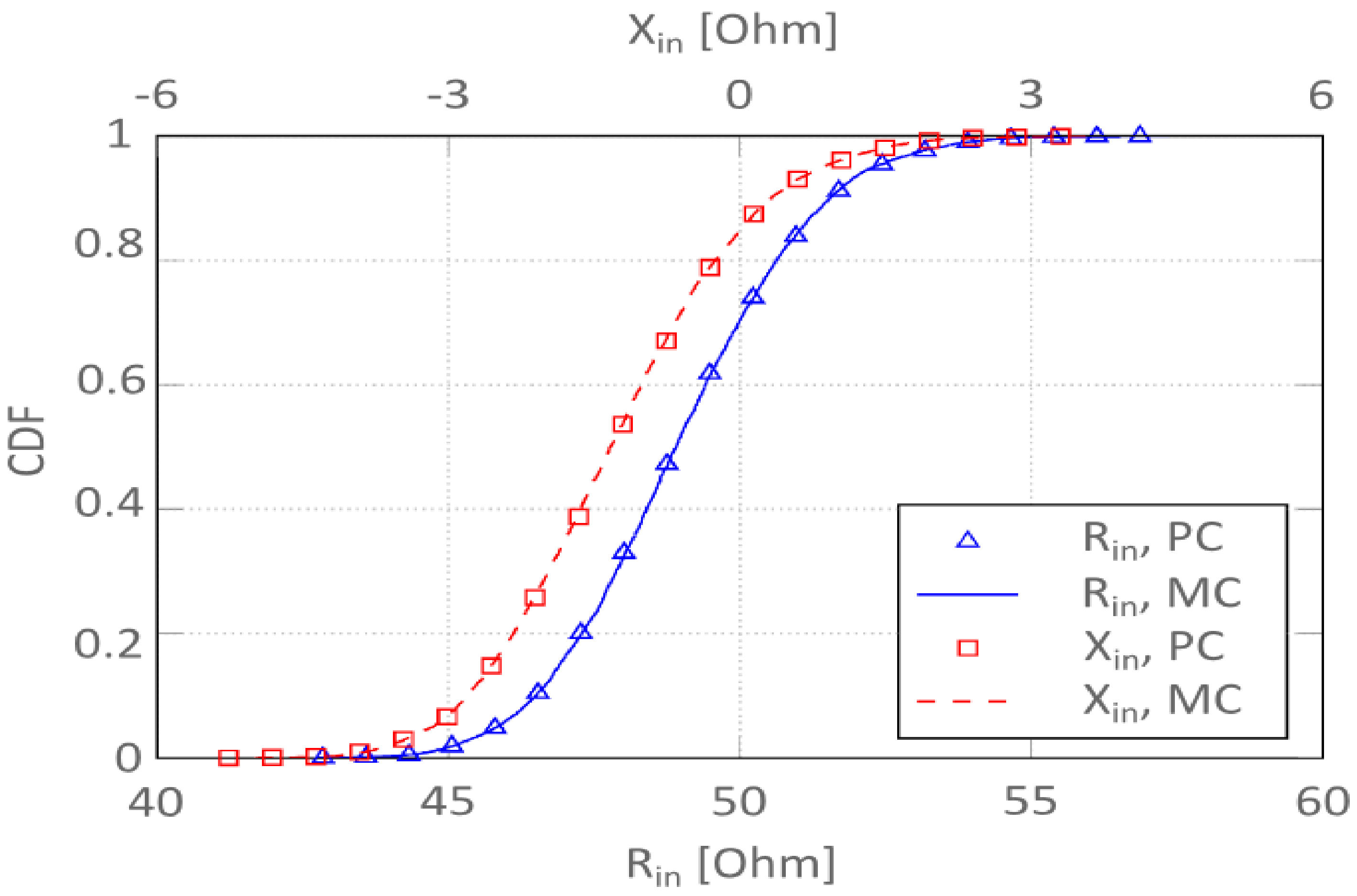
E-textile



protective foam substrate (ε_r=1.53, h=3.94 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)

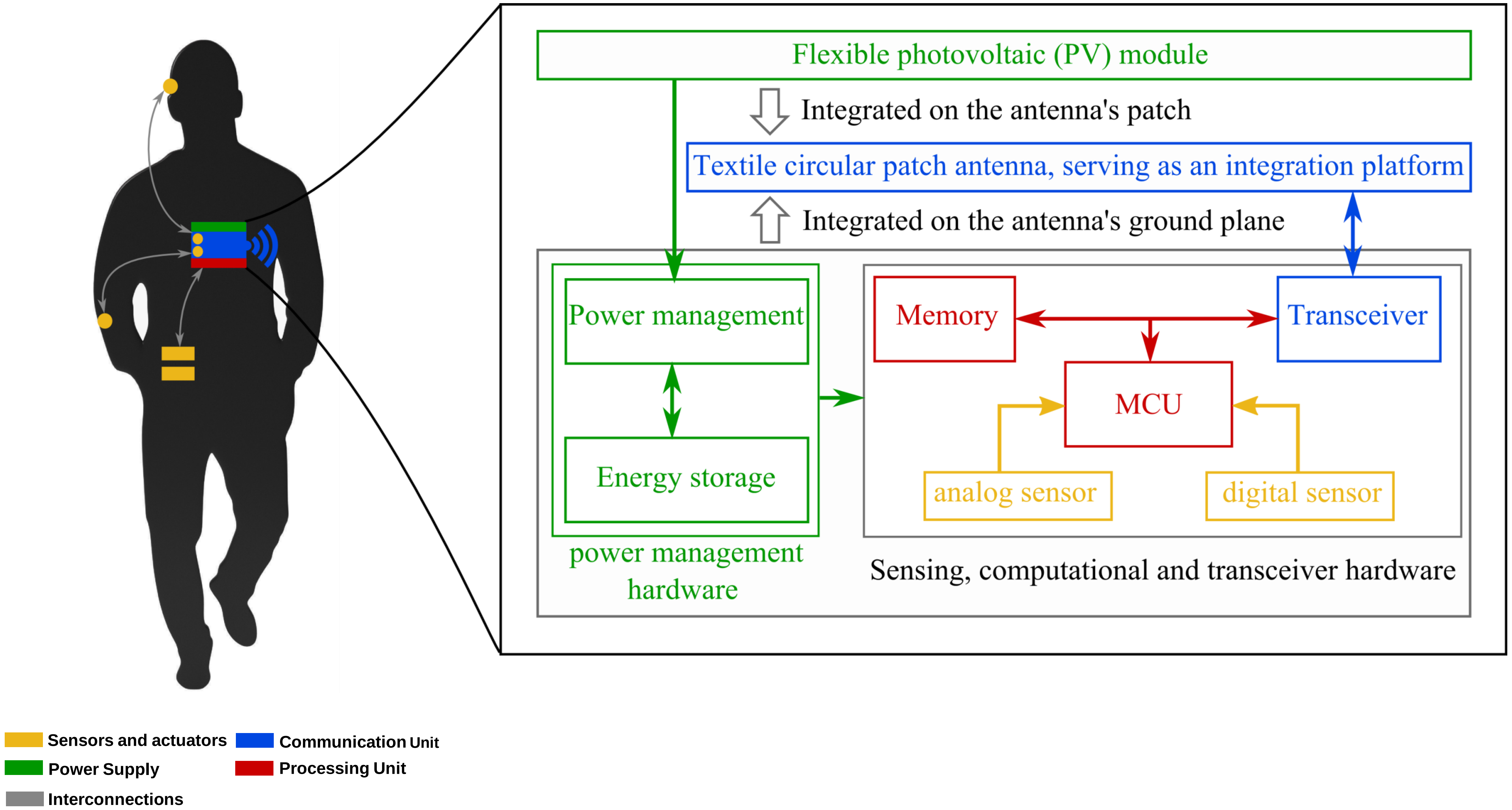


M. Rossi, A. Dierck, H. Rogier, and D. Vande Ginste, "A stochastic framework for the variability analysis of textile antennas," IEEE TRANSACTIONS ON ANTENNAS AND PROPAGATION, vol. 62, no. 12, pp. 6510–6514, 2014.

REPRESENTATIVE DESIGN EXAMPLES

AUTONOMOUS WEARABLE RFID-BASED SENSING PLATFORM

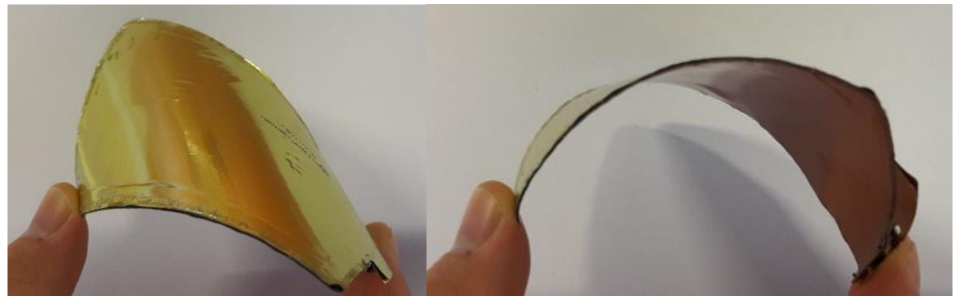
Holistic Design Approach and System Architecture



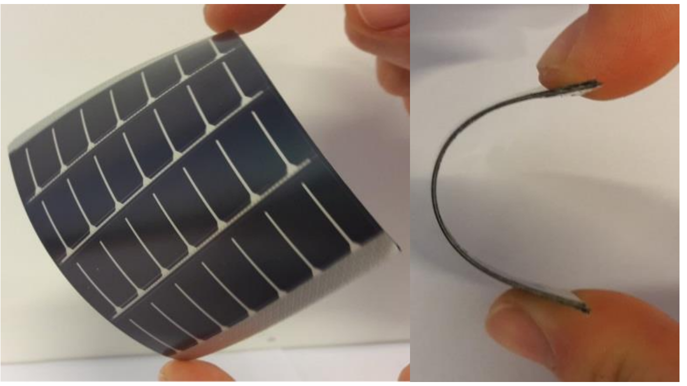
S. Lemey, S. Agneessens, P. Van Torre, K. Baes, J. Vanfleteren, and H. Rogier, “Wearable flexible lightweight modular RFID tag with integrated energy harvester,” *IEEE TRANSACTIONS ON MICROWAVE THEORY AND TECHNIQUES*, vol. 64, no. 7, pp. 2304–2314, 2016.

AUTONOMOUS WEARABLE RFID-BASED SENSING PLATFORM

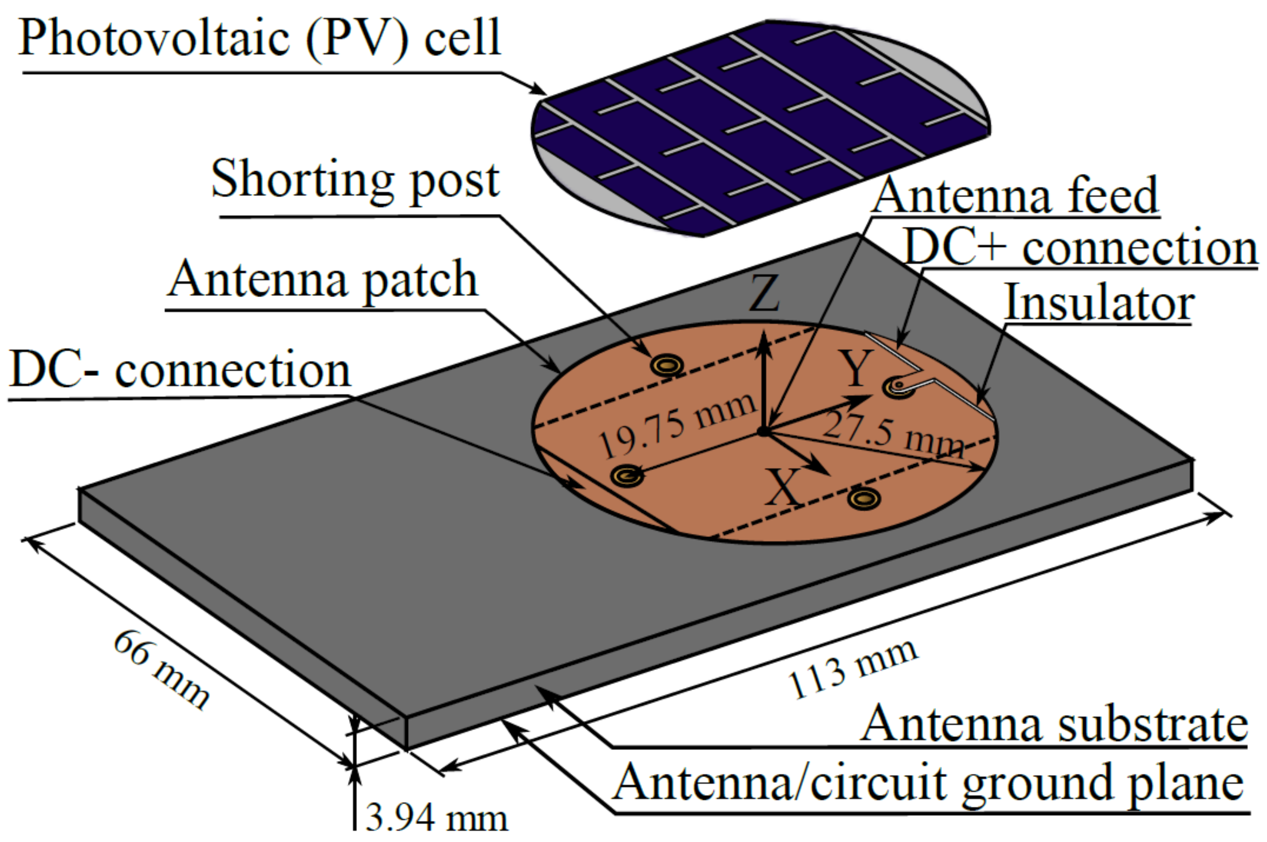
Flexible Lithium Ceramic Battery (FLCB)



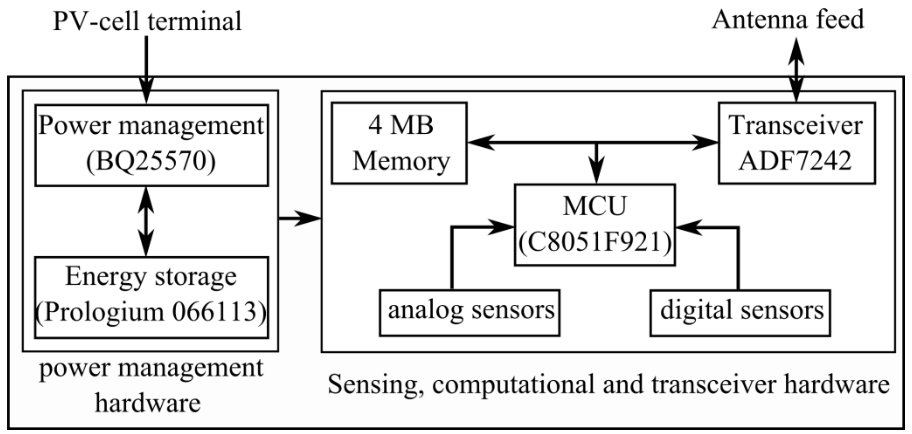
Photovoltaic (PV) cell



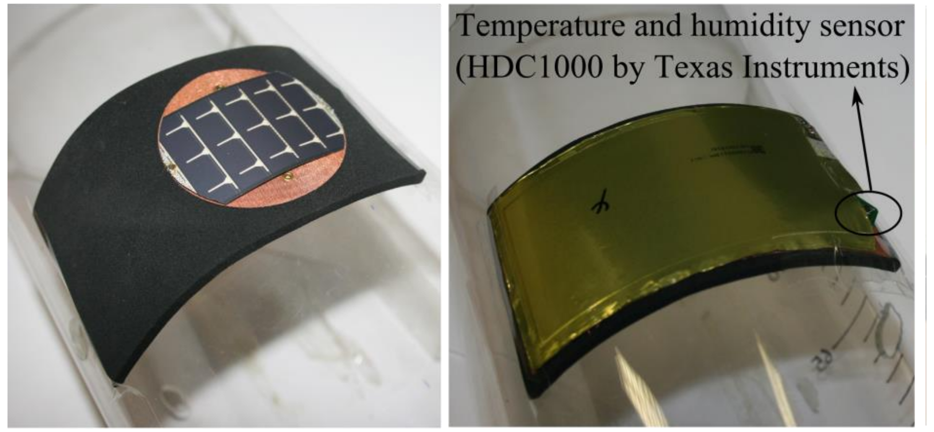
3D view



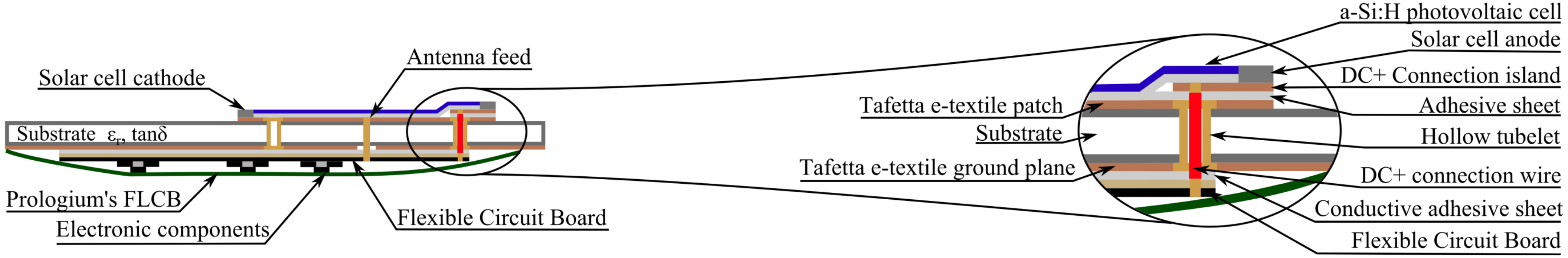
Block Diagram Flexible Circuit Board



Prototype



Cross-section



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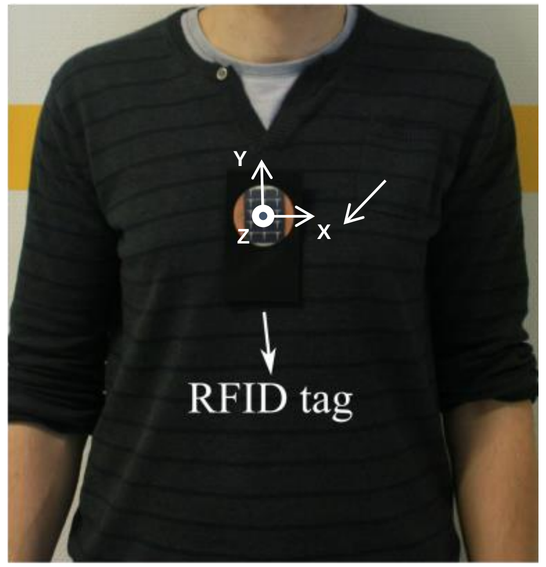
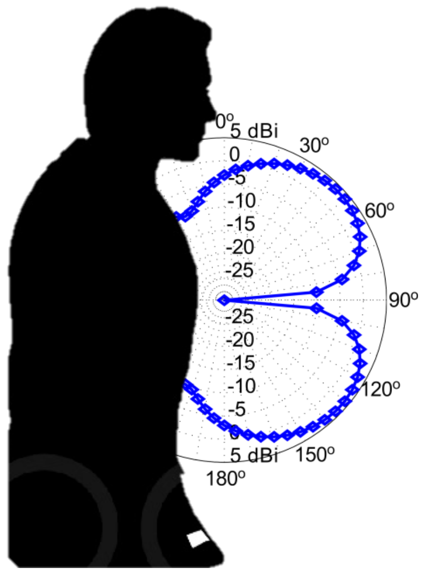
AUTONOMOUS WEARABLE RFID-BASED SENSING PLATFORM

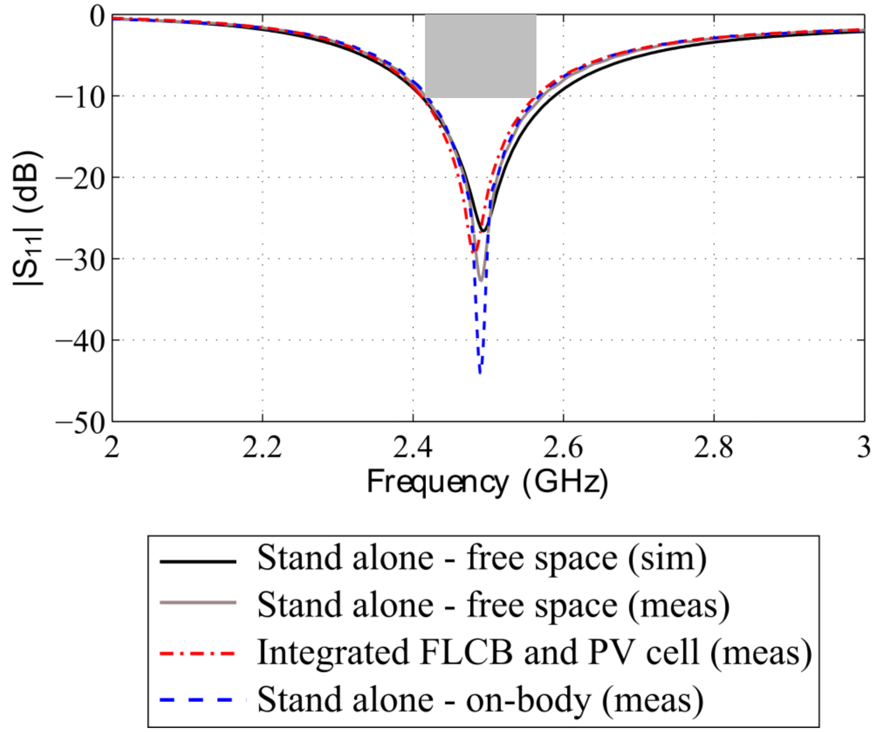
System Deployment





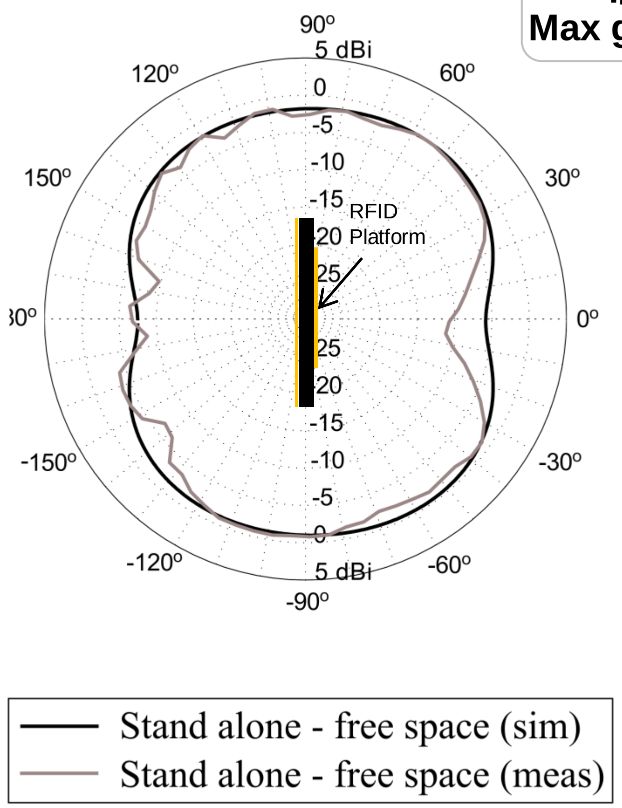
Measured Antenna Performance

Reflection coefficient

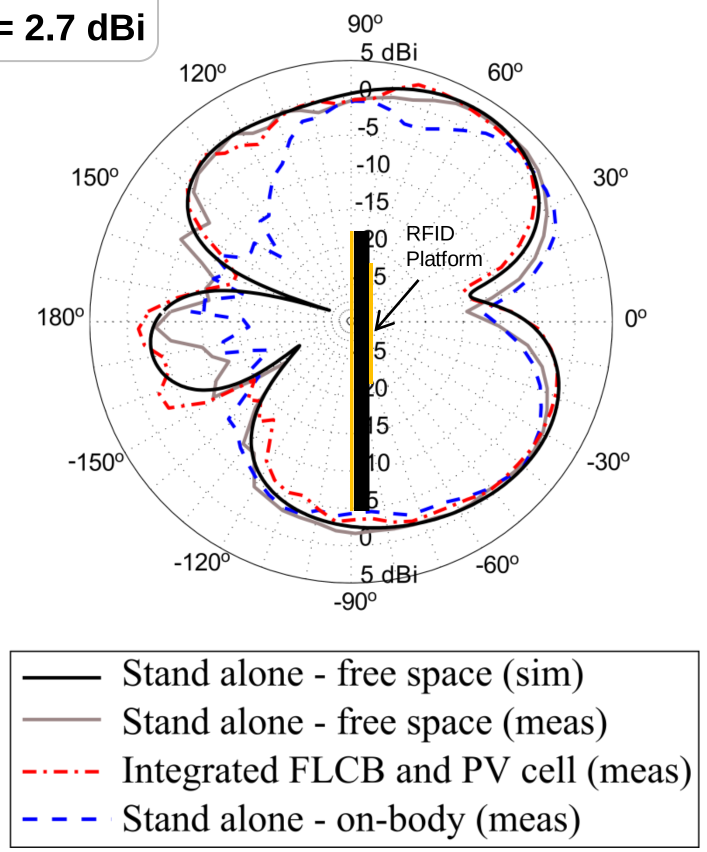


XZ-plane

η_{rad} > 65 %
Max gain = 2.7 dBi



YZ-plane



Stable, high performance

S. Lemey, S. Agneessens, P. Van Torre, K. Baes, J. Vanfleteren, and H. Rogier, "Wearable flexible lightweight modular RFID tag with integrated energy harvester," *IEEE TRANSACTIONS ON MICROWAVE THEORY AND TECHNIQUES*, vol. 64, no. 7, pp. 2304–2314, 2016.

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:

Transmitter location	Received signal level (dBm)
*LoS 1 m	−39.4
LoS 2 m	−41.2
**NLoS 5 m	−55.5
NLoS 13 m	−70.4
NLoS 23 m	−85.8
NLoS 1 floor up, overhead	−64.2
NLoS 1 floor up, 10 m off	−75.5

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

Read Range > 23 m

Measured System Autonomy

Sleep Time (s)	Average Supply Current (μA)	System autonomy (days)
1	186	31
2	97	51
5	44	84
10	26	107
60	11	138

Autonomy > 100 days

S. Lemey, S. Agneessens, P. Van Torre, K. Baes, J. Vanfleteren, and H. Rogier, "Wearable flexible lightweight modular RFID tag with integrated energy harvester," *IEEE TRANSACTIONS ON MICROWAVE THEORY AND TECHNIQUES*, vol. 64, no. 7, pp. 2304–2314, 2016.

ATTO: ULTRA-HIGH CAPACITY WIRELESS NETWORKING

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

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

***atto*-cell served by photonic-enabled RAUs**

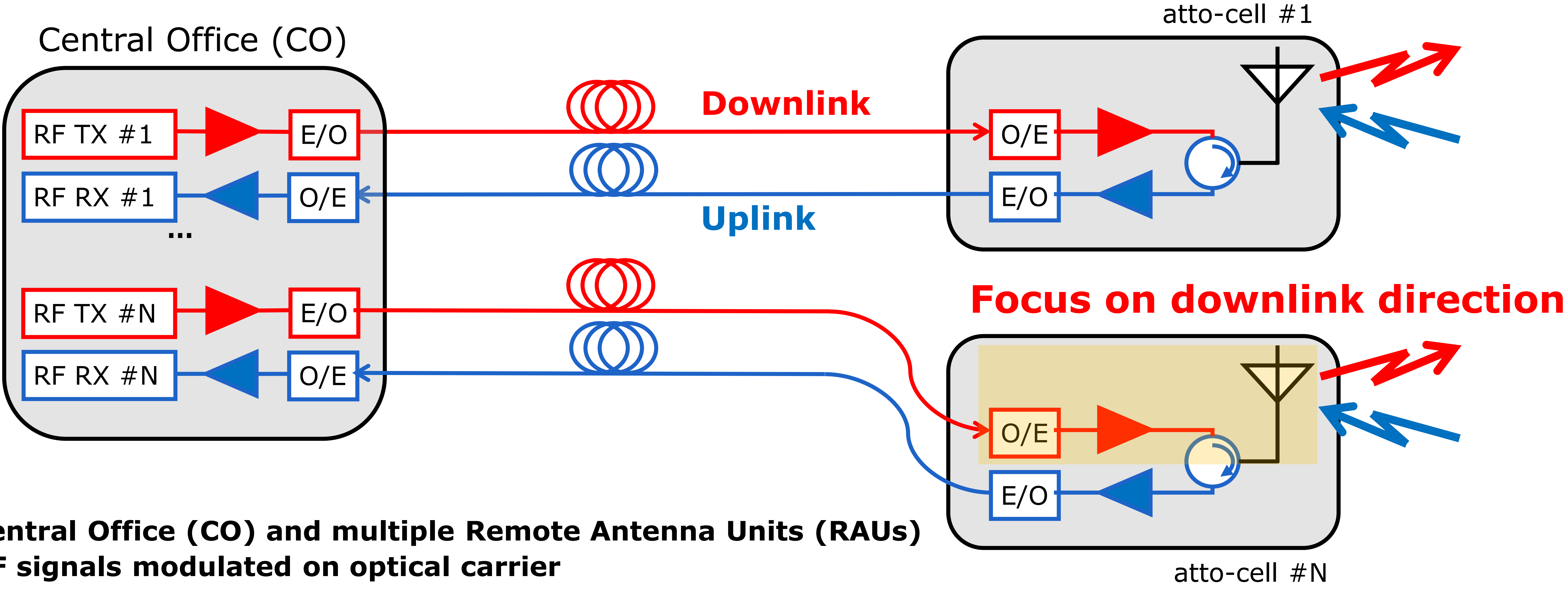
Solution

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

➔ Extreme low cost and power

G. Torfs, H. Li, S. Agneessens, J. Bauwelinck, L. Breyne, O. Caytan, W. Joseph, S. Lemey, H. Rogier, A. Thielens, D. Vande Ginste, J. Van Kerrebrouck, G. Vermeeren, X. Yin and P. Demeester, "ATTO: Wireless Networking at Fiber Speed," in Journal of Lightwave Technology.

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

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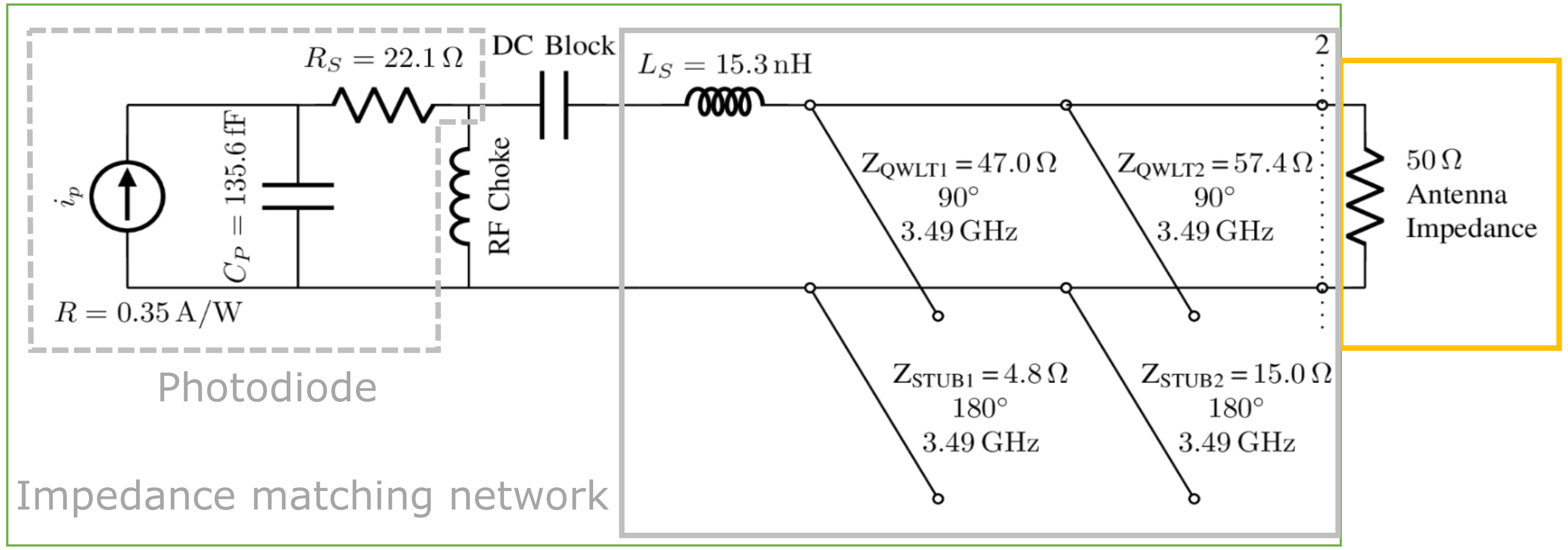
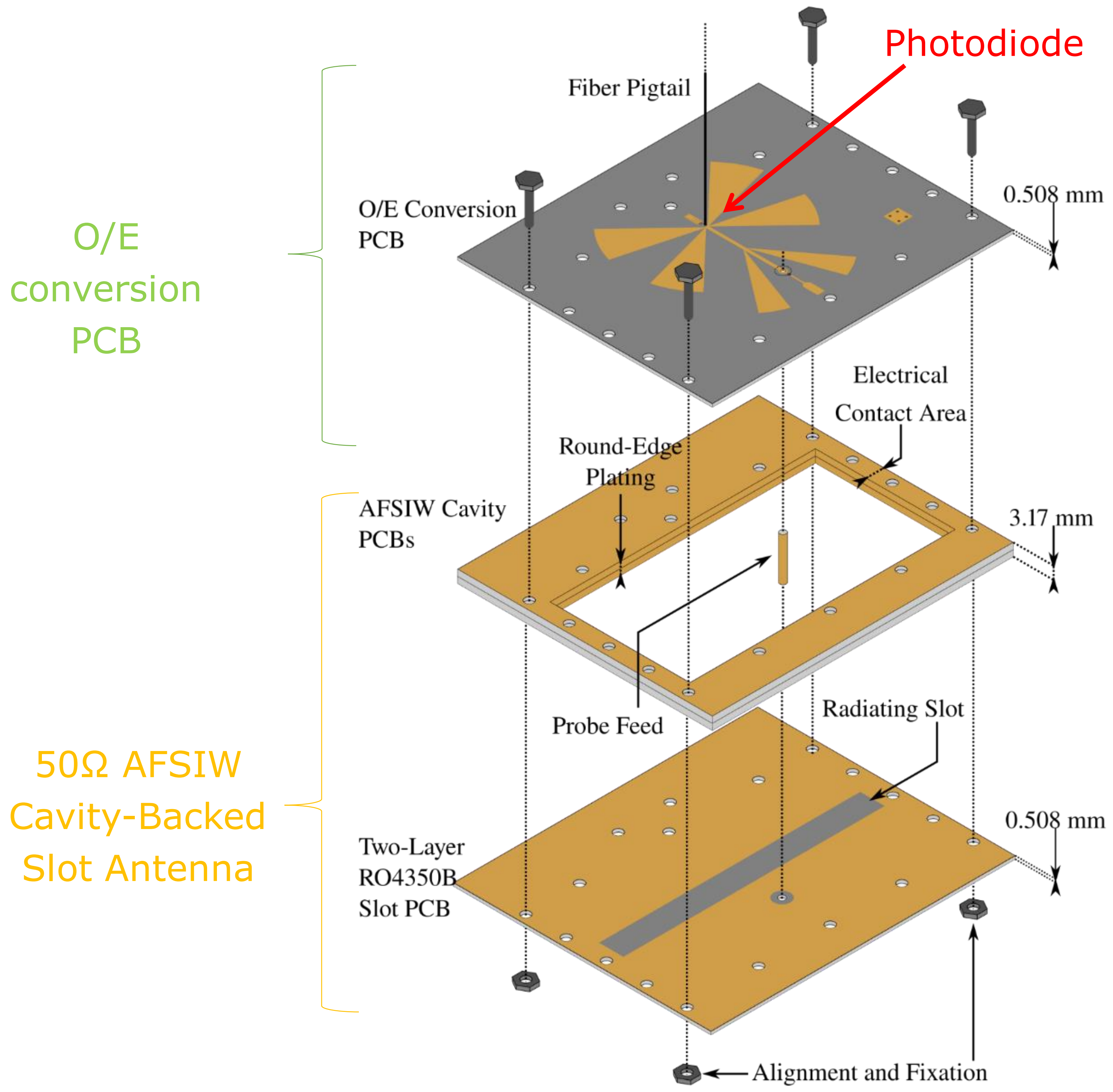
Architecture

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



Opto-electric (O/E) conversion PCB



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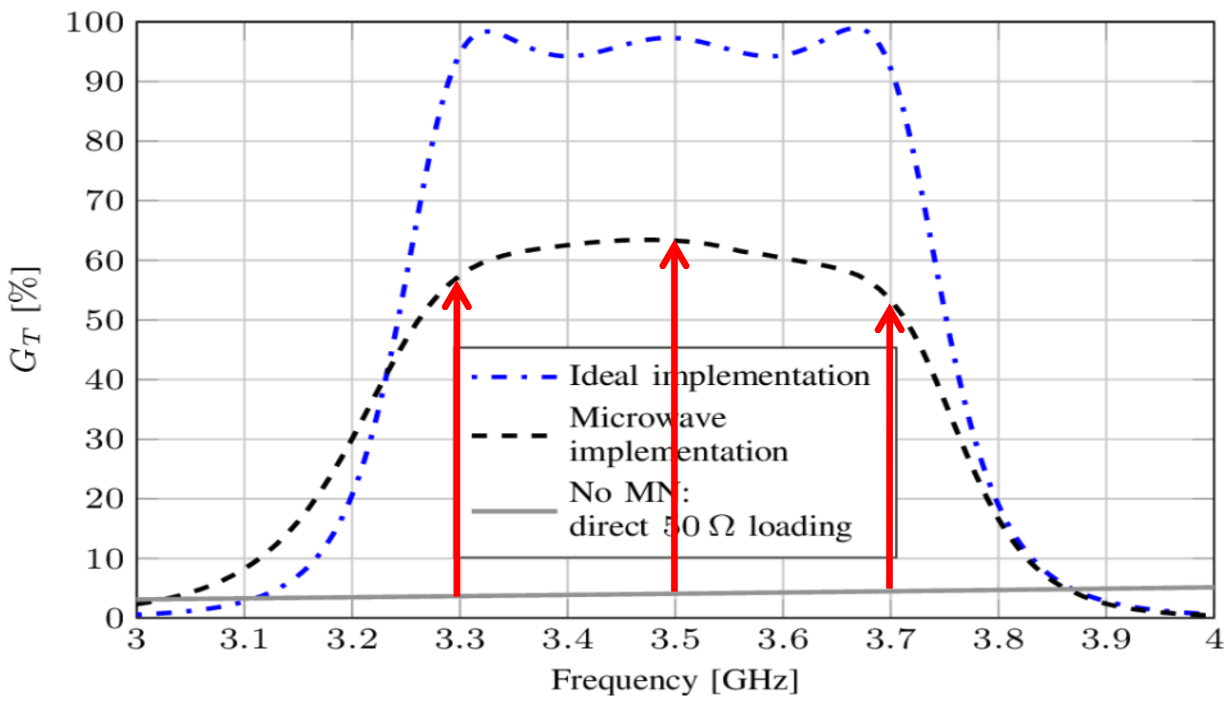
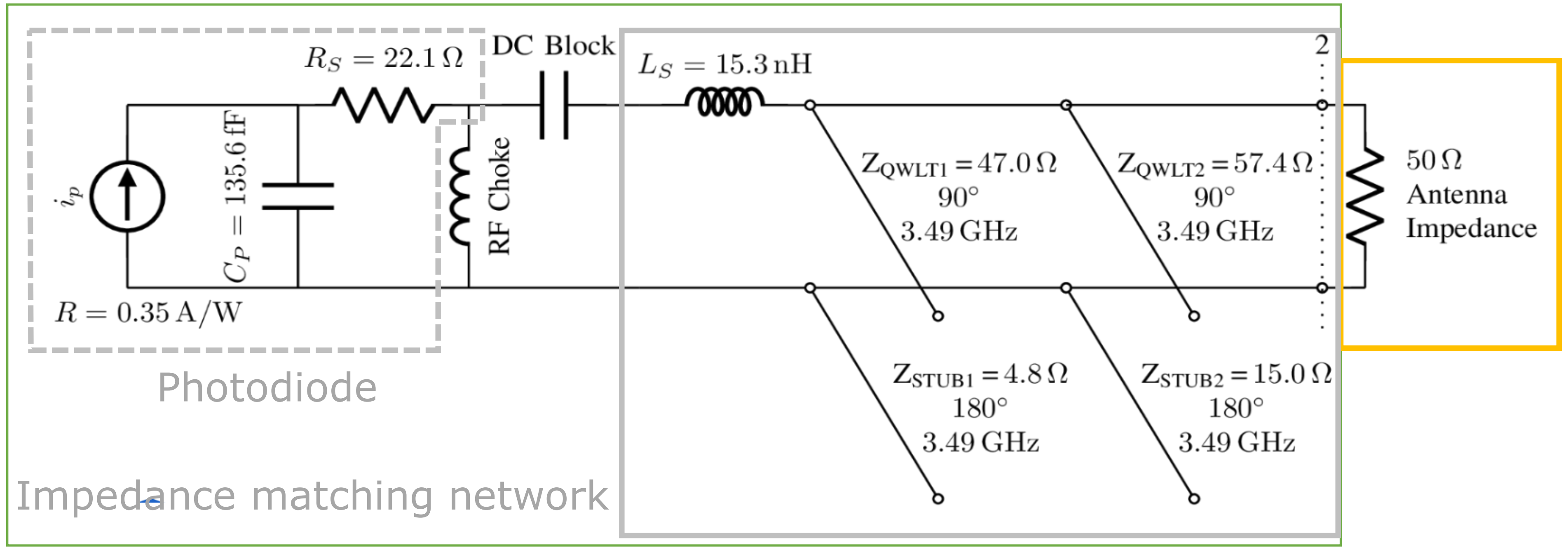


> 10 x extracted power as compared to direct loading



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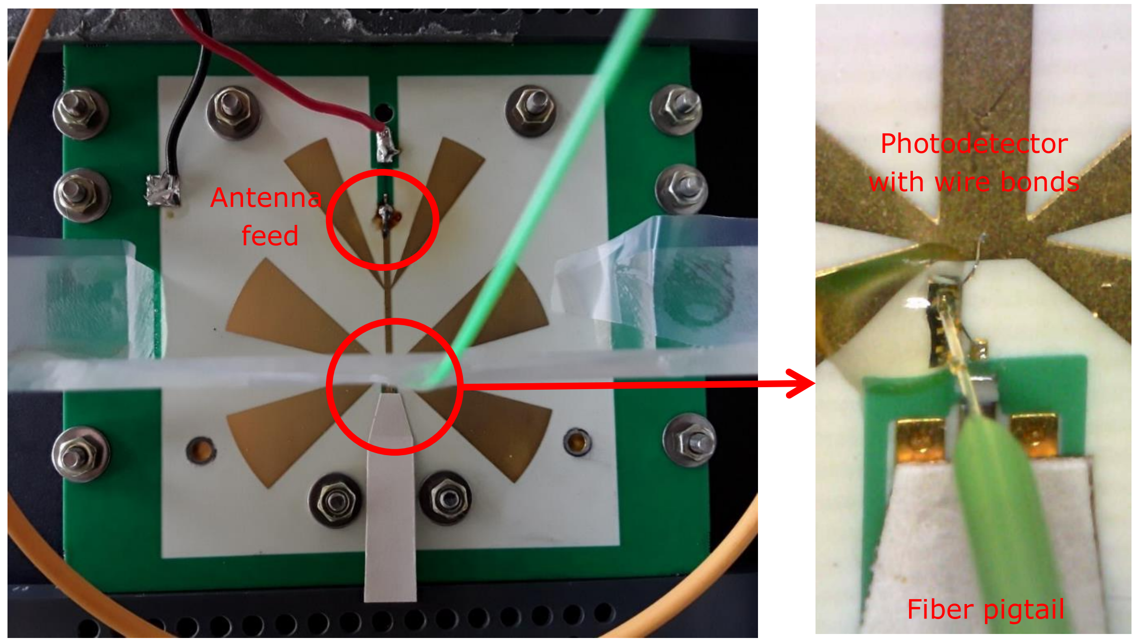

Microwave implementation of O/E conversion PCB

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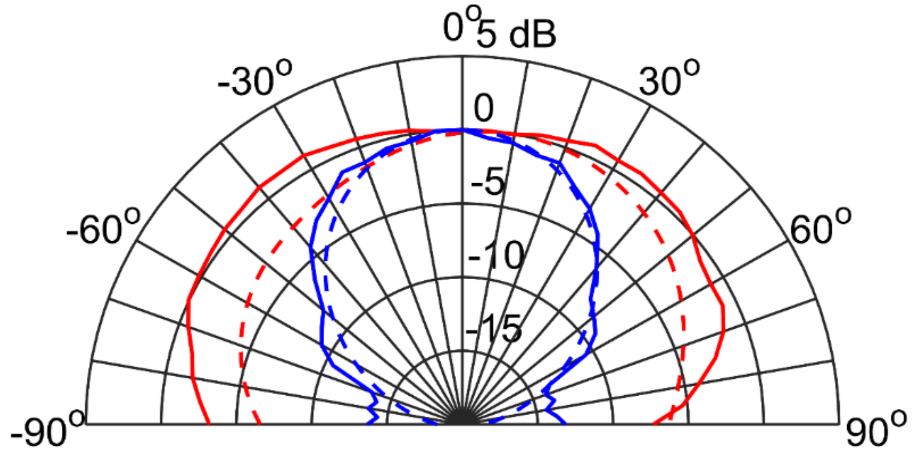
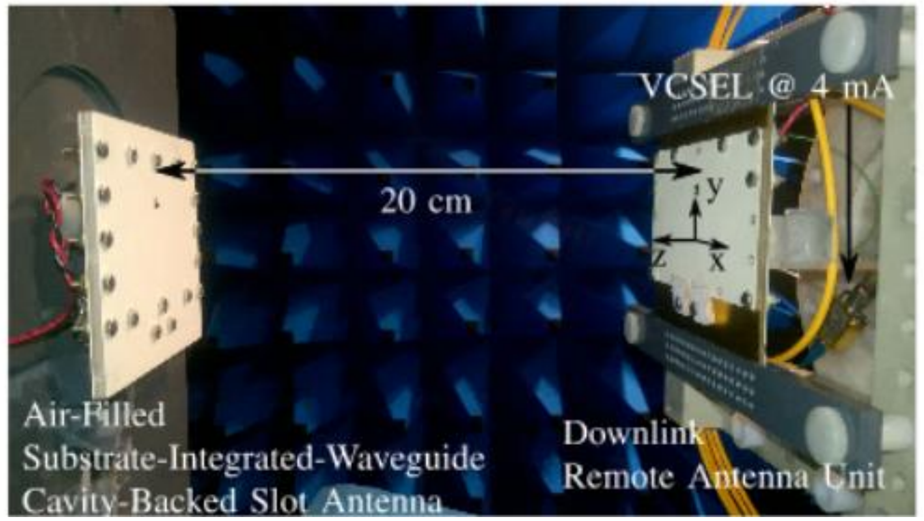
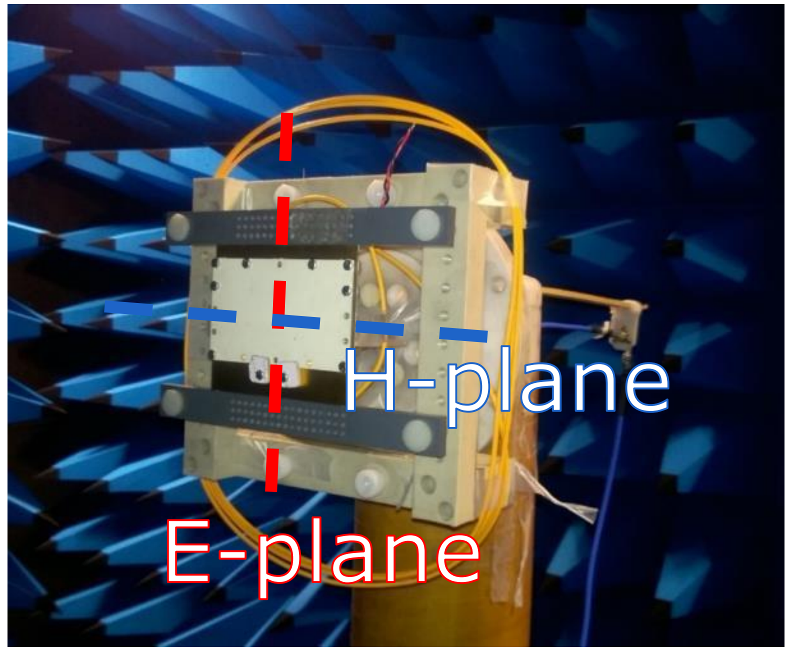
Prototype measurements (normalized w.r.t. laser)

- ✓ 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

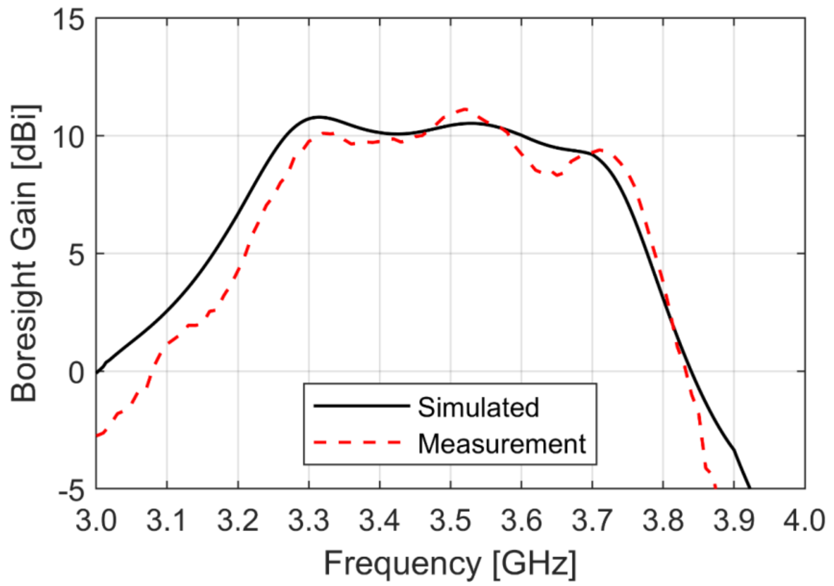


Far-field radiation patterns at 3.50 GHz:
E-plane (red) and H-plane (blue)
Measurement (solid) and simulation (dashed)

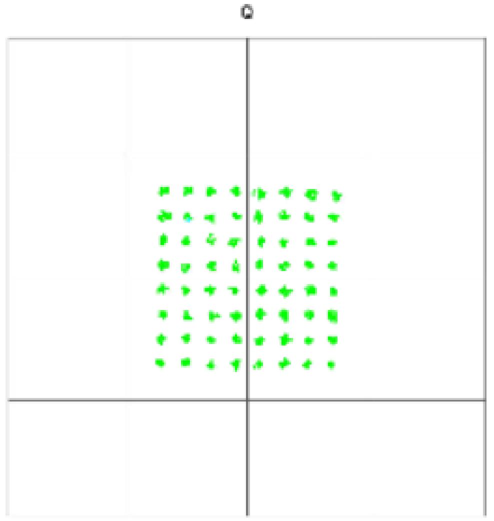




DL-RAU prototype in anechoic chamber



Radiation performance



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

Link performance

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CONCLUSION

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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