Inkjet-/3D-/4D-Printed Wireless Ultrabroadband Modules for IoT, SmartAg and Smart City Applications

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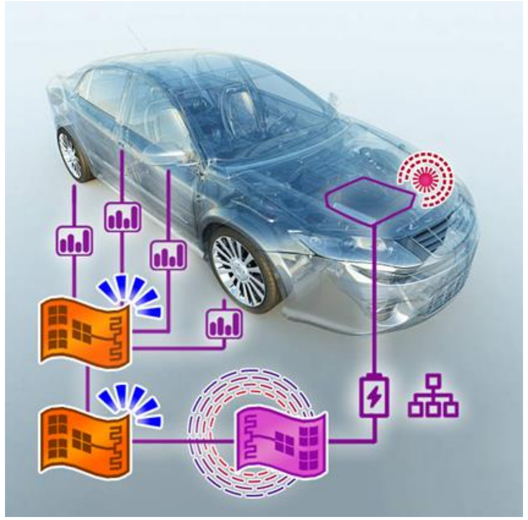
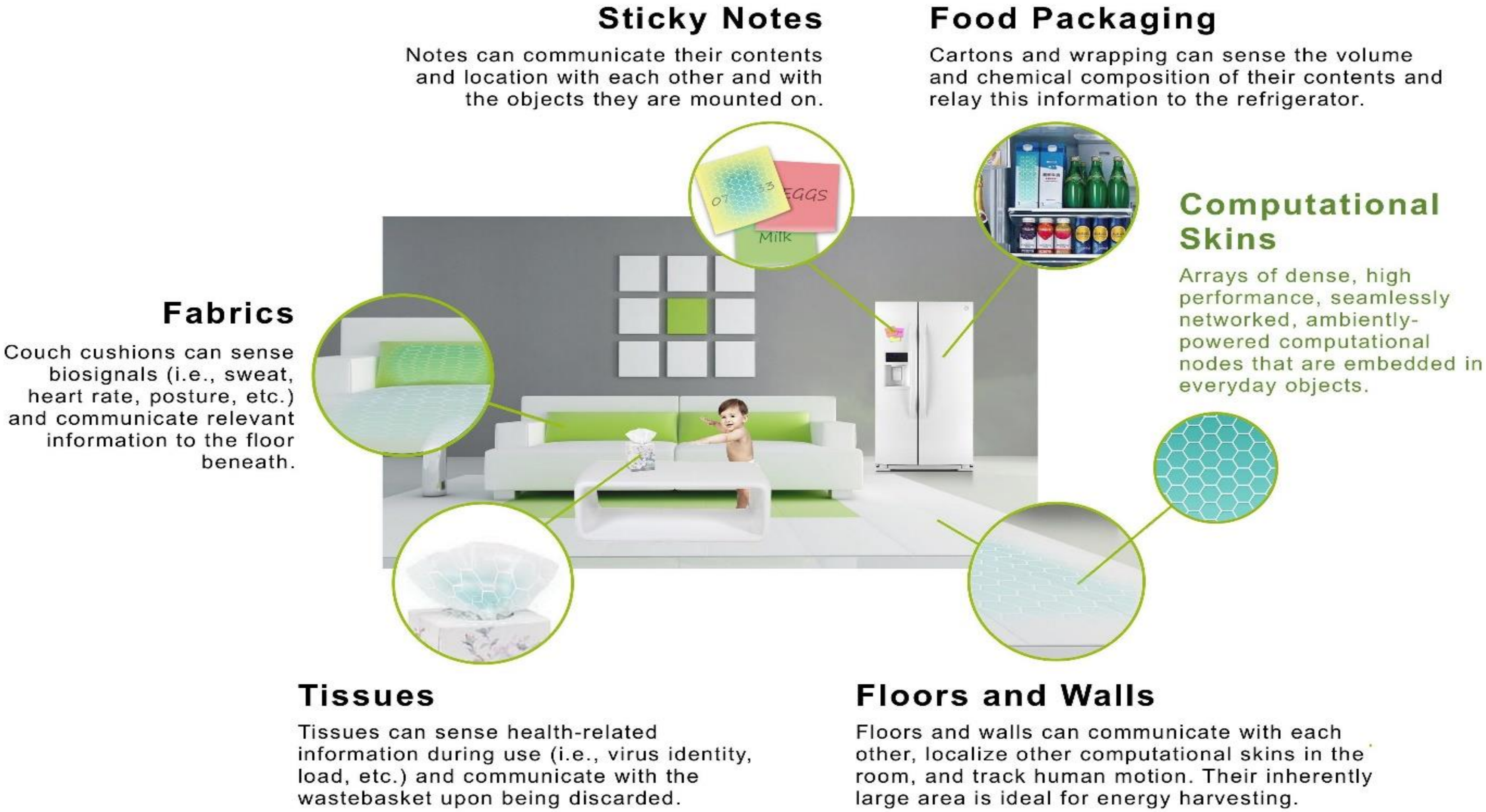
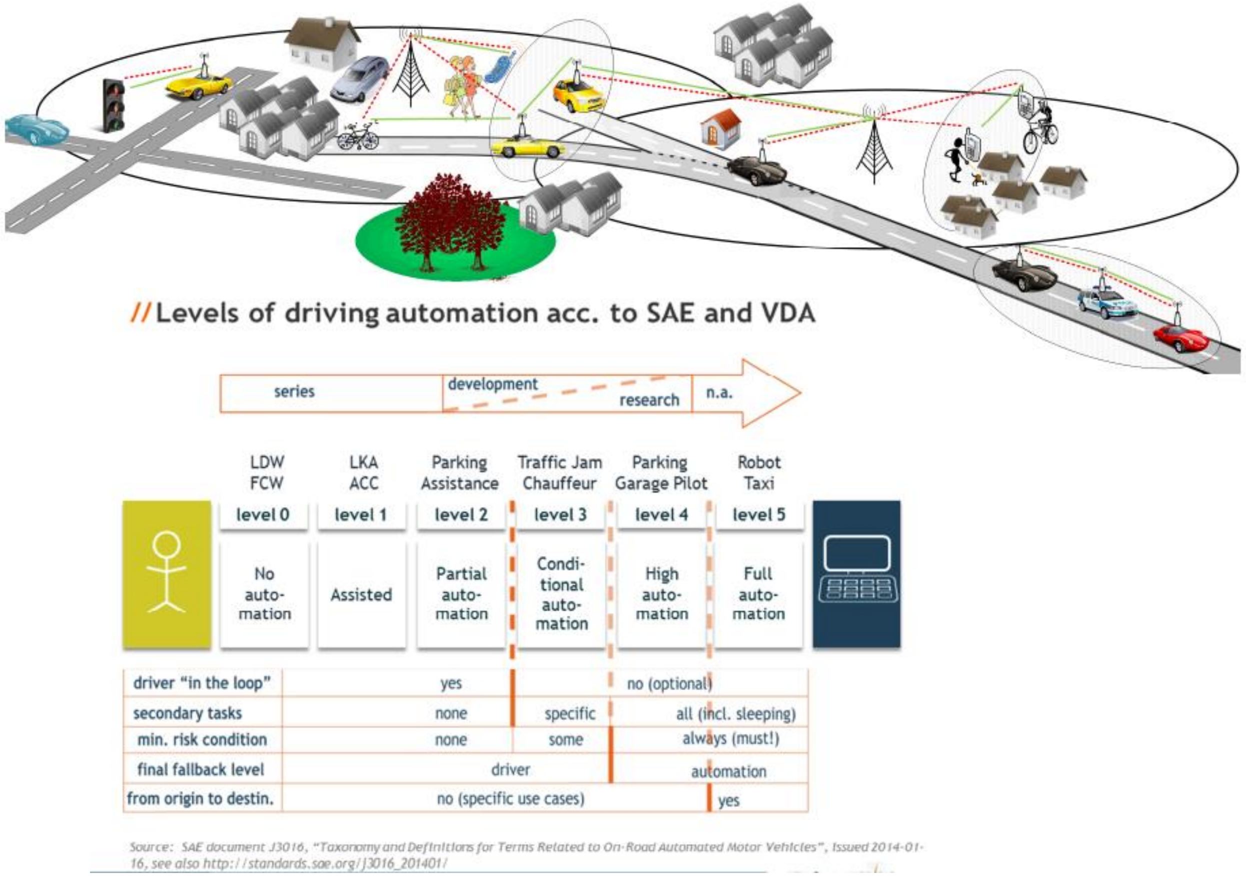
COSMOS
Computational Skins for Multifunctional Objects and Systems





Smart Cities-Autonomous Cars



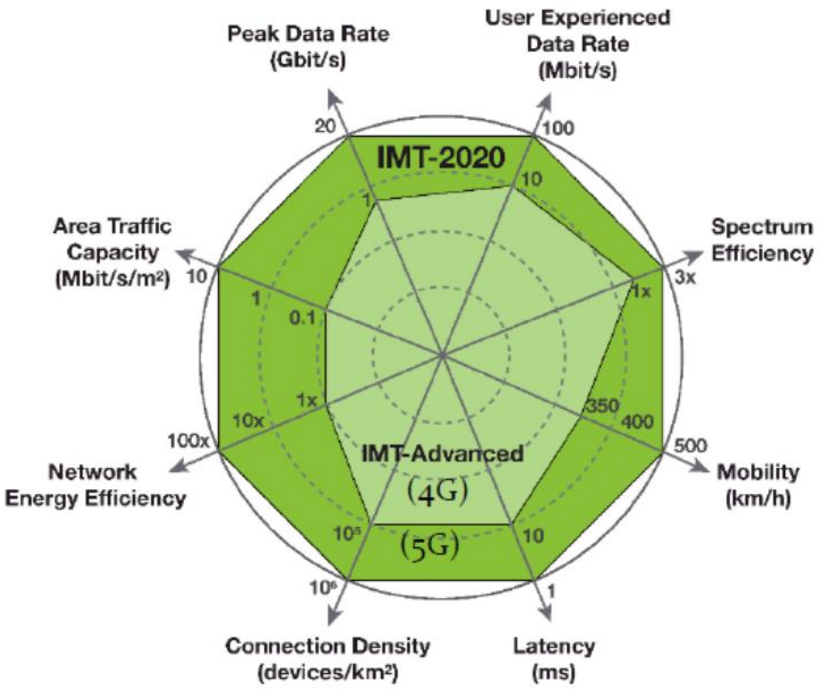
Vehicle-to-Everything (V2X): Any communication involving a vehicle as a source or destination of a message:

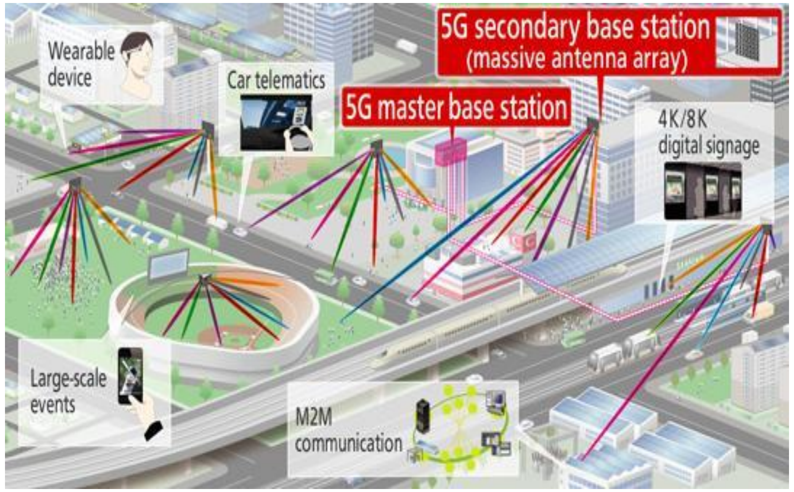
- Vehicle-to-Vehicle (V2V)
- Vehicle-to-Infrastructure (V2I)
- Vehicle-to-Network (V2N)
- Vehicle-to-Pedestrian (V2P)

5G networks

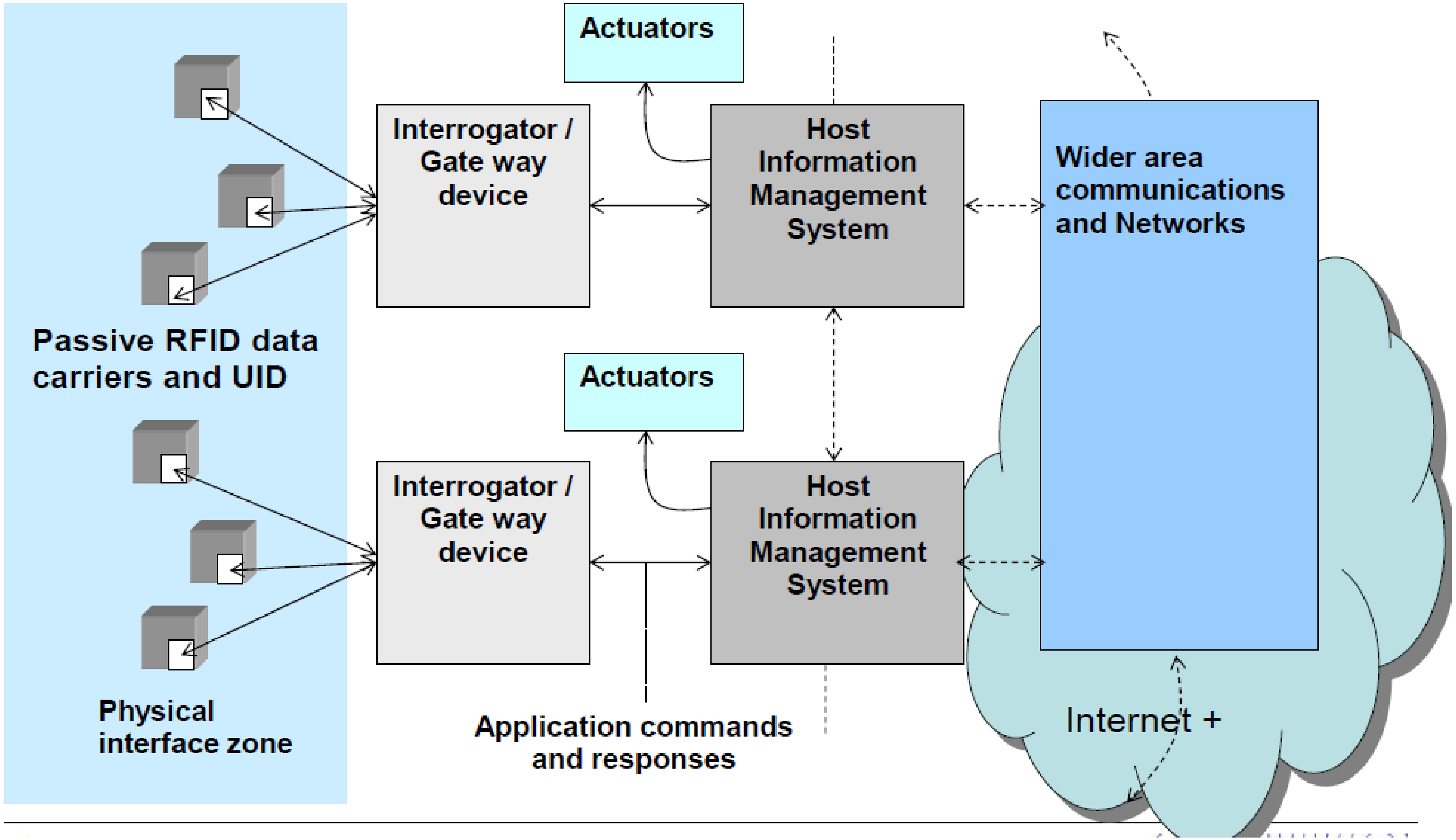
Defining characteristics

- Cellular network
- 75dBm EIRP FCC limitation (compared to 36 dBm for UHF RFID readers)
- Small cells (300-500m radius)
- Mm-wave
- **Beamforming**
- Spatial multiplexing

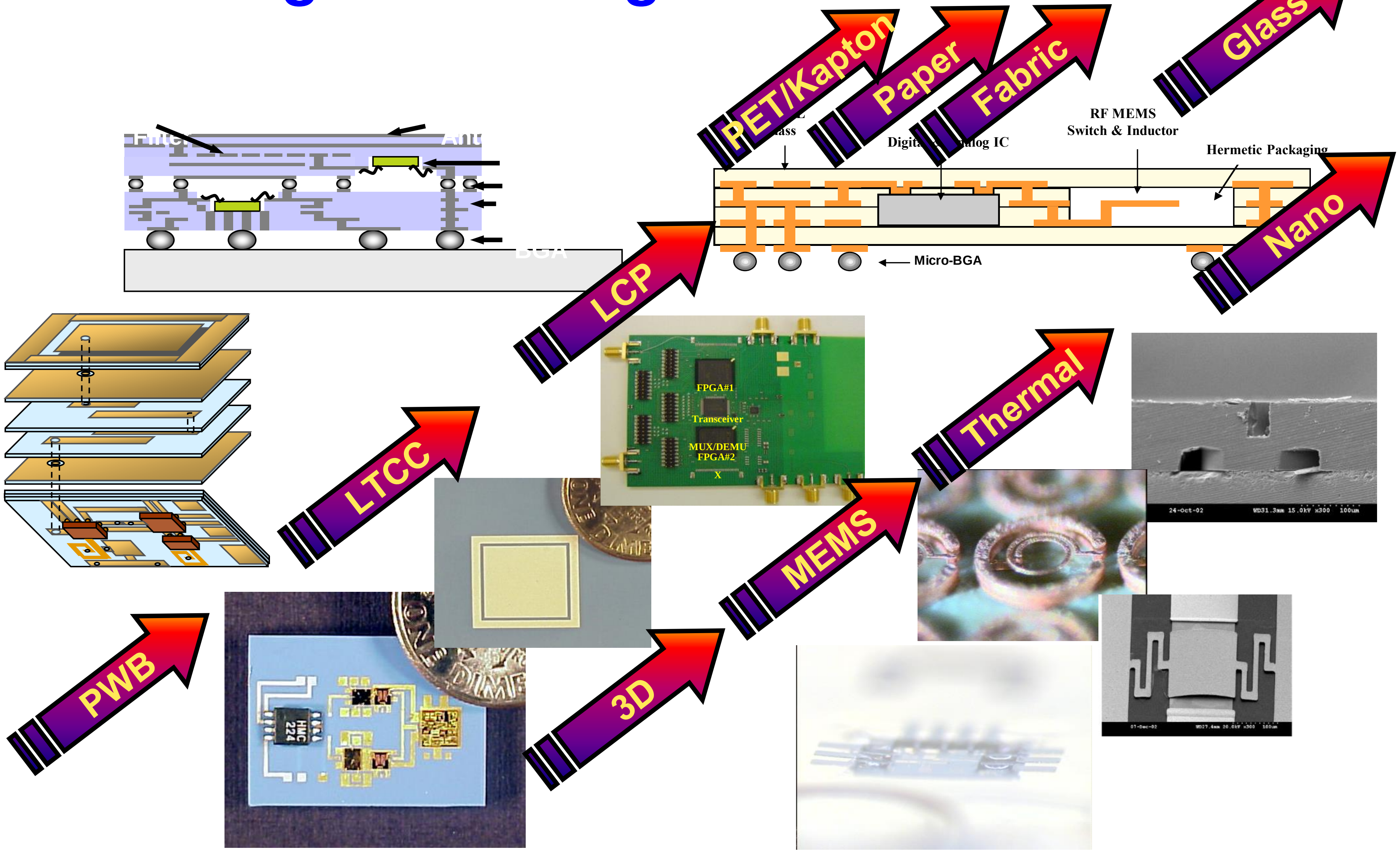




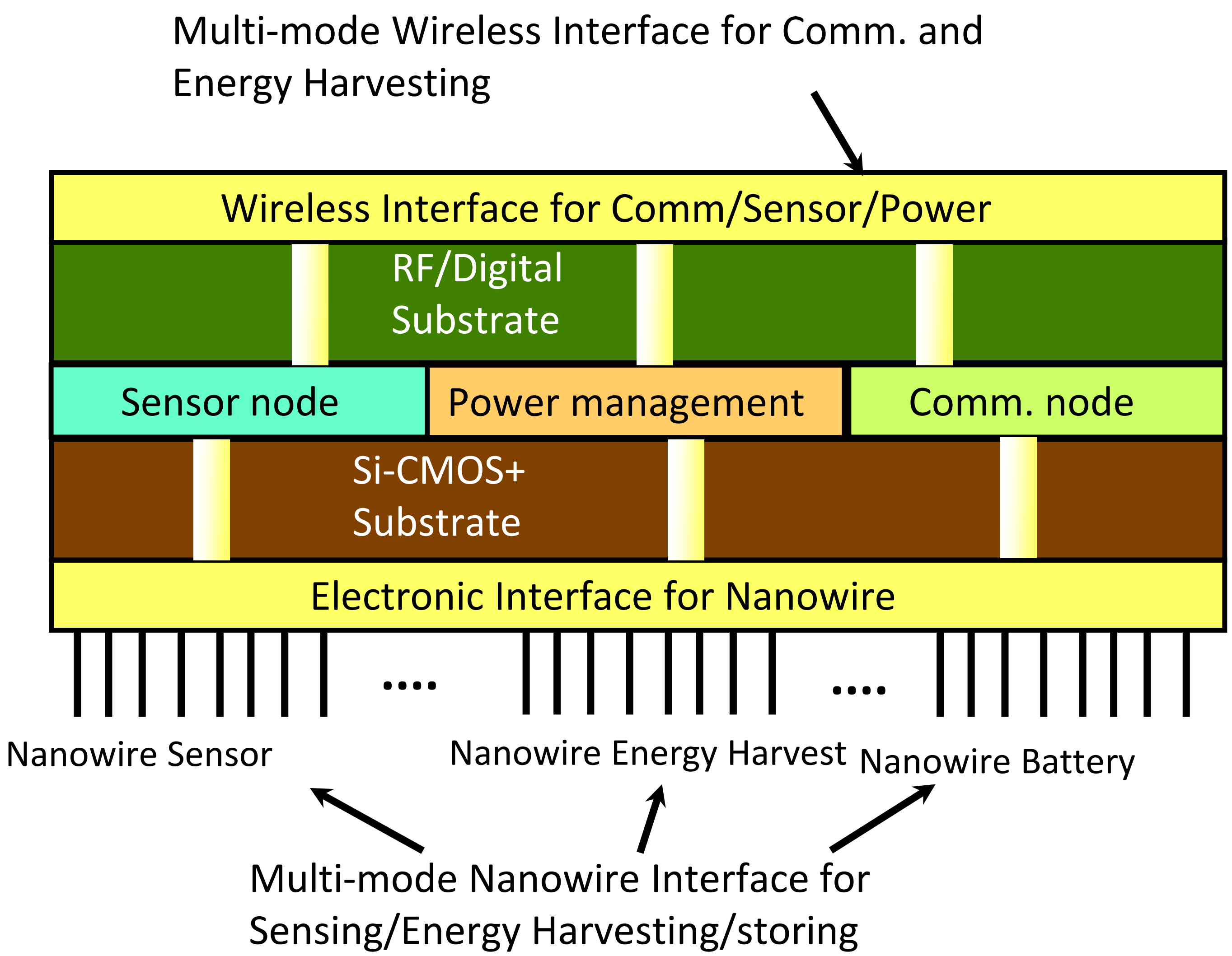
Internet of Things



Enabling Technologies in the future



3D Integrated Platforms



Additive Manufacturing

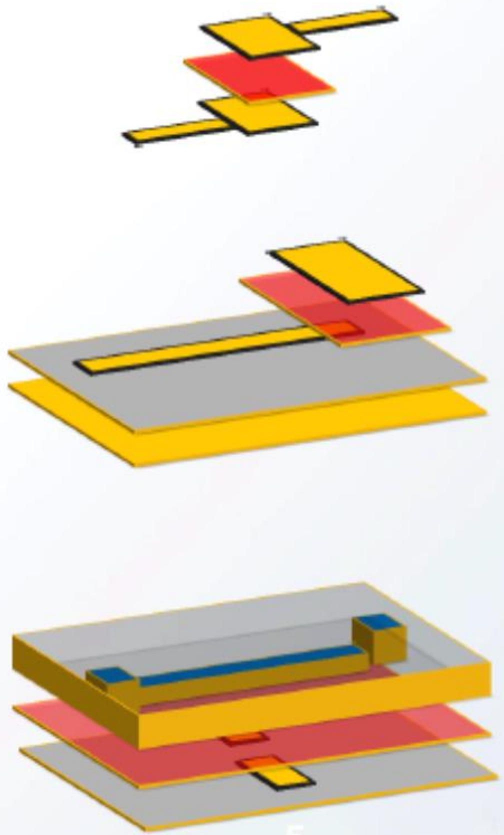
- Inkjet printing
  - Aid techniques
    - Bonding
    - Molding
  - Fully inkjet printing
- 3D printing
  - Dielectric printing
    - FDM
    - SLA/DLP
  - Metallization

- Low cost
- No cleanroom
- Fast prototyping
- Customization
- Flexible material
- Environmental friendly

Advantages of Fully-Printed Systems

- Low-cost fully-printed systems
  - Removal of mounted discrete components
  - Stackable interconnects and crossovers
  - Higher levels of complexity and integration

- Ability to post-process onto CMOS (Long Term)
  - High gain antennas
  - Reduce chip area (Post-processed inductors and capacitors)
  - Non-CMOS compatible components and sensors



ATHENA

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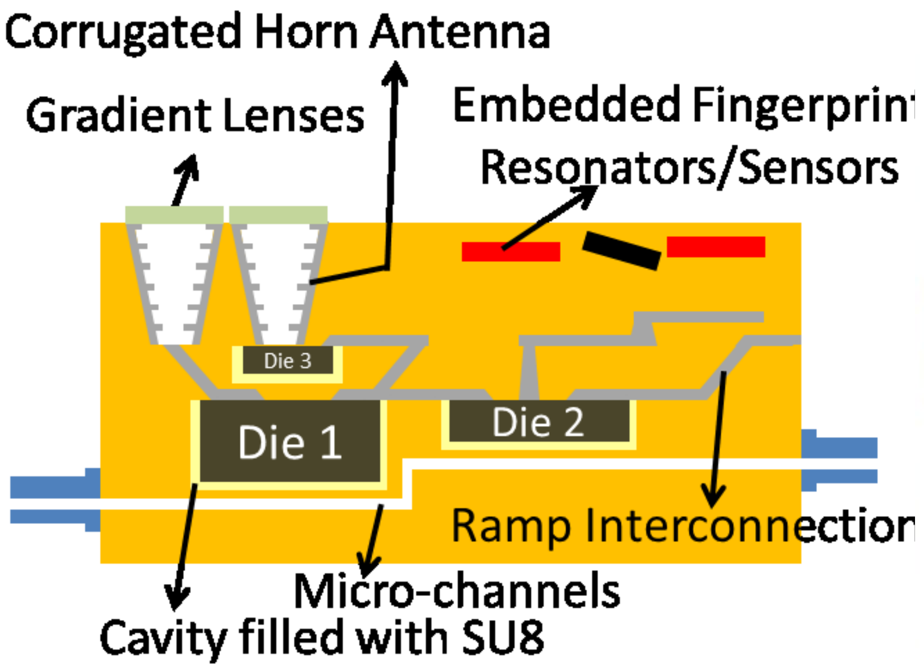
Georgia Tech

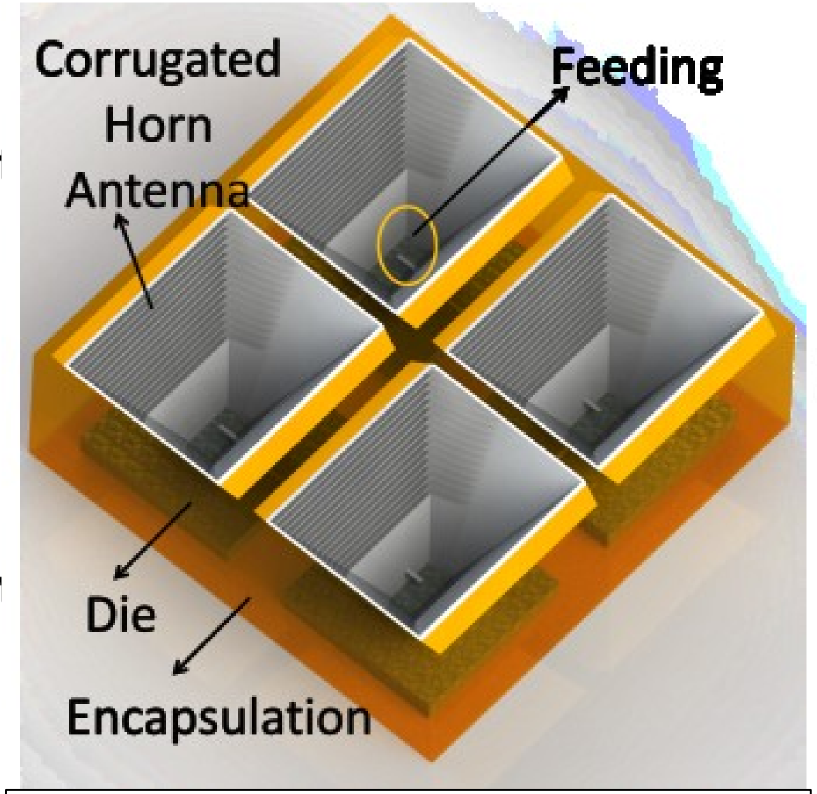
Additive vs Subtractive Fabrication

Technology	Feature Size (um)	Multi-Layer	Cost	Speed	Waste	Area (m^2)
Milling	200	No	Low	Slow	High (Dust)	0.1
Laser Ablation	20	No	High	Slow	Medium (Vapors and Dust)	0.05
Photolithography	0.01	Yes	High	Slow	High (Chemical)	0.66
Microcontact Printing	0.1	Yes	Medium	Medium	Negligible	0.01
Gravure Printing	5-10	Yes	High	Fast	Medium (Excess Ink)	∞
Screen Printing	10-20	Yes	Medium	Fast	Low(Excess Ink)	0.8
Inkjet-Printing	1-20	Yes	Low	Fast	Negligible	∞

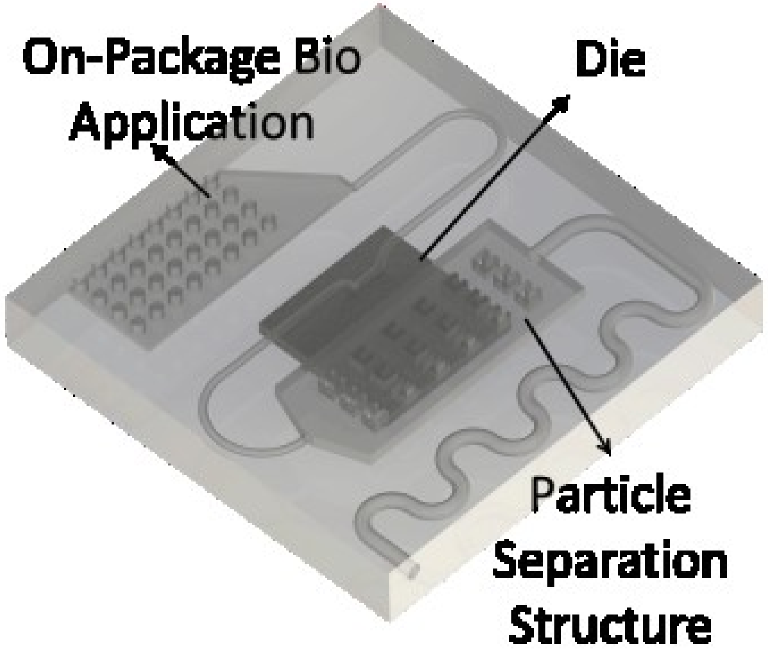
Vision: AM Smart Packaging and mmWave transceivers



Full smart package with multiple features.



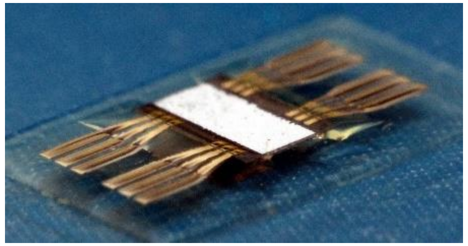
Horn antenna array integrated into MCM, for compact high gain mm-Wave transceivers.



Integration of BIOMEMS inspired structures for wearable and implantable wireless biosensors

Mm-Wave Systems and Packaging with Printing

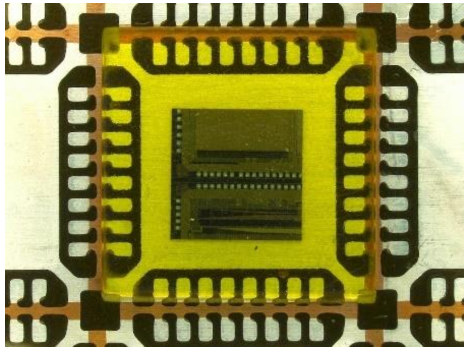
Inkjet Printing



Materials:
Polymer solutions, metallic nanoparticle dispersions, carbon nanomaterial suspensions

- 3D interconnects
- RF substrates
- Die attach

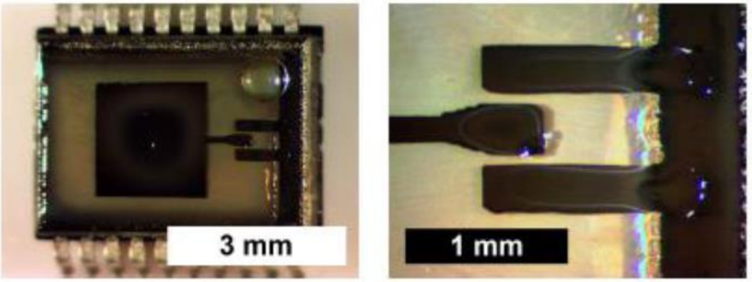
3D Printing



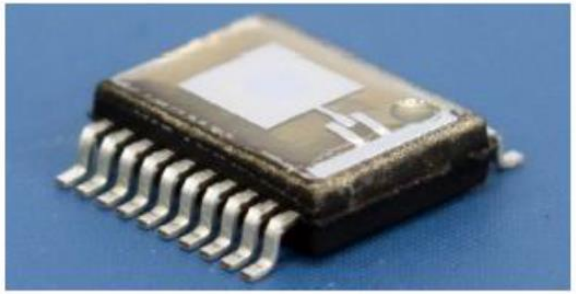
Materials:
Photoactive resins, thermoplastics, ceramic pastes, conductive adhesives

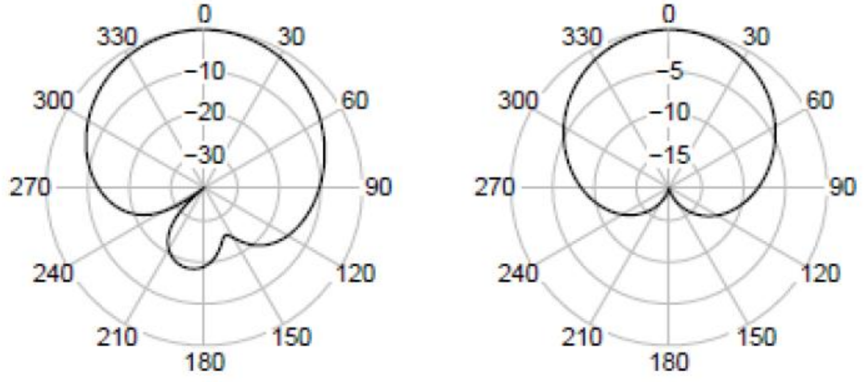
- Dielectric lenses
- Encapsulations
- Die-embedded leadframes

On-Package 30 GHz Antenna



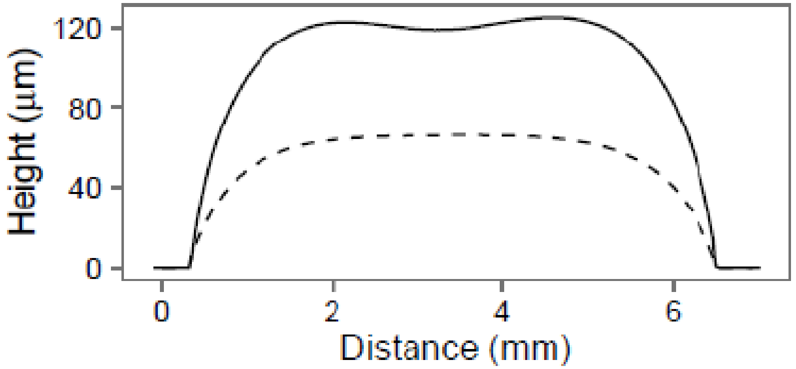
(a) (b)

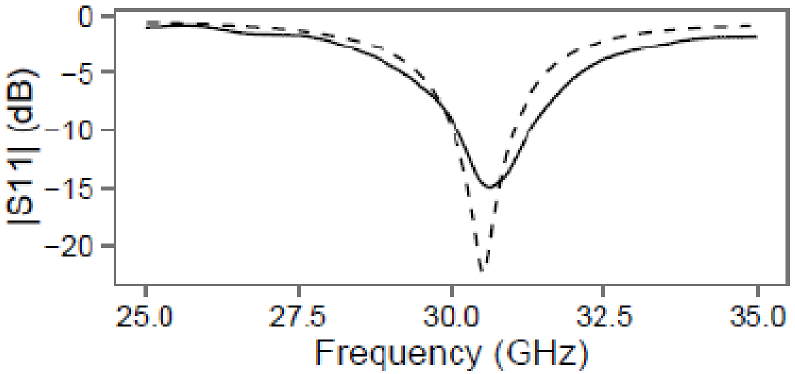




(a) (b)

Fig. 4. Simulated (a) YZ and (b) XZ normalized radiation pattern cuts.

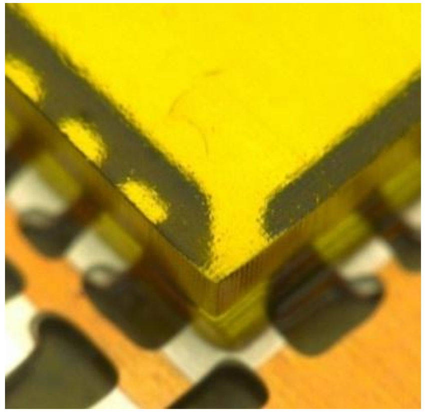


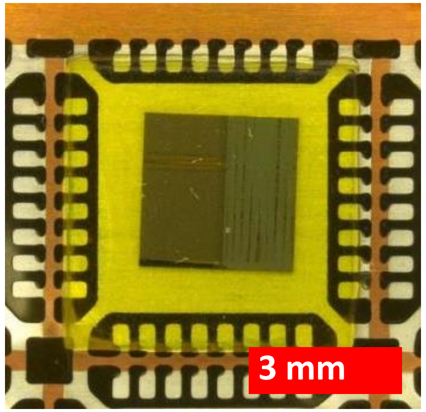


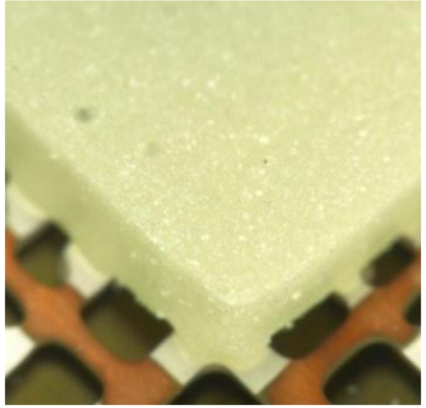
Source from Prof. Manos M. Tentzeris

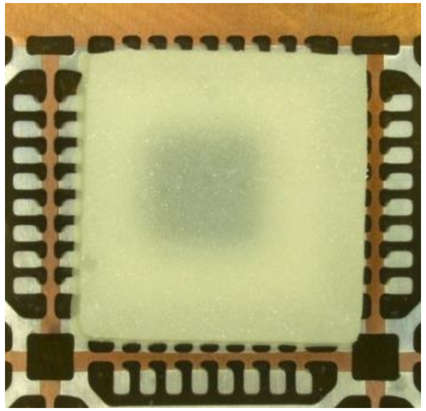
3D-Printed Encapsulation

Standard 1 mm-Thick Encapsulation

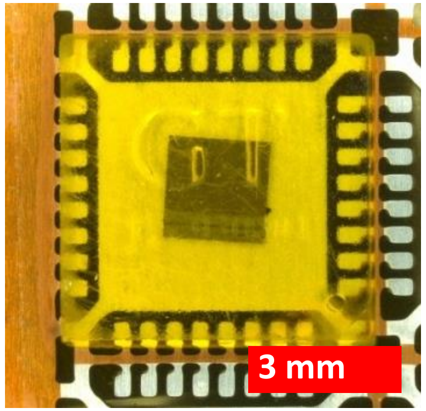


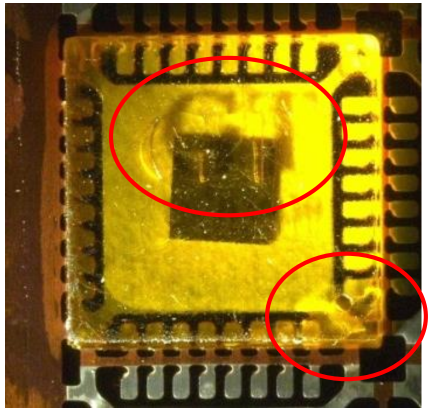




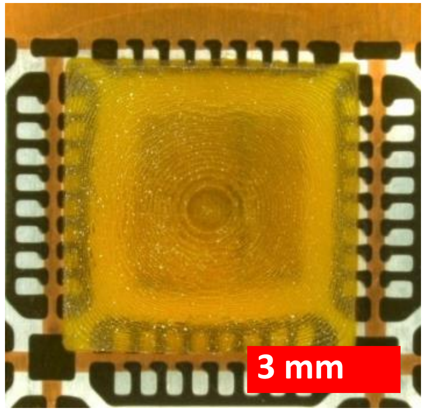


Text and Detailing

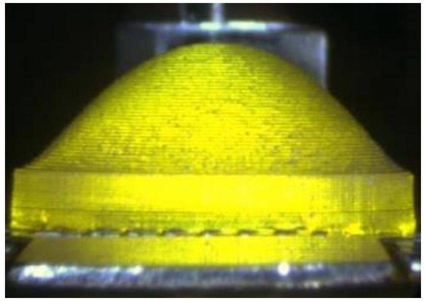




Lens Integration

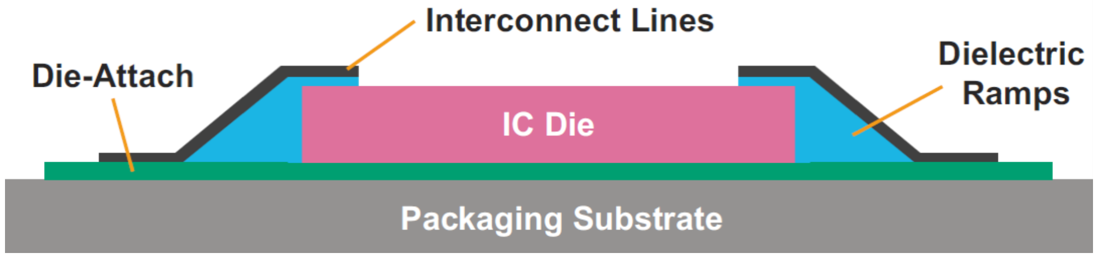


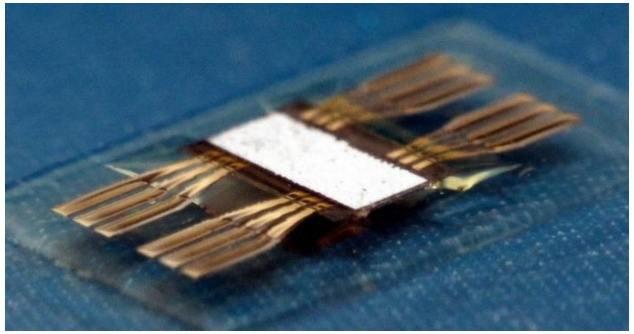
Side View

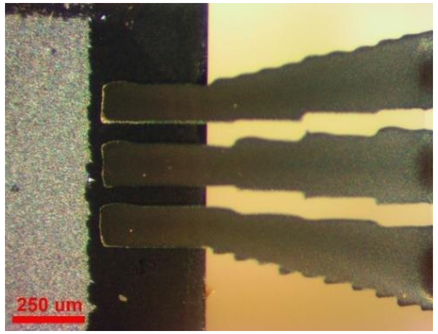


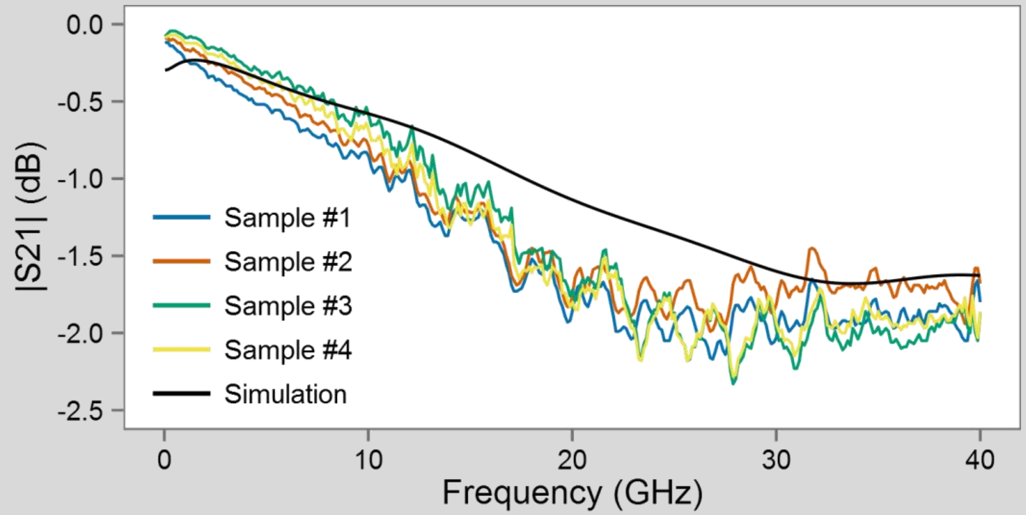
Inkjet-Printed 3D mm-Wave Interconnects

- Efficient interconnects essential for system-on-package (SoP) solutions
- Use inkjet printing to realize 3D mm-wave interconnects between IC die and packaging substrate



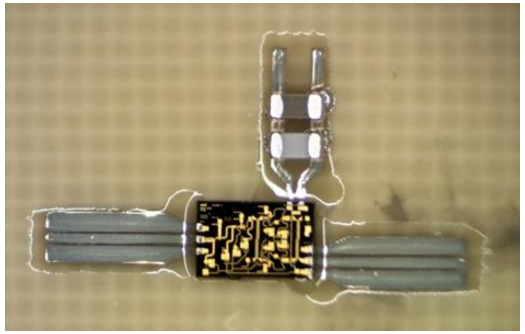




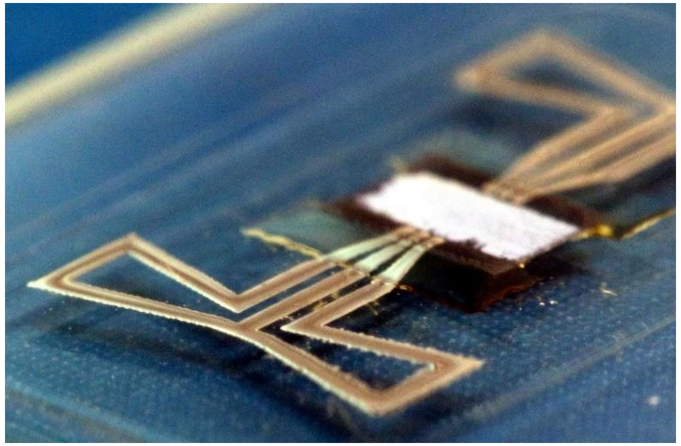


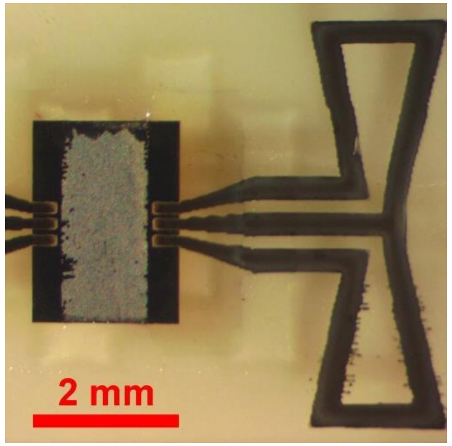
- Loss at 40 GHz: **0.6–0.8 dB/mm**
- Inductance **half** of typical wirebond (0.4 nH/mm)

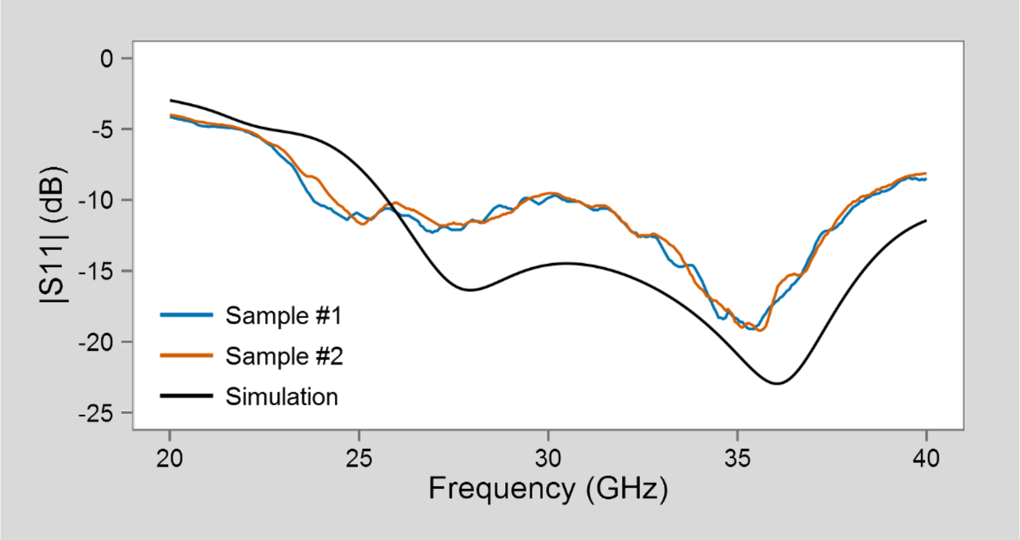
Mm-Wave SoP Antenna Integration



- Use inkjet-printed interconnects to **directly interface** IC die with SoP antenna
- Minimize system complexity, interconnect length, and transmission losses

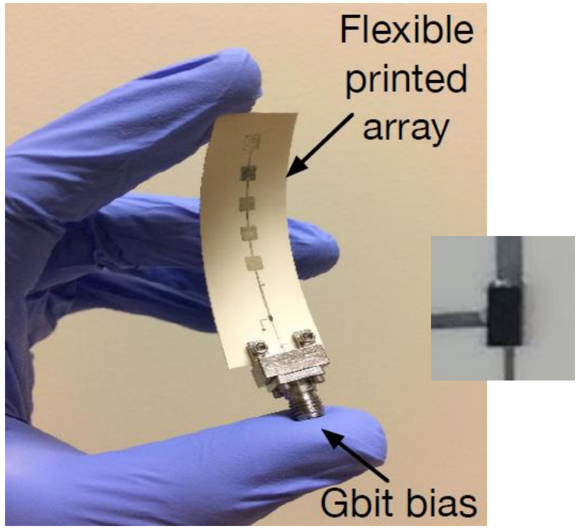


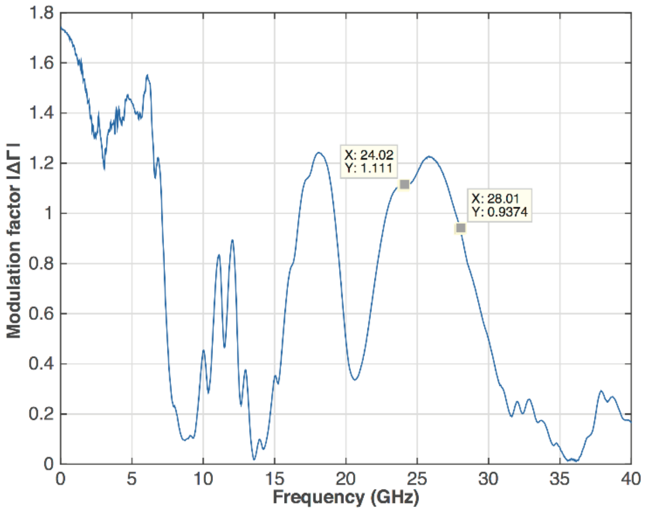




- Wideband CPW-fed bowtie antenna covering 23–40 GHz using glass as RF substrate
- Multilayer printing allows for **isolation from packaging substrate** in future efforts

Gbps Millimeter-wave Backscatter





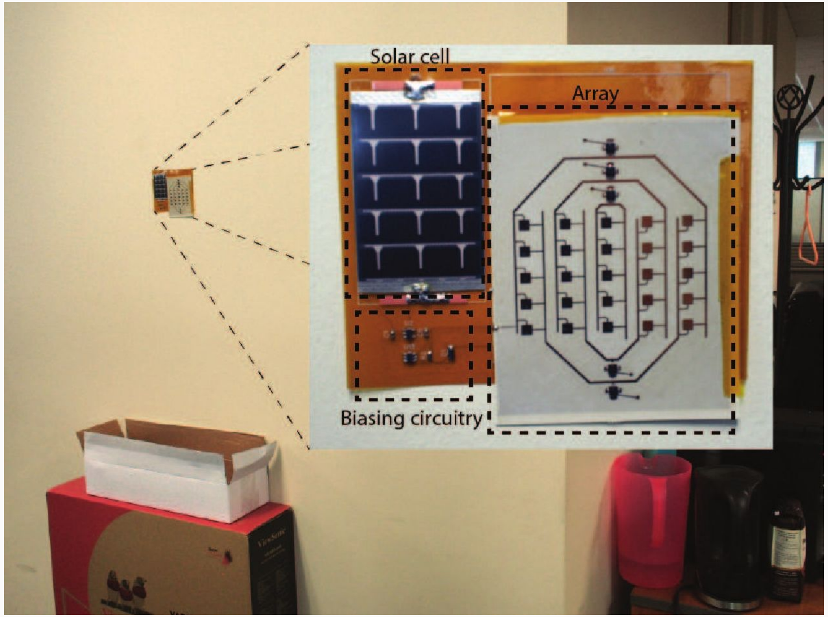
- Printed **flexible** 24-28 GHz tag
- Ultra low-loss substrate
- **First time reported Gigabit** backscatter data rates (> 4 Gbps)
- Extreme energy efficiency < 0.15 pJ/bit
- **3-4 orders of magnitude** beyond current RFIDs

J. Kimionis and M.M. Tentzeris, “Millimeter-wave Backscatter: A Quantum Leap for Gigabit Commu- nication, RF Sensing, and Wearables,” in IEEE MTT-S International Microwave Symposium (IMS) 2017, Honolulu, HI, USA, Jun. 2017.

S. Daskalakis, J. Kimionis, A. Collado, M.M. Tentzeris, and A. Georgiadis, “Ambient FM Backscattering for Smart Agricultural Monitoring,” in IEEE MTT-S International Microwave Symposium (IMS) 2017, Honolulu, HI, USA, Jun. 2017.

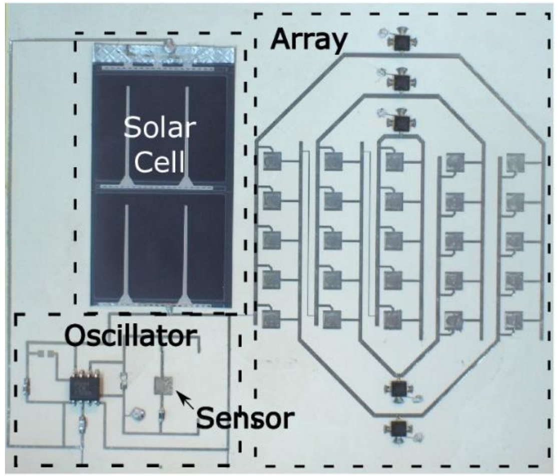
The Internet of Skins

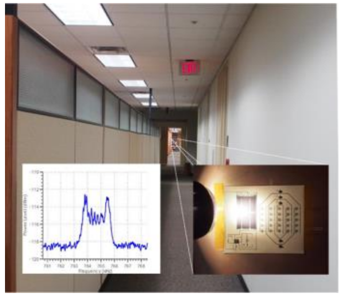
- Flexible device: the Skin
- Ultra-low-power: 20 μW
- Battery-less: Energy Harvesting
- Long-range: 250m to 1km
- Localizable in real time: single-reader localization (AoA+range)
- Metal-mounting compatible.

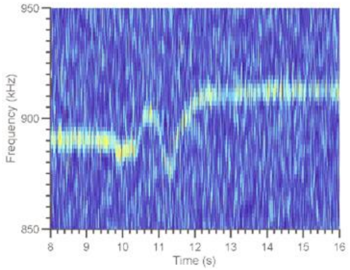


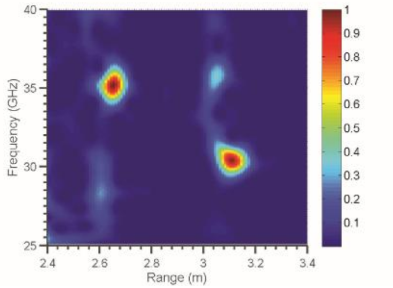
Printed, flexible, backscatter-modulation Van-Atta sensor km-Range "patch" structure

- Active backscatter-modulation Van-Atta
- All the advantages of the passive Van-Atta + non-linear response
- Enables this new structure with
  - Ultra-long-range reading capabilities (up to several kilometers)
  - Outdoor or indoor energy autonomy with solar cell:
    - Ultra-low power consumption (200uW)
  - Almost immediate integration of any of our printed gas sensors
    - Several on the same platform, in the future
    - Great resolution (below 0.5m)



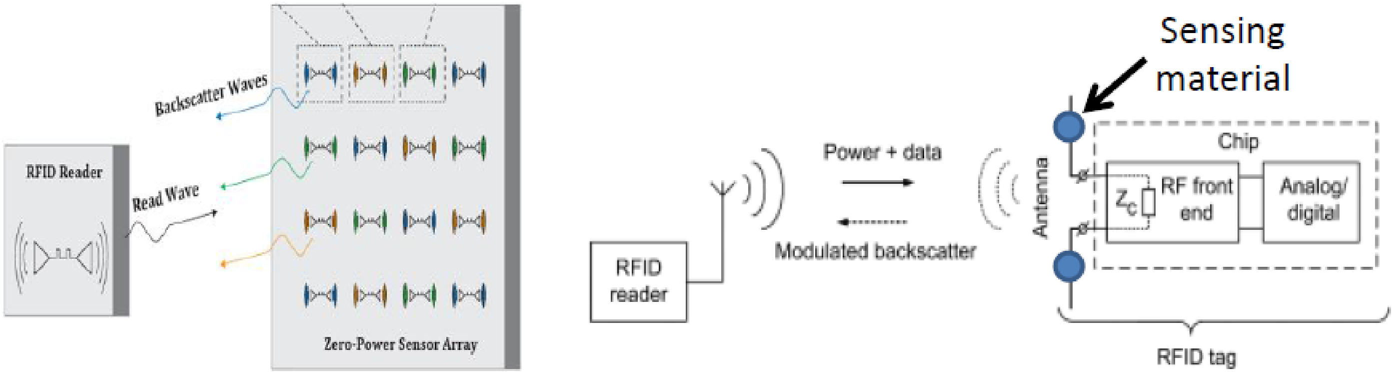






J.Hester and Manos M. Tentzeris, "A mm-Wave Ultra-Long-Range Energy-Autonomous Printed RFID-Enabled Van-Atta Wireless Sensor: at the Crossroads of 5G and IoT", *IEEE International Microwave Symposium (IMS)*, 2017, accepted

Smart Computational Skins

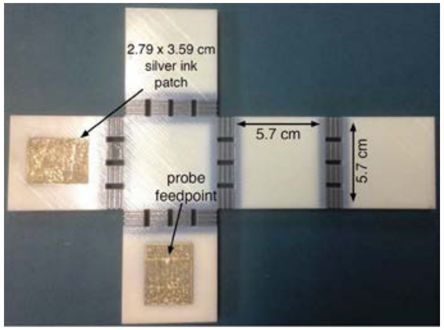


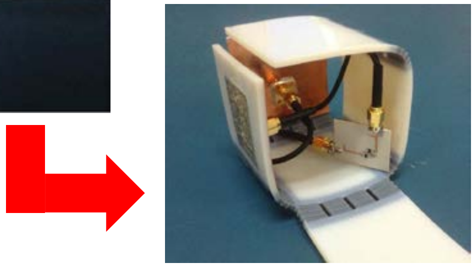
< RFID-based wireless sensor system >

- Array of nanomaterial-based sensors
- Ubiquitous coverage with few readers
  - Low cost compared to equivalent system using standard sensors
- Many applications: gas sensor, strain sensor, etc.

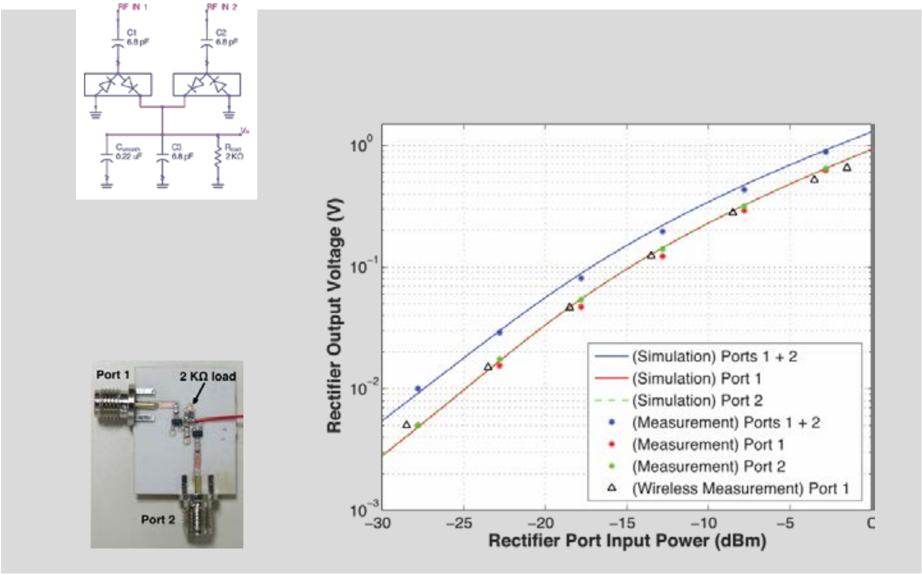
Printed Origami-Enabled Sensor

- 3D printing fabricates foldable cube package, inkjet printing fabricates metallic patch antennas
- SMP (TangoBlack/VeroWhite blend) hinges exposed to thermal treatment (50~60 °C) allowing for folding and shaping, holds shape when returning to ambient

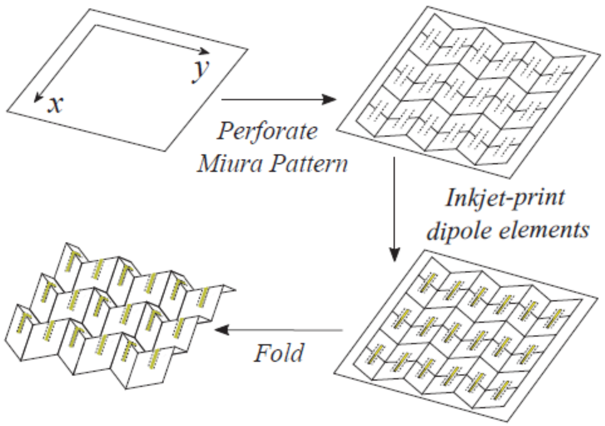




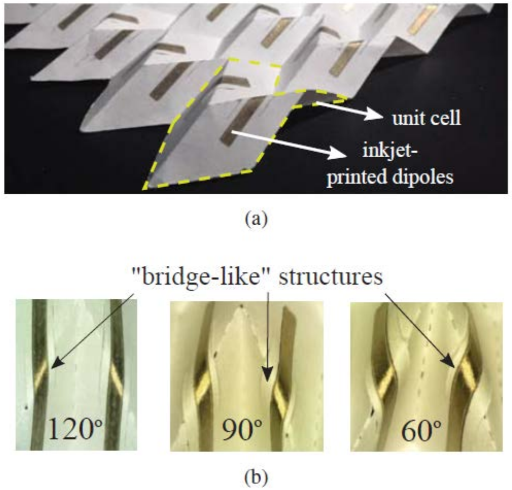
Multi-Port Wireless Harvesting



Fabrication process and prototypes



Fabrication process

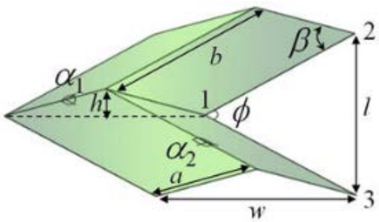


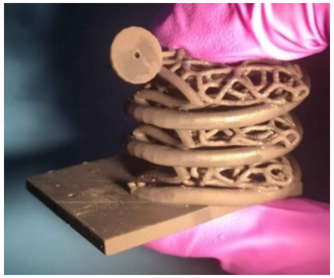
(a) Folded Miura-FSS (b) close-up of dipole elements with different folding angle ϑ.

- Special “bridge-like” structures increases the flexibility of the conductive traces
- Uniform folding angle is ensured by using specially designed 3D-printed frames

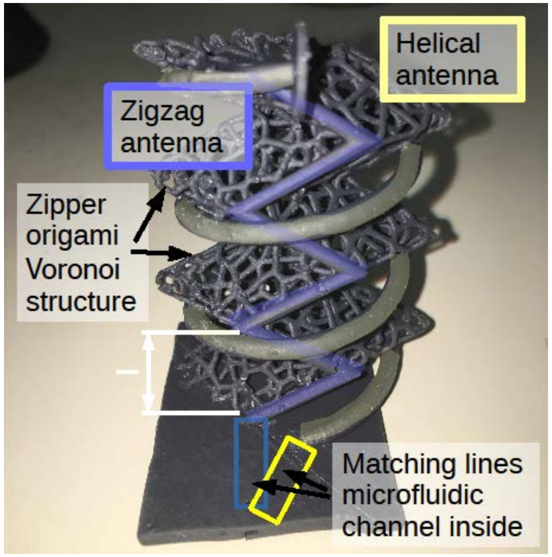
Origami Reconfigurable Antenna “Trees”

- First-of-its-kind antenna integration topologies
- Origami scaffold structure
  - Mechanical tuning
- Liquid metal
  - Reconfigurable
- Dual antennas system with minimal interference
  - Helical antenna
  - Zigzag antenna
- 3D SLA printed
- Flexible/foldable





Comp.



Wenjing Su, Ryan Bahr, Syed Abdullah Nauroze, and Manos M. Tentzeris, “Novel 3D printed Liquid-metal-alloy microfluidics-based zigzag and helical Antennas for Origami Reconfigurable Antenna “Trees””, *IEEE International Microwave Symposium (IMS)*, 2017, accepted

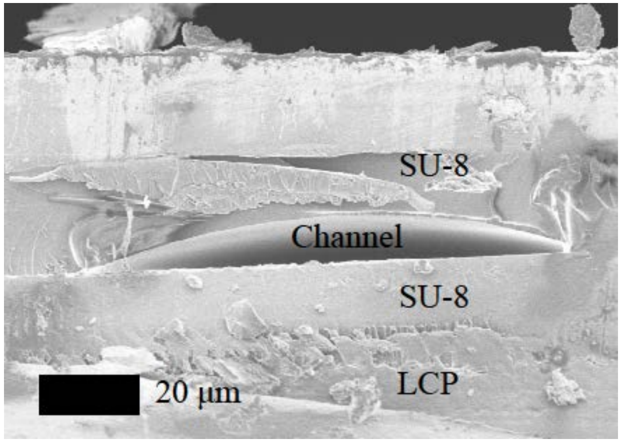
Inkjet-Printed Soil Moisture and Leaf Wetness Sensor

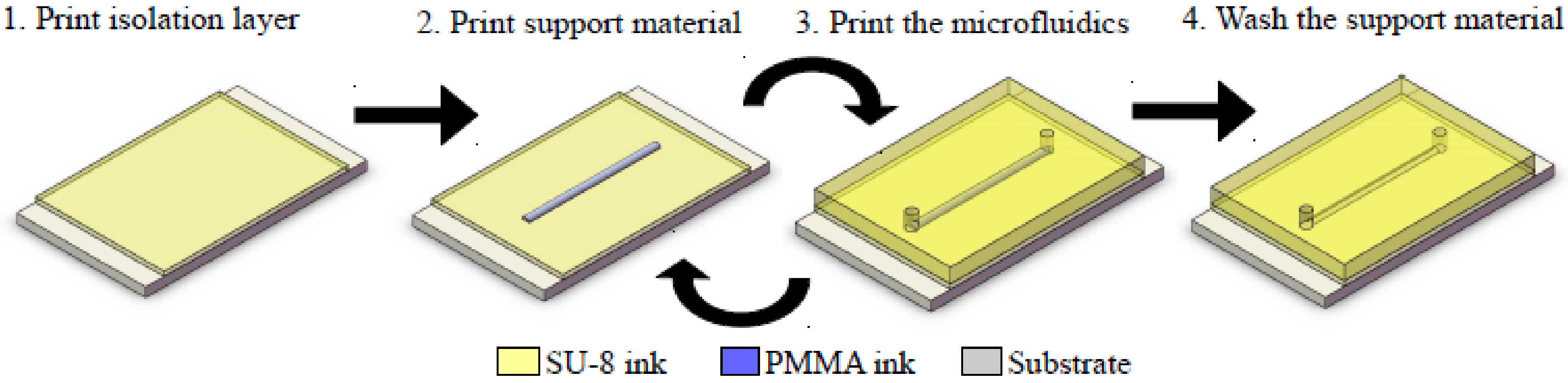
Features:
Inkjet-printed capacitive sensor for soil moisture and rain detection

Applications:
Irregation optimization, quality control of high-value fruit, and land-slide detection in mountains

Inkjet-Printed Microfluidics

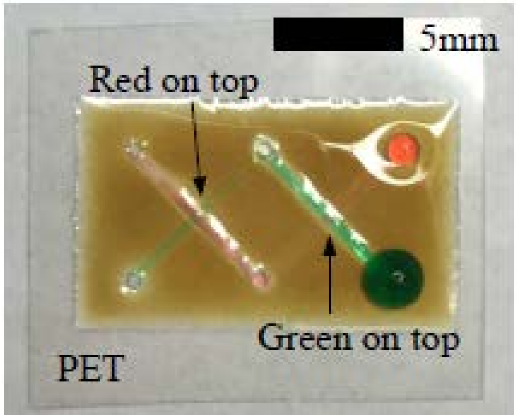
- Use inkjet-printed channels to achieve microfluidics cooling, etc.
- The process can be used in constructing various 3D micro structures

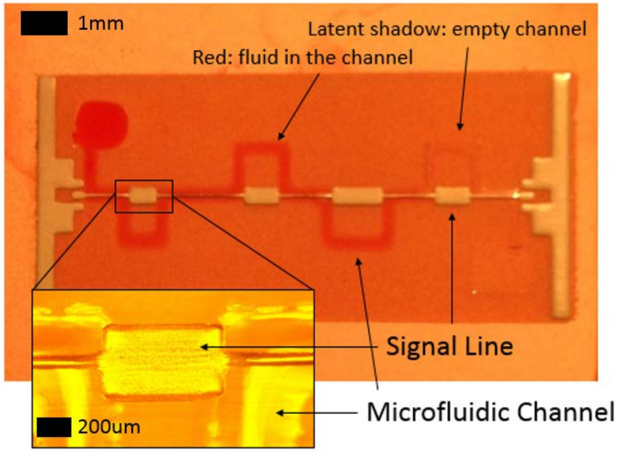


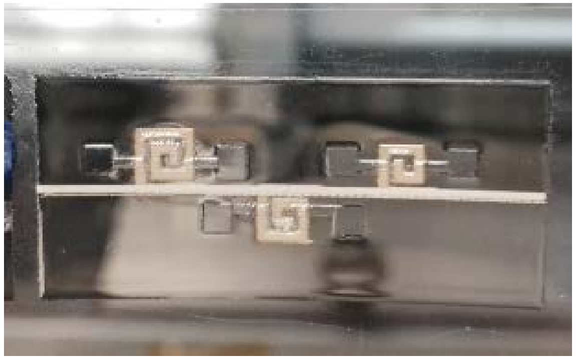


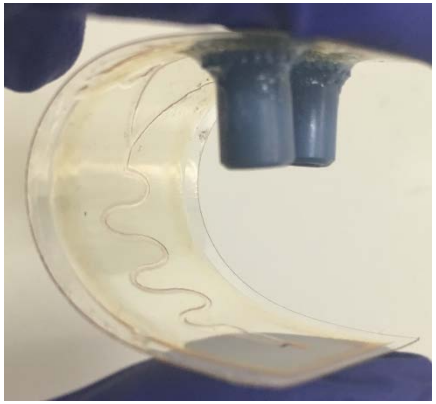
Inkjet-Printed Microfluidics

- Small channel down to 60 um*0.8 um
- Flexible
- On virtually any substrate (e.g.glass)
- Tunable microwave structures

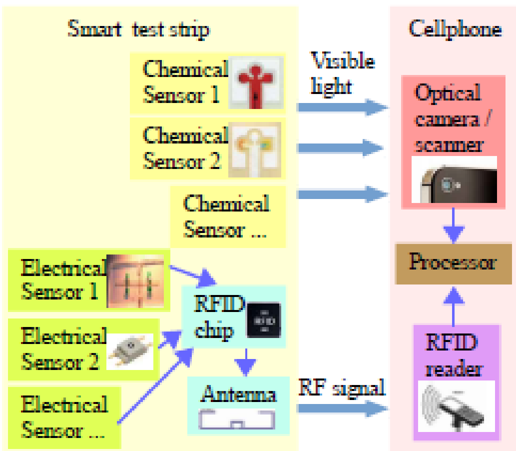


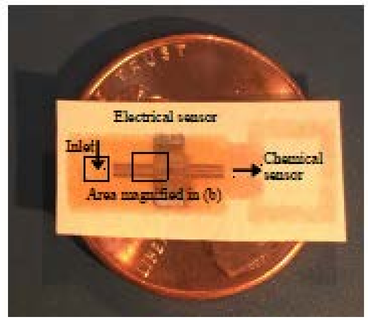


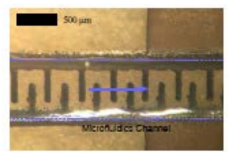


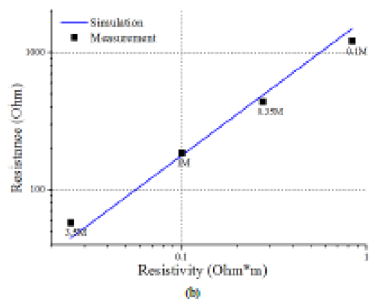


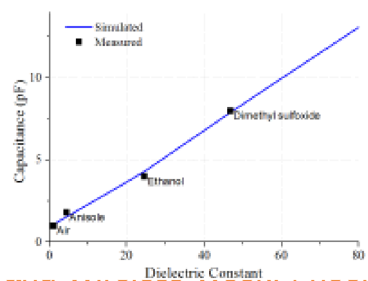
Smart Test Strips through Inkjet-Printed Microfluidics

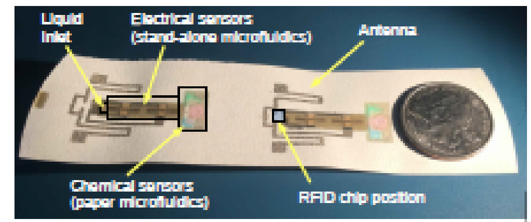




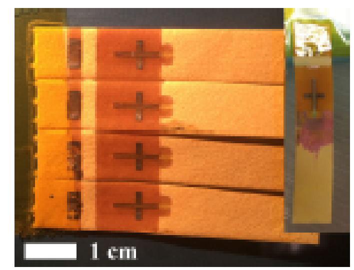




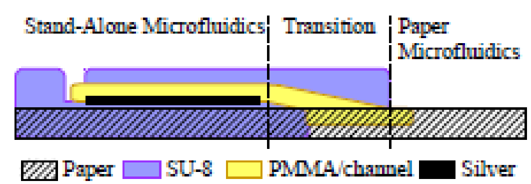


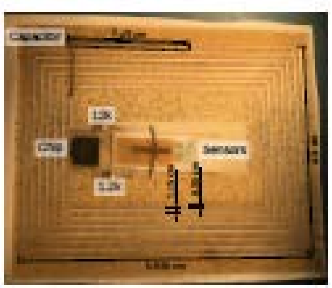


(a)



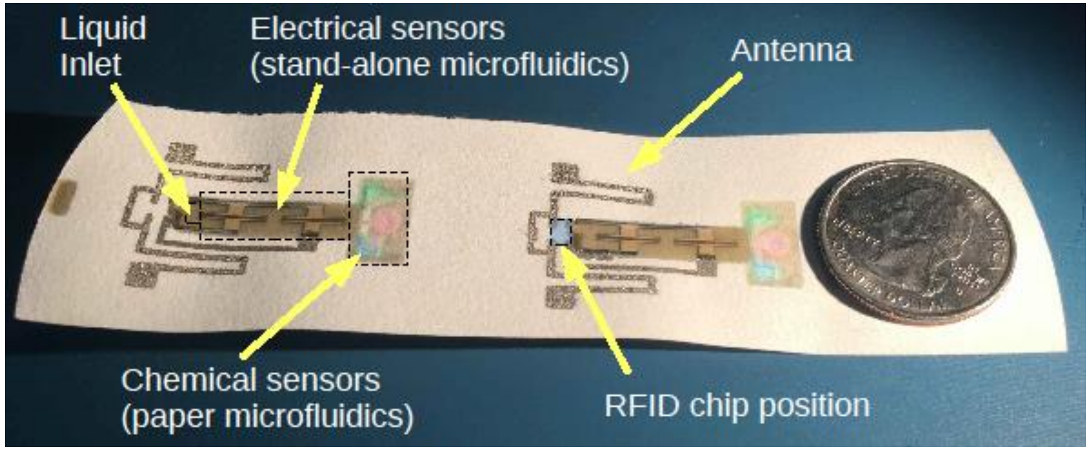
(b)

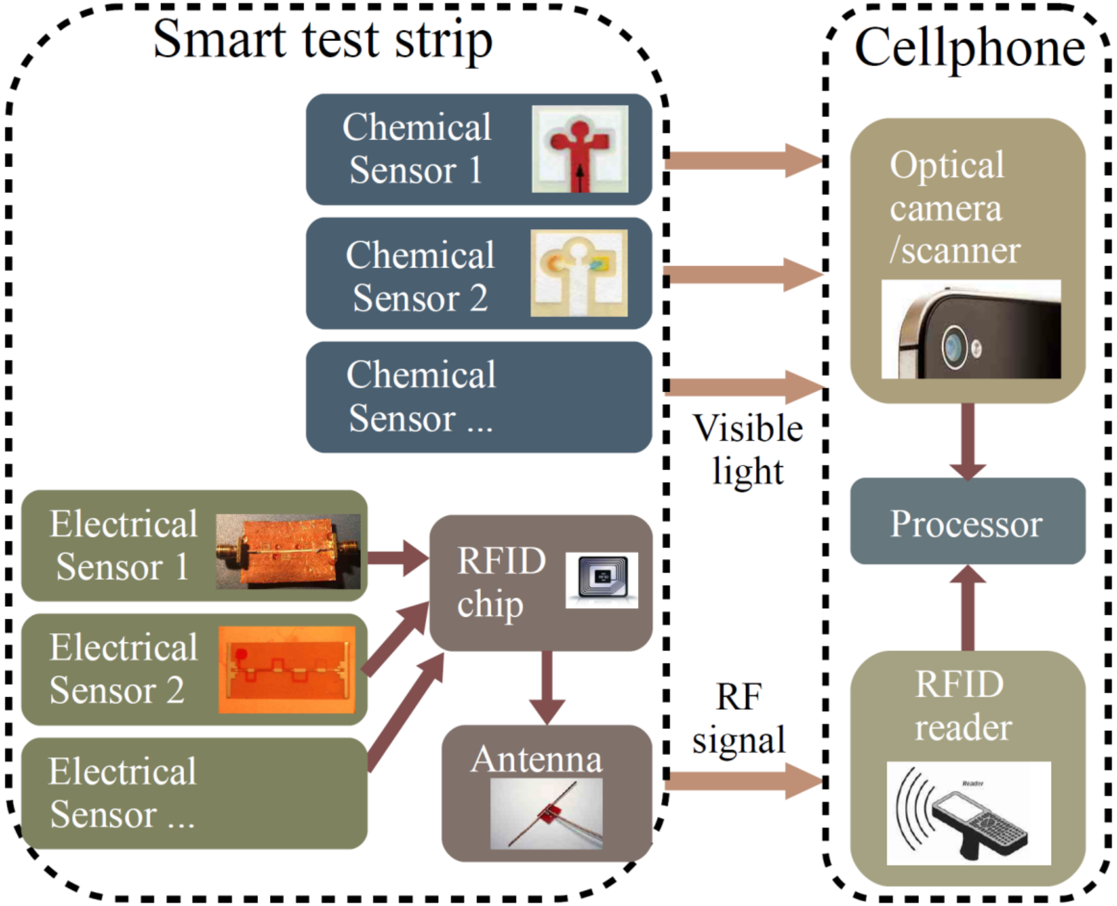




Smart Test Strip

- First-of-its-kind platform for wireless comprehensive liquid sensing
- RFID + paper-microfluidics
- Portable diagnose





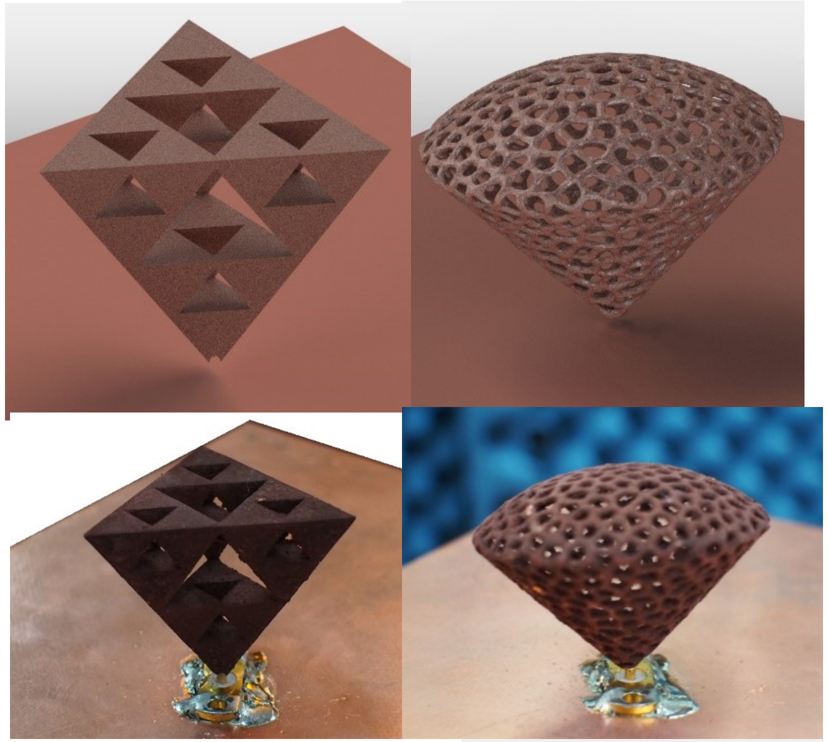
Liquid metal alloy (LMA)

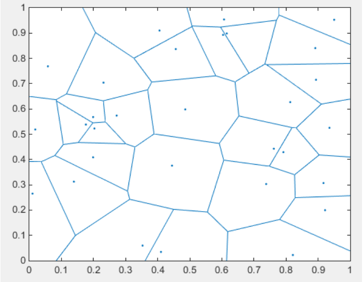
- Work with 3D printed microfluidic channels
- No failure point when folding
- EGaIn (75 wt % Gallium and 25 wt % Indium)
  - Conductivity: 3.4483e6 S*m (1/17 of bulk copper)
  - Flexible/stretchable
    - Melting point: $15.5^{o}C$
  - Flowable
    - Viscosity: 1.9910 mPa*s (2x of water, 1/4000 of ketchup)
  - Non-toxic
  - NaOH to avoid oxidation skin

<https://www.youtube.com/watch?v=jow4idr6HNs>

Mathematically Inspired 3D printing

- Modified Surface for improved electroless deposition of pure copper
- Voronoi Tessellation
  - Leads to low cost, easily applicable to any design for exposed sensors
- Fractal 3D Antenna
  - Near impossible to fabricate without additive manufacturing (AM).
  - Demonstrates multiple resonances for a multi-band antenna

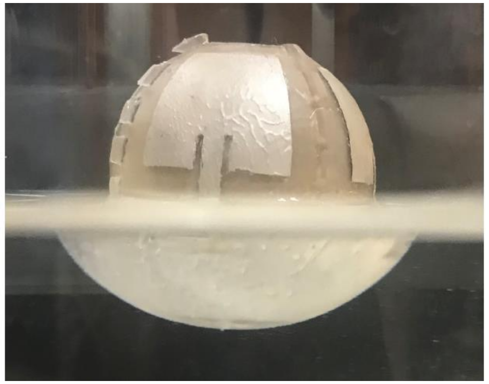


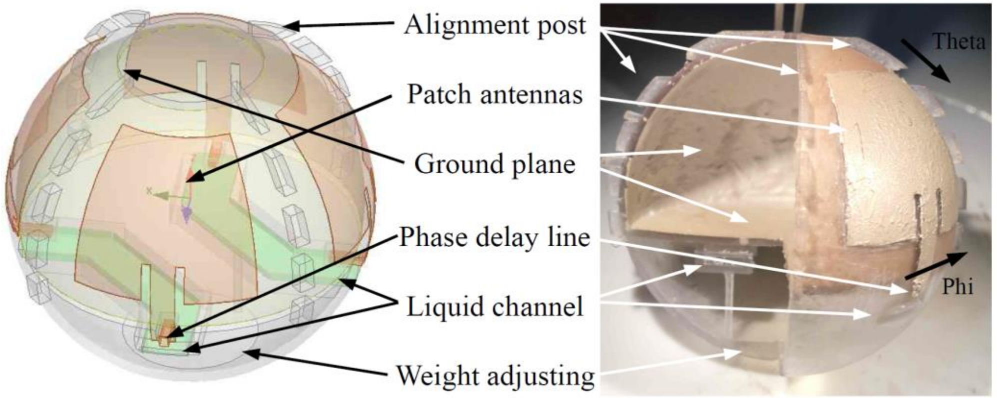


(Left Column) Fractal Antenna. (Right Column) Voronoi based Inverted feed discone antenna.

Smart Floating Balls

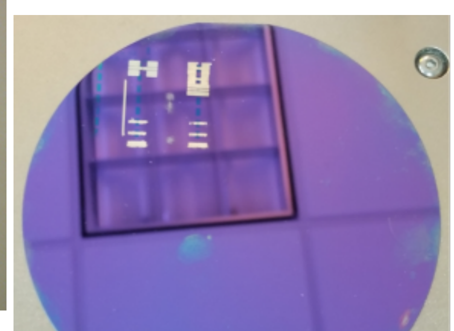
- Phase configuration chipless RFID
- Shadowing balls to save water by reducing evaporation in reservoirs
- Water quality monitoring for contamination, such as oil and gas wastewater (low permittivity)





Inkjet Printed RF Switches

- CNTs have (ideally) >10000 cm^2/Vs hole mobility
- Previous work has been demonstrated in fabrication of RF circuits/switches
- Comes in aqueous solution, “printable”



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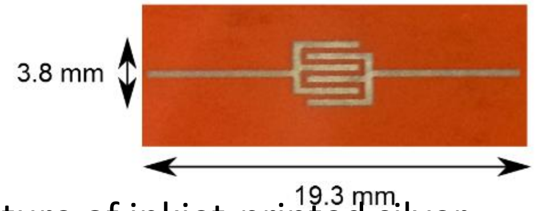
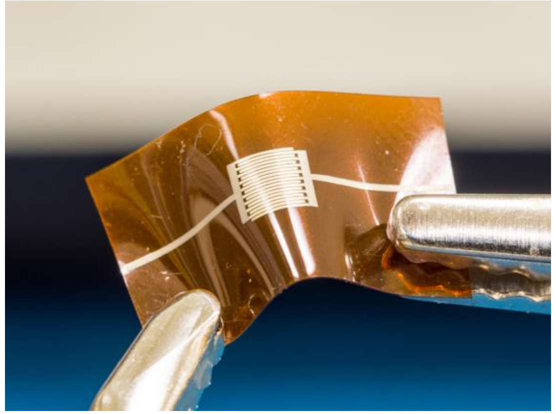
Wireless CNT-Based Gas Sensors

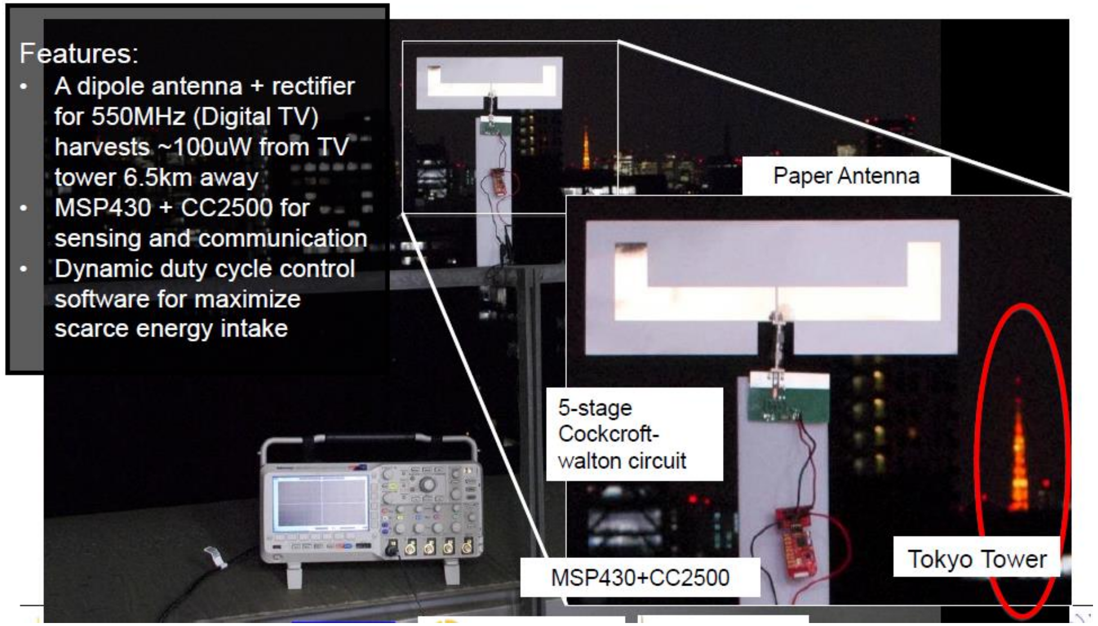
- Printing of 5 to 30 layers of CNT ink
- Drying at 100°C for 10 hours, under vacuum
- Chemical functionalization of film
- Printing of electrodes with silver nanoparticle ink (SNP)
- Drying and sintering at 110°C for 3 hours

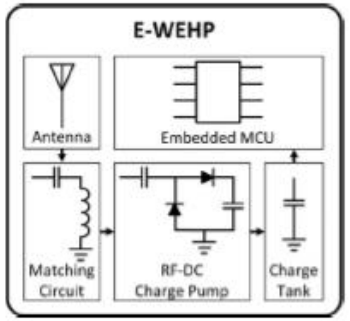


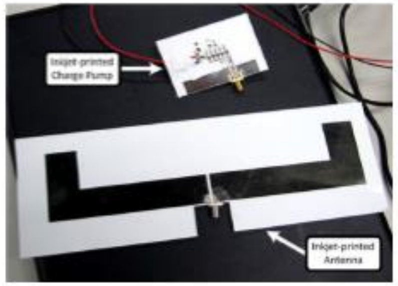
Picture of inkjet-printed silver electrodes



Additively Manufactured Ambient Long-Range RF Energy Harvester



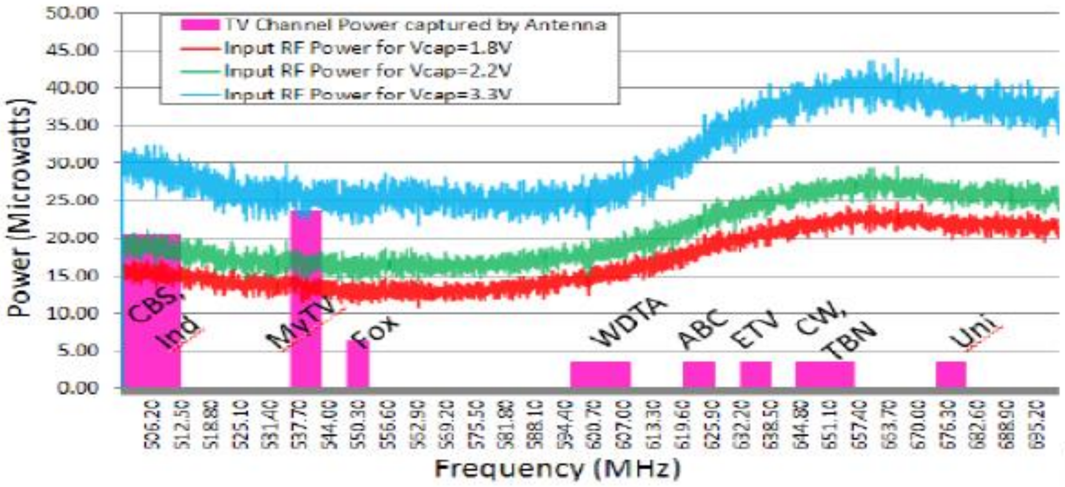




R.J.Vyas, B.Cook, Y.Kawahara and M.M.Tentzeris, ``E-WEHP: A Batteryless Embedded Sensor Platform Wirelessly Powered from Ambient Digital-TV Signals", IEEE Transactions on Microwave Theory and Techniques, Vol.61, No.6, pp.2491-2505, June 2013.

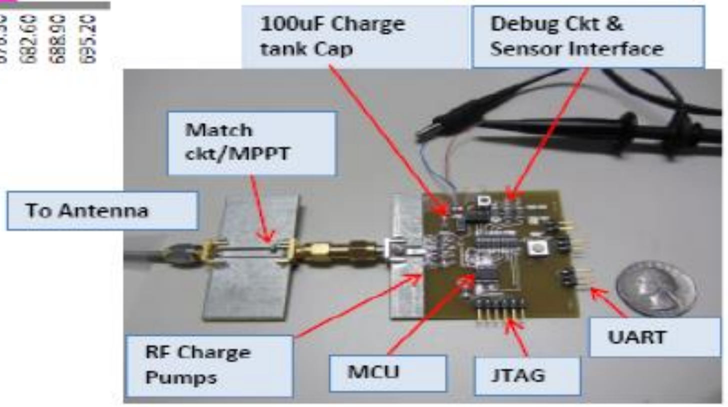
S.Kim, R.Vyas, J.Bito, K.Niotaki, A.Collado, A.Georgiadis and M.M.Tentzeris, ``Ambient RF Energy-Harvesting Technologies for Self-Sustainable Standalone Wireless Platforms", Proceedings of IEEE, Vol.102, No.11, pp.1649-1666, November 2014.

Energy Harvesting circuit to capture power from air



- **EH Circuit performance**
- 12 μ-watts of wireless power -> 1.8V DC out
- 17 μ-watts of wireless power ->2.2V DC Out
- 25 μ-watts of wireless power -> 3.3V DC out

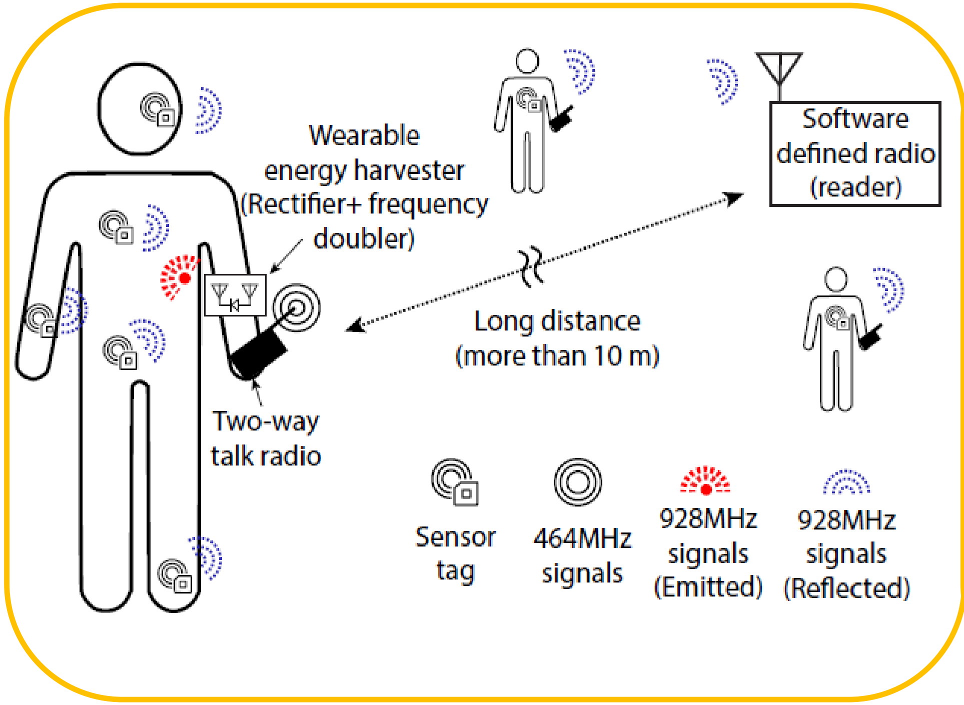
- **EH Circuit design includes:**
  - Converts microwatts of wireless power to over 3V of DC output signal
  - No batteries - Uses Capacitor to wireless power
  - Powers up microcontroller for power management and sensing applications



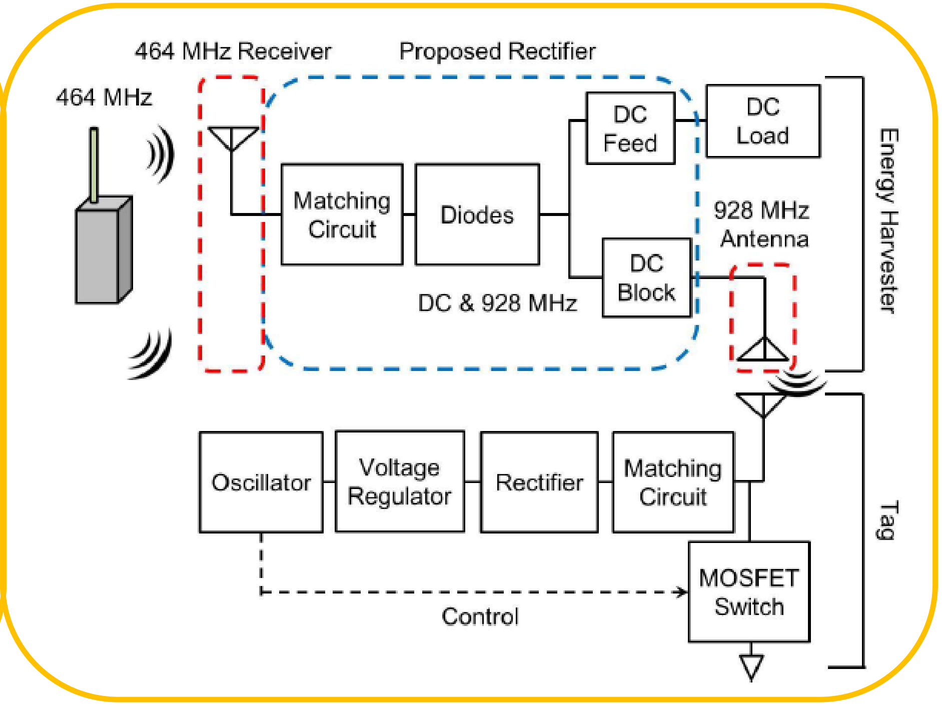
- R.Vyas, B.Cook, Y. Kawahara, M. Tentzeris. *"EA Self-sustaining Autonomous Wireless Sensor Beacon Mote Powered from Long Range, Ambient RF Energy"*, accepted to IEEE International Microwave Symposium, 2013

Wearable Energy Harvester RFID-Based On-Body Autonomous Sensing Network

Autonomous Sensing Network



System Architecture



- ➢ Wearable energy harvester harnessing RF energy from 464 MHz two-way radio
- ➢ Provide two output energy source: DC power and 928 MHz signal beacon
- ➢ DC application: drive amplifier, drive IC chips, wearable reader
- ➢ RF application: Illuminate wearable RFID and sensors to extend sensing range