Additively Manufactured Wireless Sensors for Rugged IoT, Structural Health Monitoring, Smart Agriculture and Smart Cities Applications

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ATHENA

COSMOS

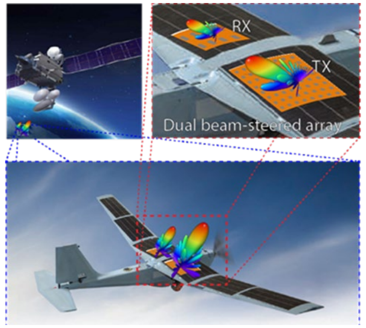
Computational Skins for Multifunctional Objects and Systems

Sticky Notes

Notes can communicate their contents and location with each other and with the objects they are mounted on.

Food Packaging

Cartons and wrapping can sense the volume and chemical composition of their contents and relay this information to the refrigerator.

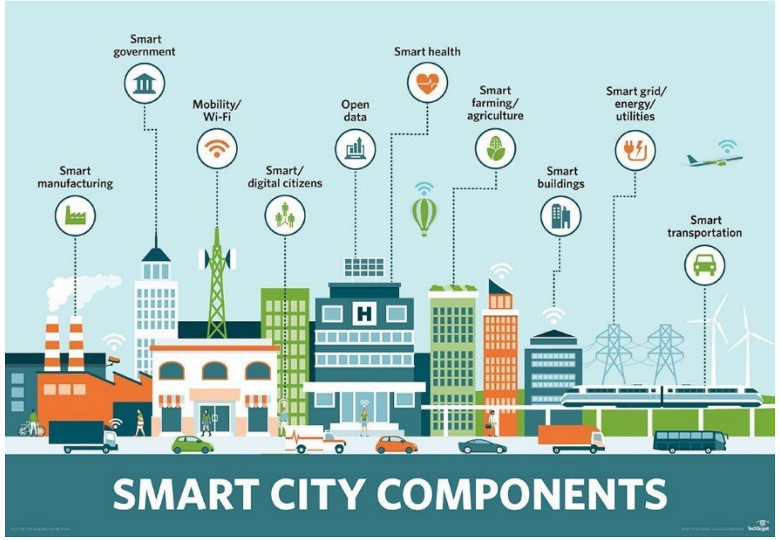


Computational Skins

Arrays of dense, high performance, seamlessly networked, ambiently-powered computational nodes that are embedded in everyday objects.

Fabrics

Couch cushions can sense biosignals (i.e., sweat, heart rate, posture, etc.) and communicate relevant information to the floor beneath.



Tissues

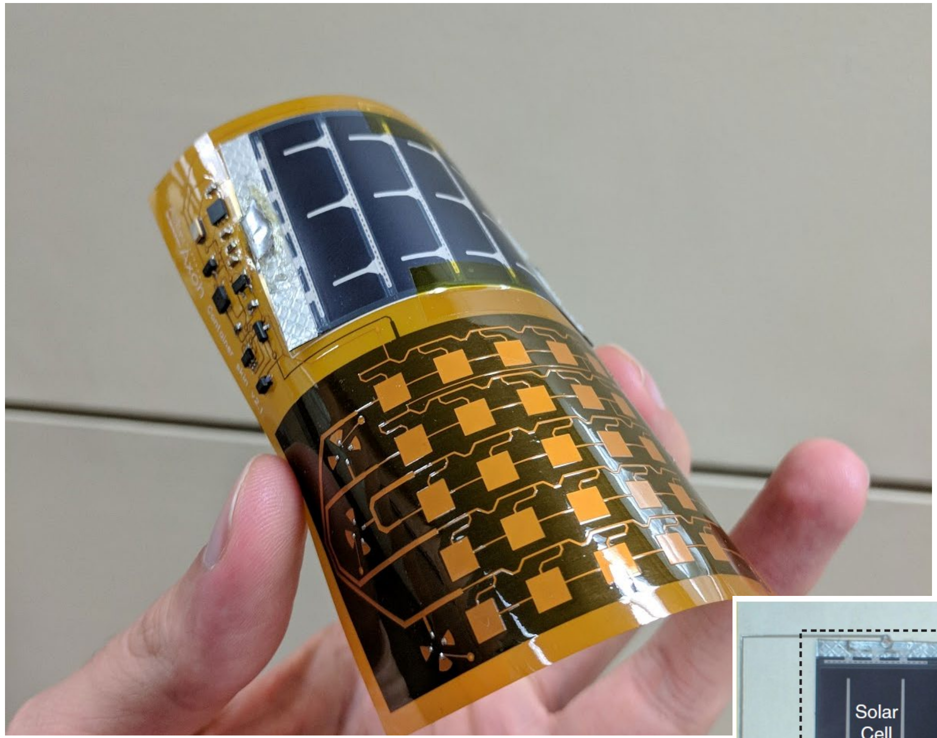
Tissues can sense health-related information during use (i.e., virus identity, load, etc.) and communicate with the wastebasket upon being discarded.

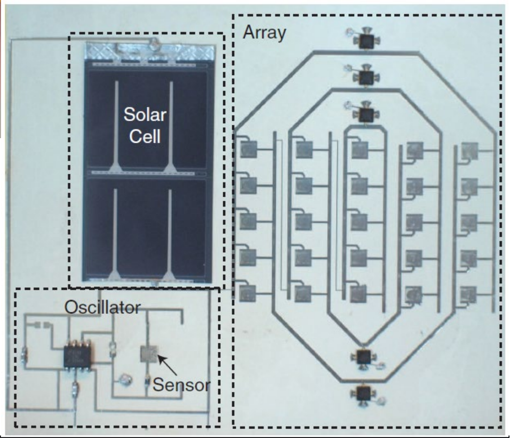
Floors and Walls

Floors and walls can communicate with each other, localize other computational skins in the room, and track human motion. Their inherently large area is ideal for energy harvesting.

The Internet of Smart Skins

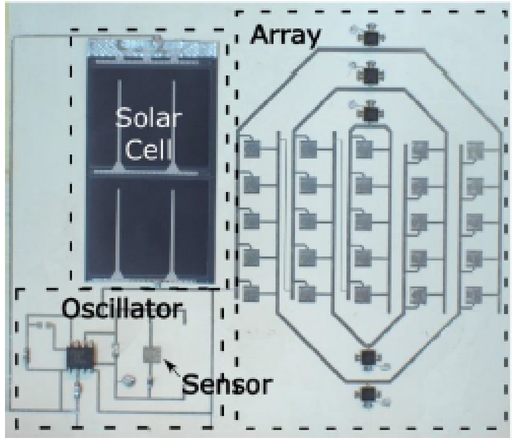
- Thin, Flexible device: the Skin
- Ultra-low-power: <20 μW
- Battery-less: Energy Harvesting
- Long-range: 250m+
- Localizable in real time (**cm accuracy**): single-reader localization (Angle+range)
- Metal-mounting compatible
- Enhanced by 5G+/6G.

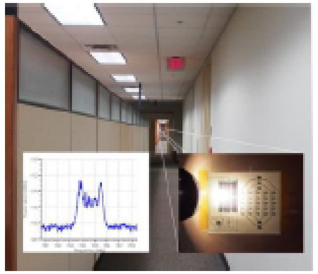


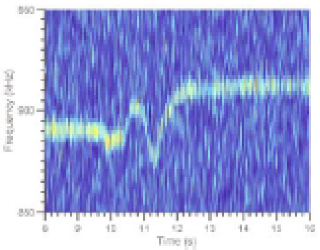


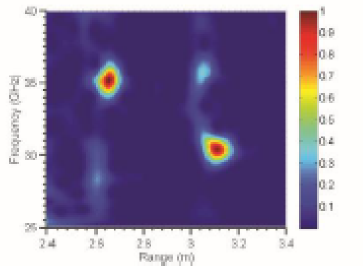
Printed, flexible, backscatter-modulation Van-Atta sensor km-Range "patch" structure

- 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 (20uW)
  - Almost immediate integration of any of our printed gas sensors
    - Several on the same platform, in the future
    - Great resolution (below 0.5m)





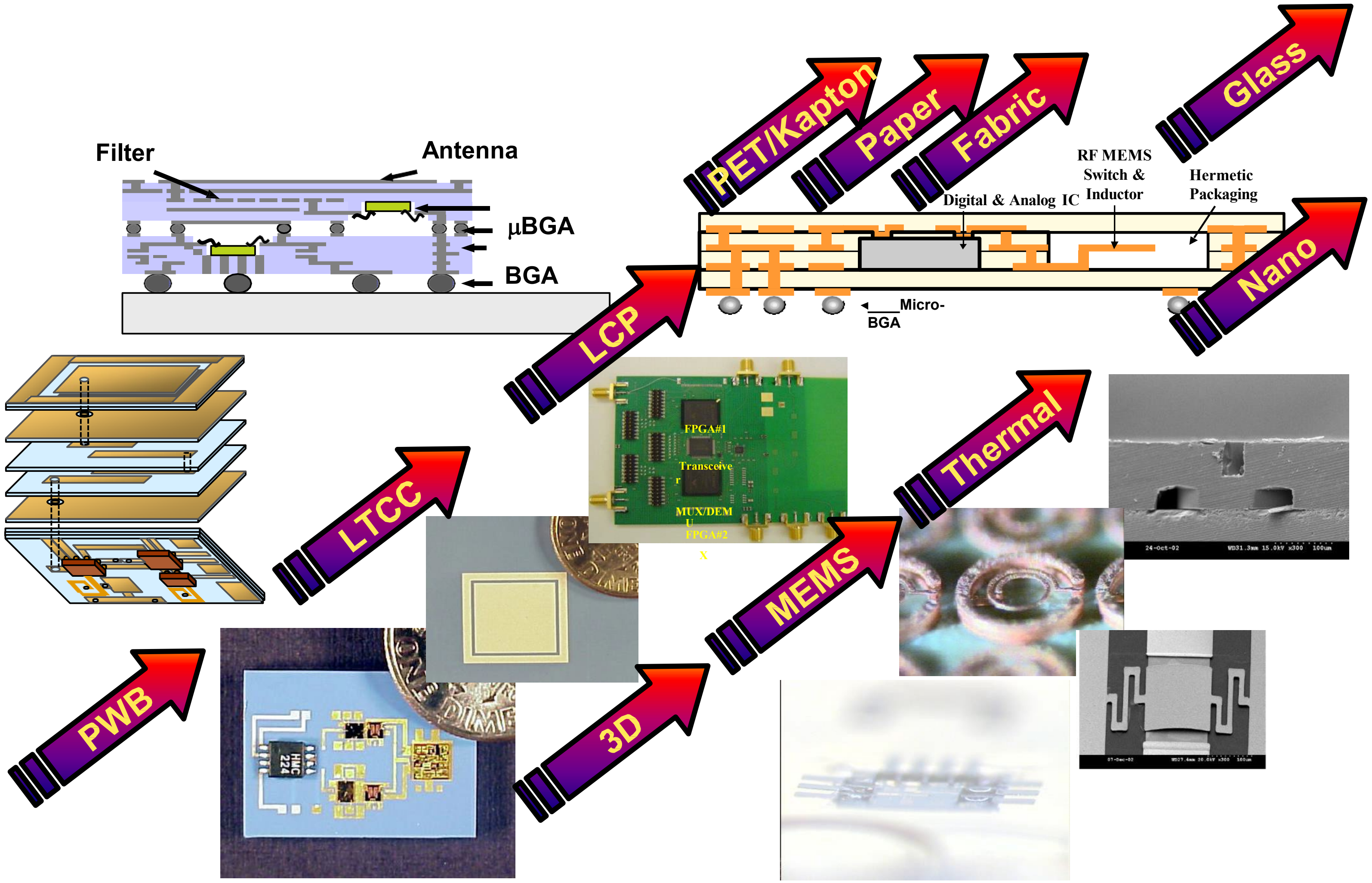




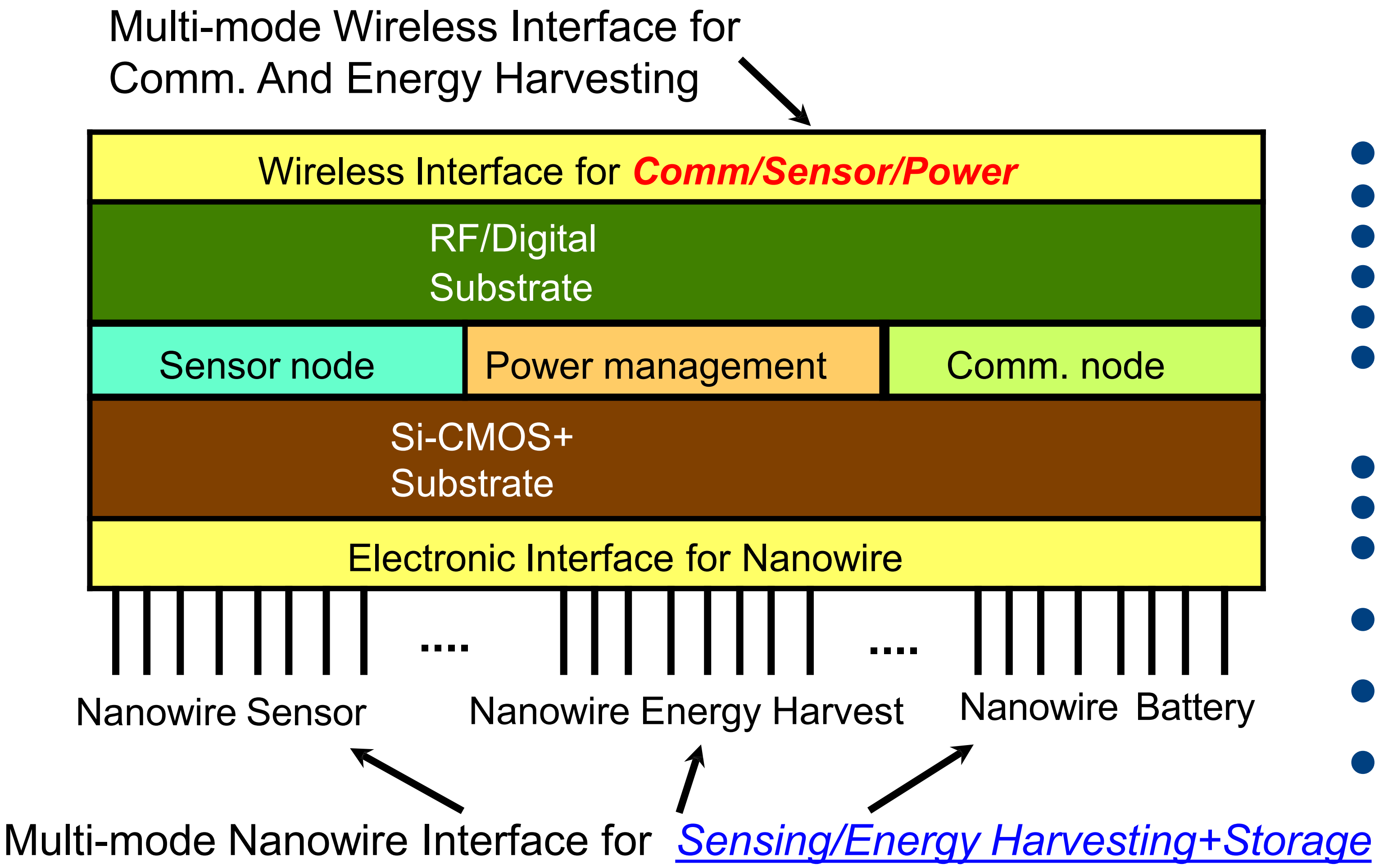
J.Hester and Manos M. Tentzeris, "A mm-Wave Ultra-Long-Range Energy-Autonomous Printed RFID-Enabled Van-Atta Wireless Sensor: at the Crossroads of 5G and IoT", *IEEE International Microwave Symposium (IMS)*, 2017, accepted

J.Hester and M.M.Tentzeris, ``Inkjet-Printed Flexible mm-Wave Van-Atta Reflectarrays: A Solution for Ultralong-Range Dense Multitag and Multisensing Chipless RFID Implementations for IoT Smart Skinsâ€IEEE Transactions on Microwave Theory and Techniques, Vol.64, No.12, pp.4763-4773, December 2016.

Disruptive Wireless Modules Technological Steps



The "Tricorder" Challenge for IoT, Smart Ag and Smart Cities Platforms



- Range
- Miniaturization
- Data Rate
- Integrability
- Mass Scalability
- Smart Packaging

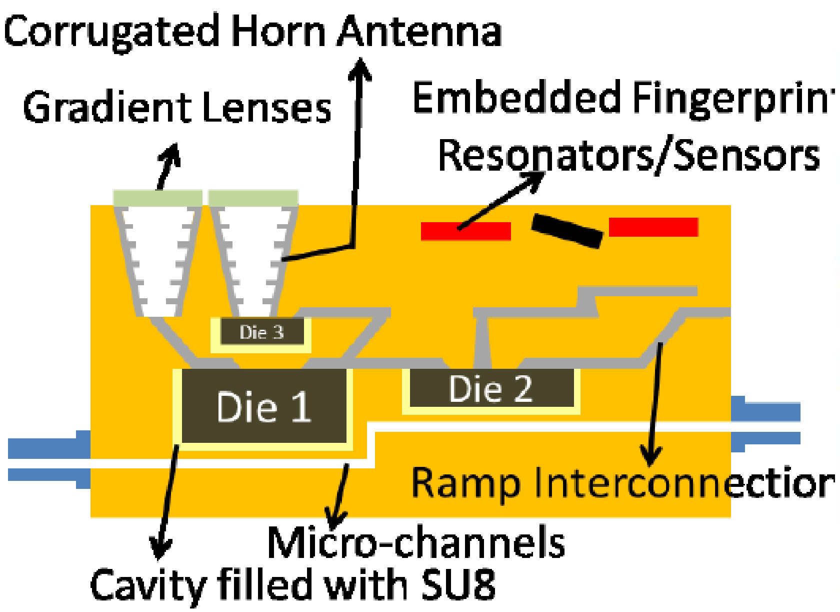
- Flexibility
- Power/Autonomy
- ID/Resolution

- Security

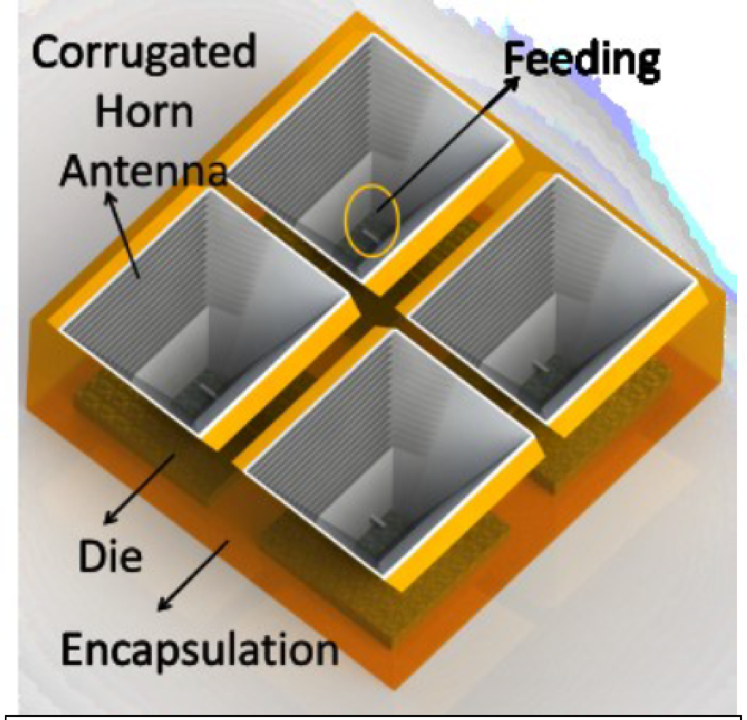
- EMI Immunity

- Anti-Counterfeiting

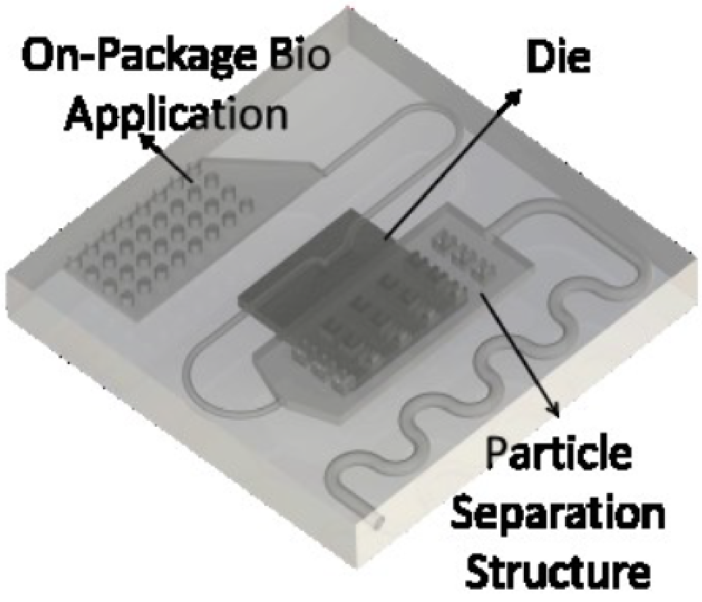
Vision: AM Smart Packaging and "Self-Healing" mmWave transceivers



Full smart package with multiple features.

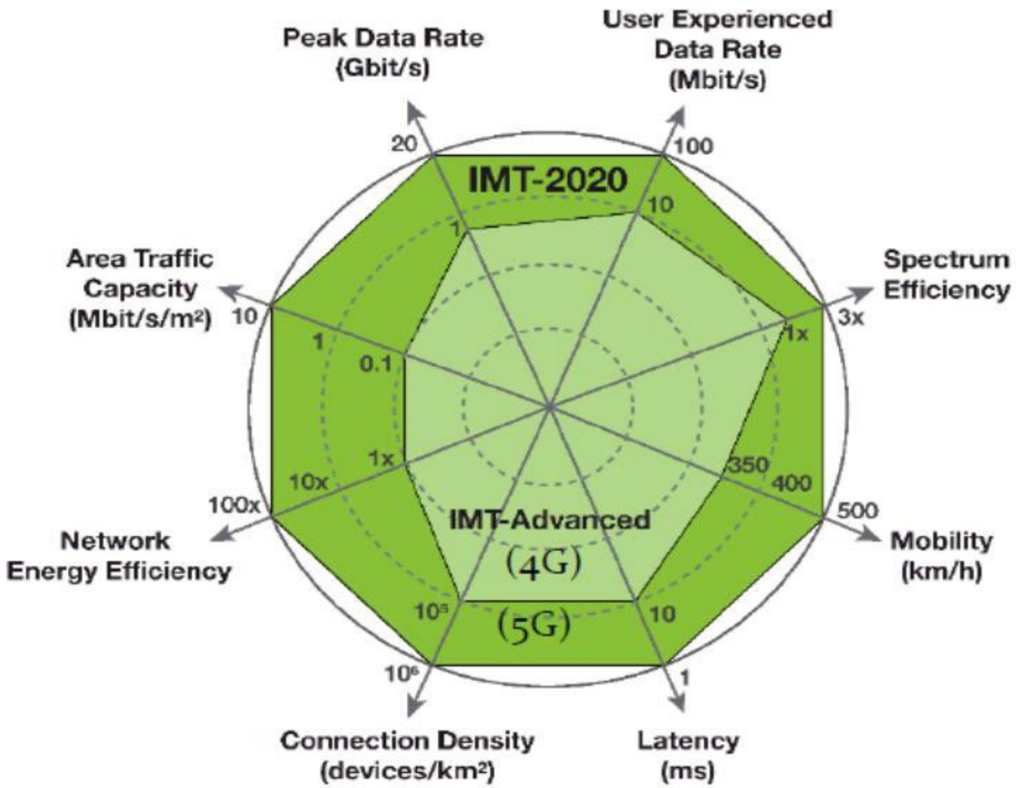


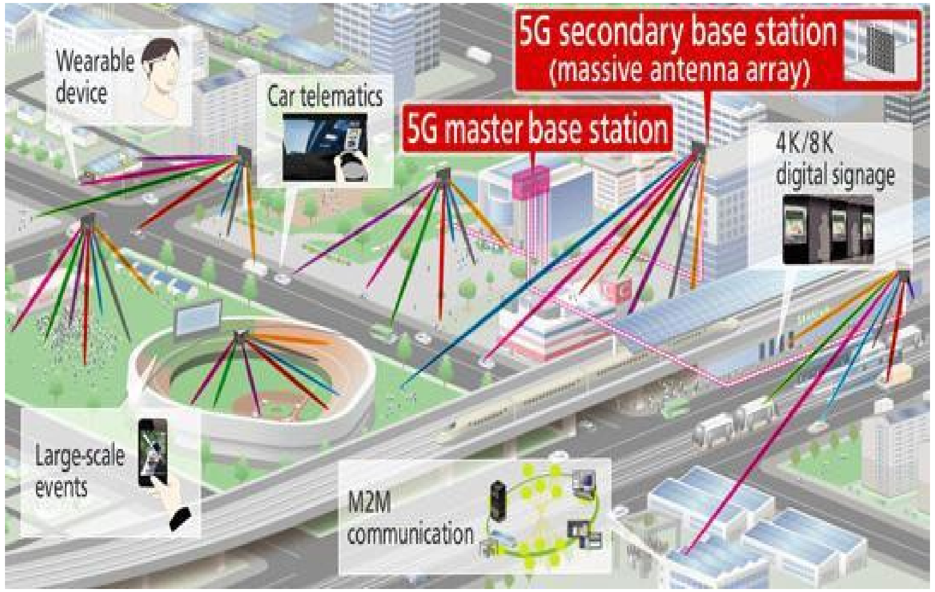
Horn antenna array integrated into MCM, for compact high gain mm-Wave transceivers.



Integration of BIOMEMS inspired structures for wearable and implantable wireless biosensors

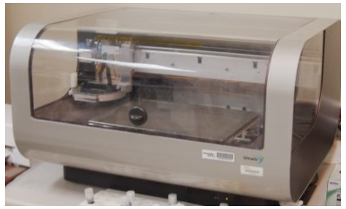
5G+ Networks: Enabling Ultrafast Ultrabroadband



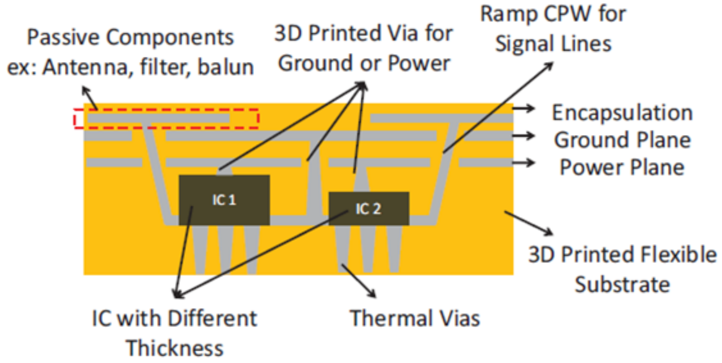


Additive Manufacturing Technologies: A Manufacturing Revolution

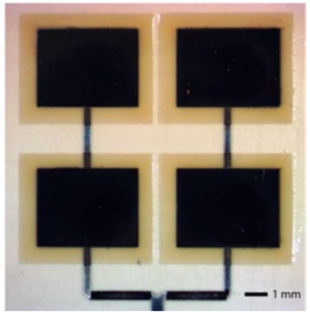
Additive Manufacturing technologies

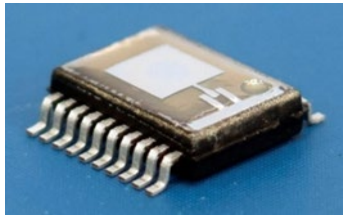


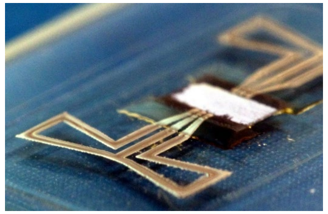
Inkjet Printing

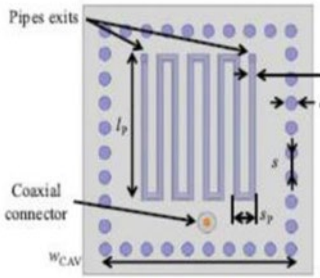


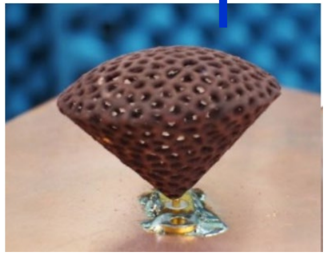
3D Printing

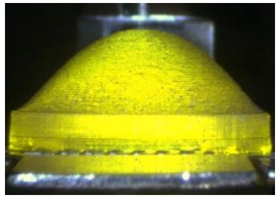


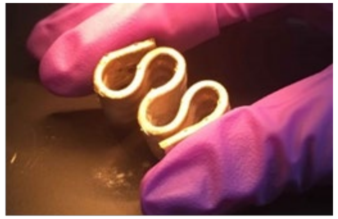


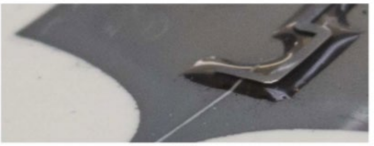


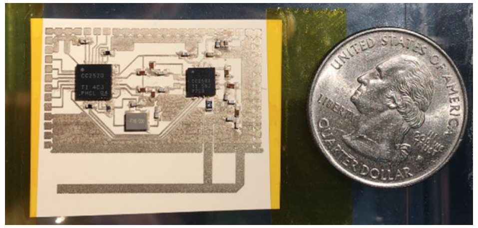


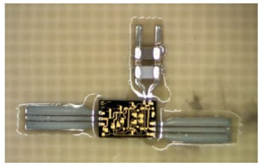


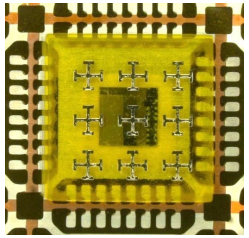


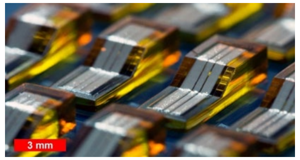


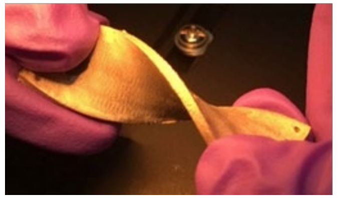




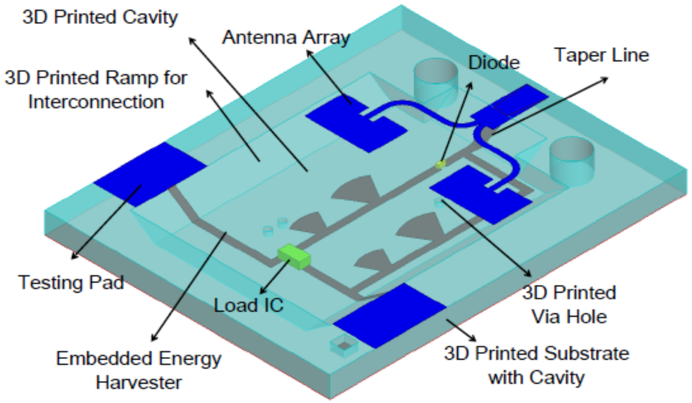


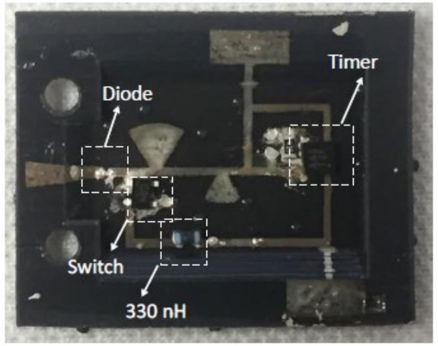




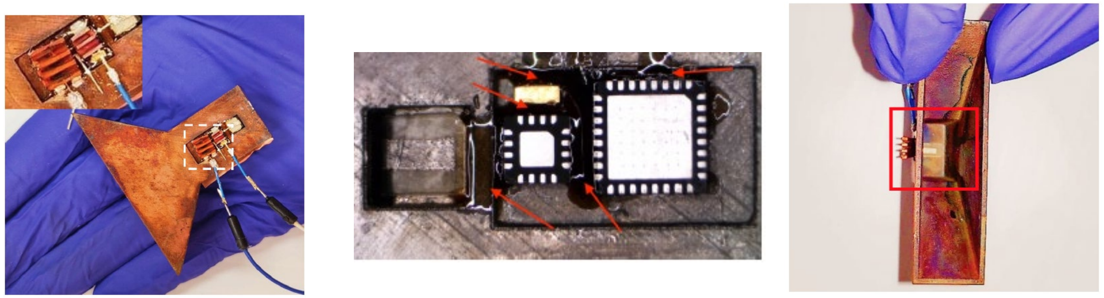


The First Fully Printed Autonomous Wireless Modules (IoT/5G)

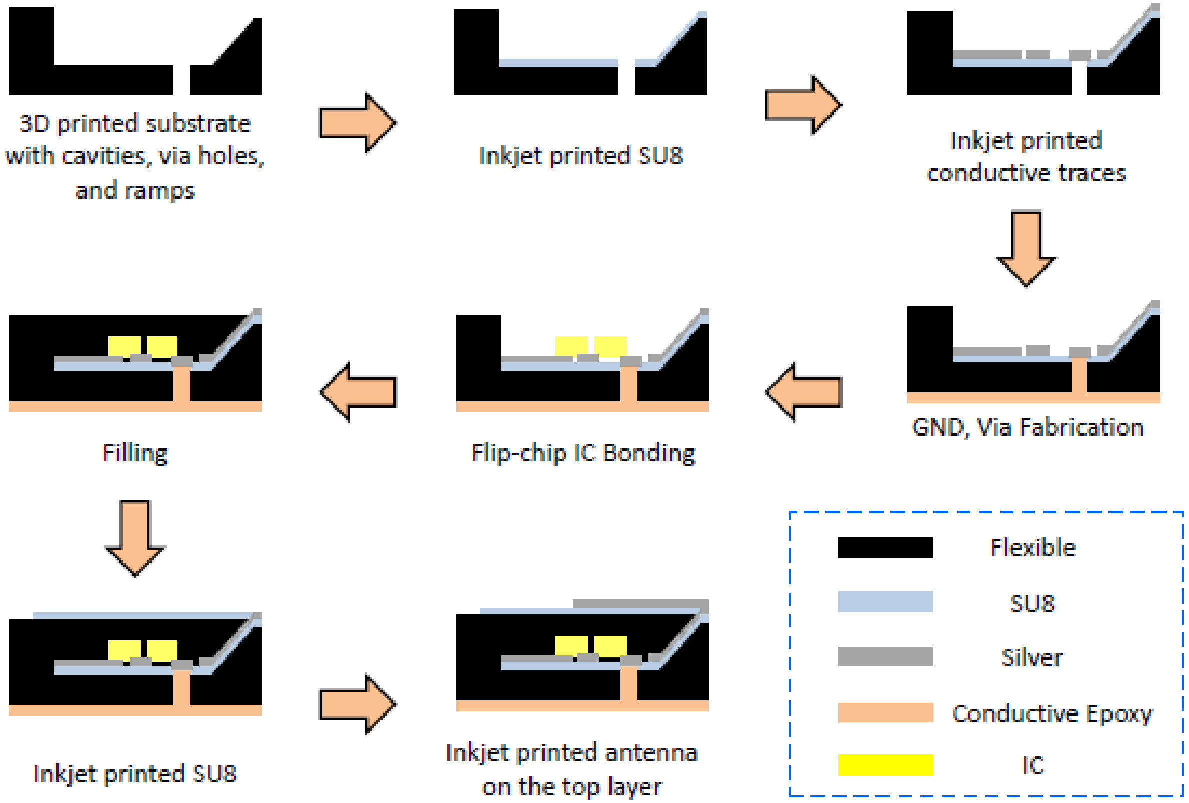




28GHz Backscatter RFID-enabled Sensing 5G/IoT module

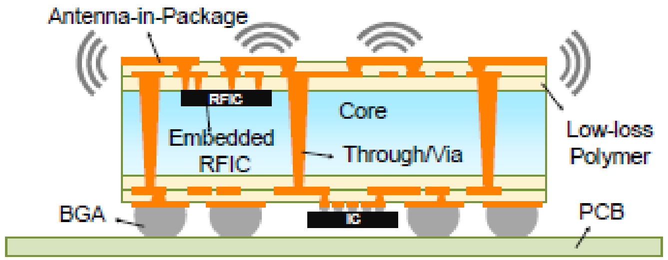


12-18 GHz Tunable System-on-Antenna for IoT

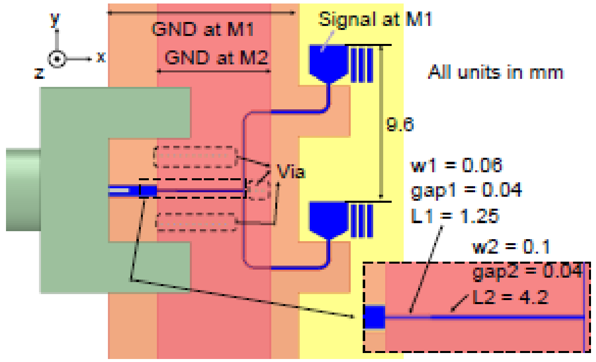


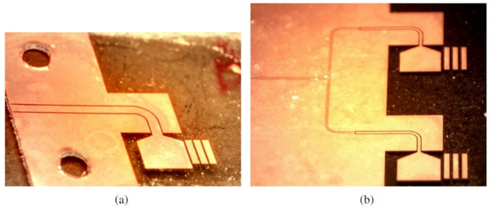
5G Broadband and Miniaturized Antenna-in-Package

3D and inkjet printed SoP Design

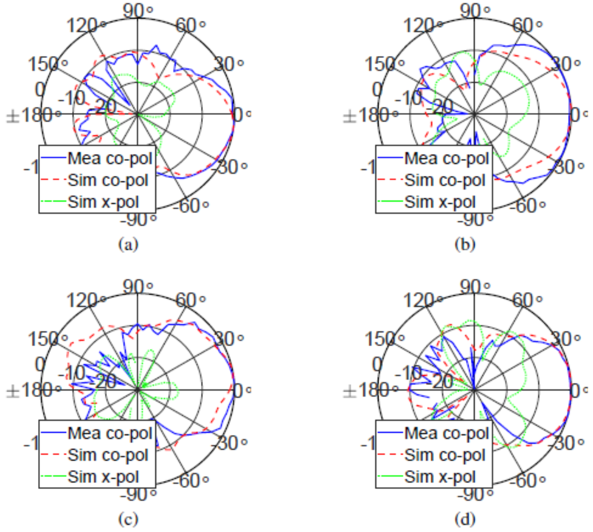


AiP design details

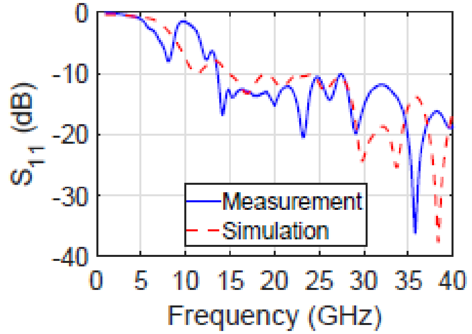


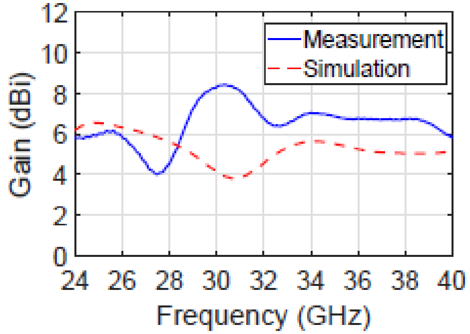


- Fully additive manufacturing (3D and inkjet printing)
- Broadband 5G package-integrated antenna
- Flexible materials for resistance to shocks and vibrations
- First to Cover 24.25 GHz – 40 GHz (FBW: 49%)
- Realized gain > 4 dBi
- 0.25λox0.45λo element size



Measured and simulated normalized radiation patterns for Yagi AiP element design at (a) 24.25 GHz E-plane, (b) 24.25 GHz H-plane, (c) 40 GHz E-plane, and (d) 40 GHz H-plane.

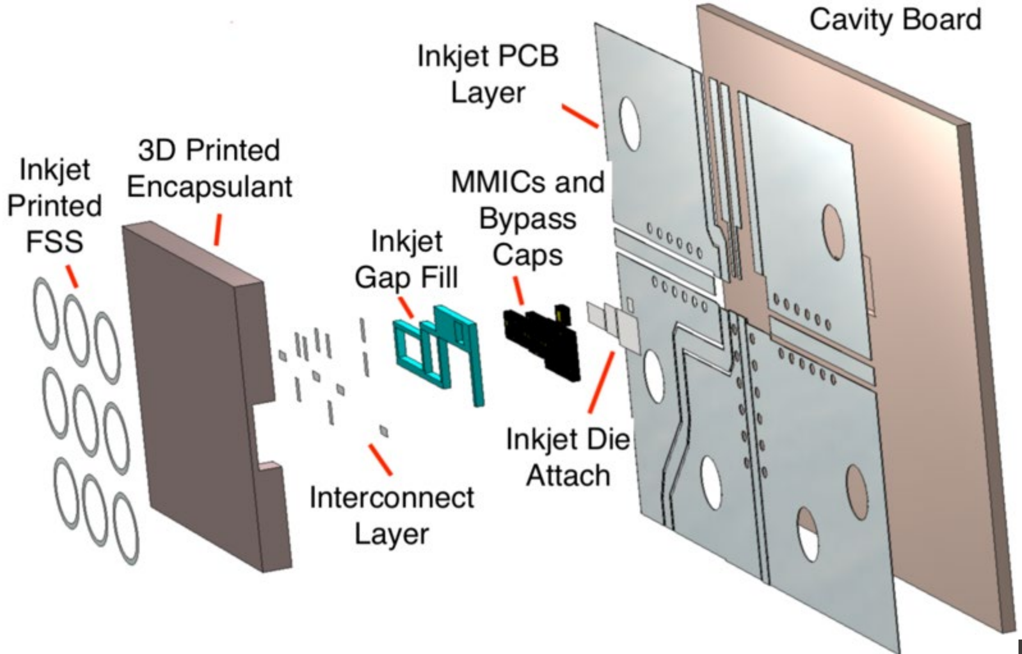


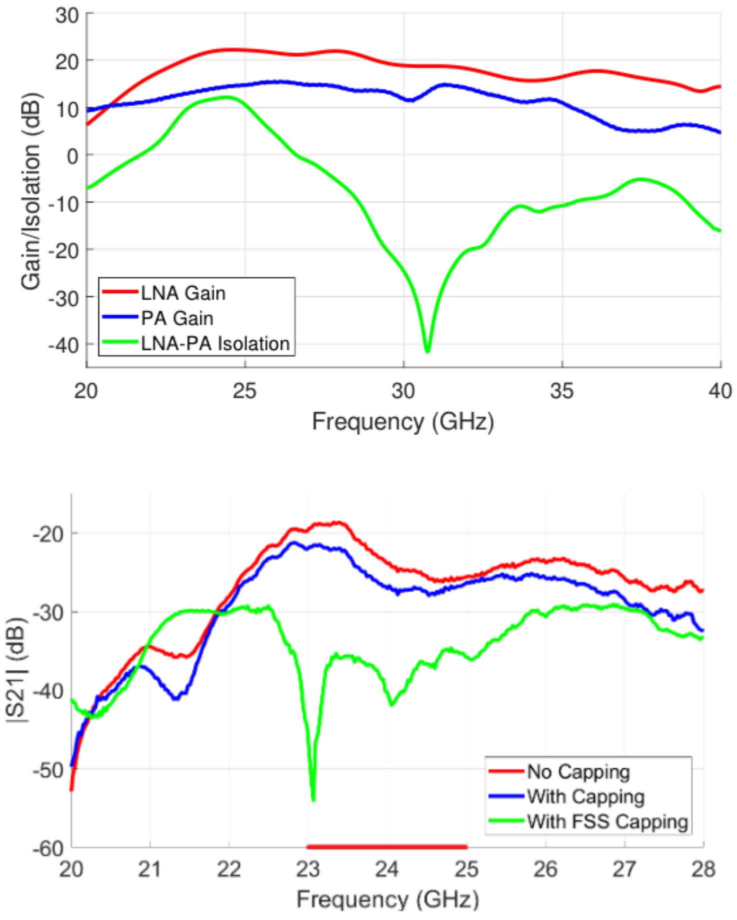


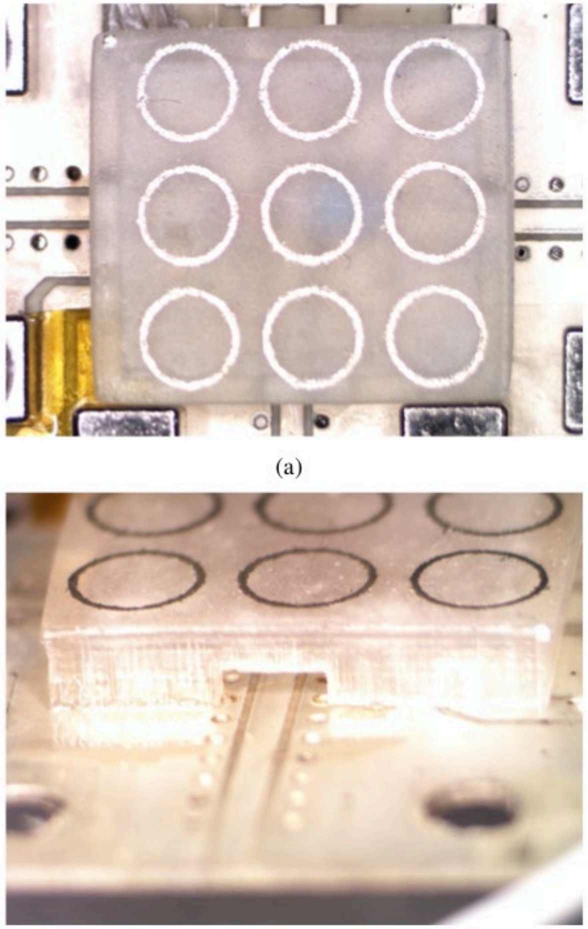
T.-H. Lin, K.Kanno, A.O. Watanabe, P.M.Raj, R.Tummala, M.Swaminathan and M.M.Tentzeris, "Broadband and Miniaturized Antenna-in-Package (AiP) Designs for 5G Applications", accepted for publication to IEEE Antennas and Wireless Propagation Letters

Fully Additively Manufactured Self-Monitoring MultiChip Modules (MCM)

FEM MCM Includes PA LNA and Switch MMICs integrated onto printed "intelligent" (EMI Suppressing/ self monitoring) package







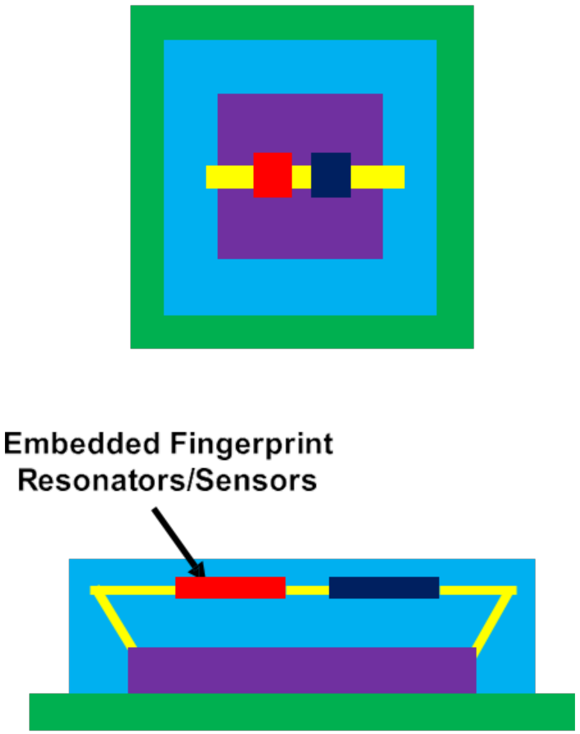
(a)

(b)

X.He, B.K.Tehrani, R.Bahr, W.Su and M.M.Tentzeris, "Additively Manufactured mm-Wave Multichip Modules with Fully Printed "Smart" Encapsulation Structures", IEEE Transactions on Microwave Theory and Techniques, Vol.68, No.7, pp.2716-2723, July 2020.

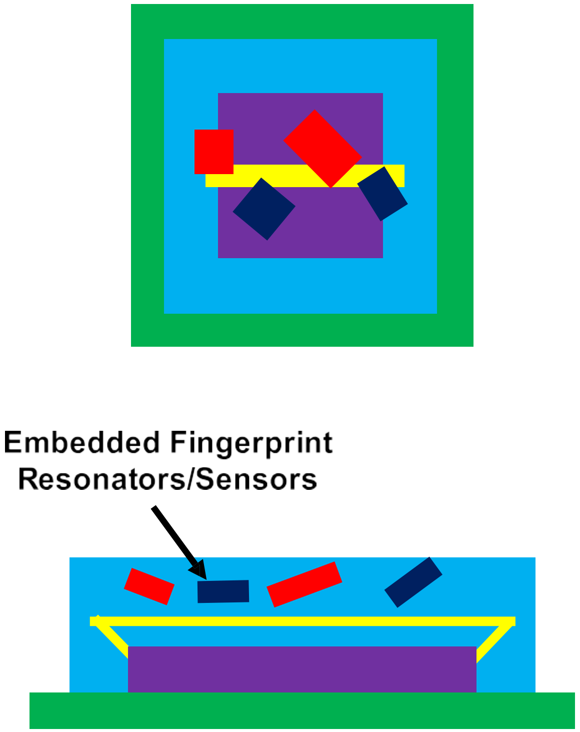
Self-Monitoring/Anti-Counterfeiting/Self-Diagnostic AM Wireless Modules

Top View



(e)

Top View



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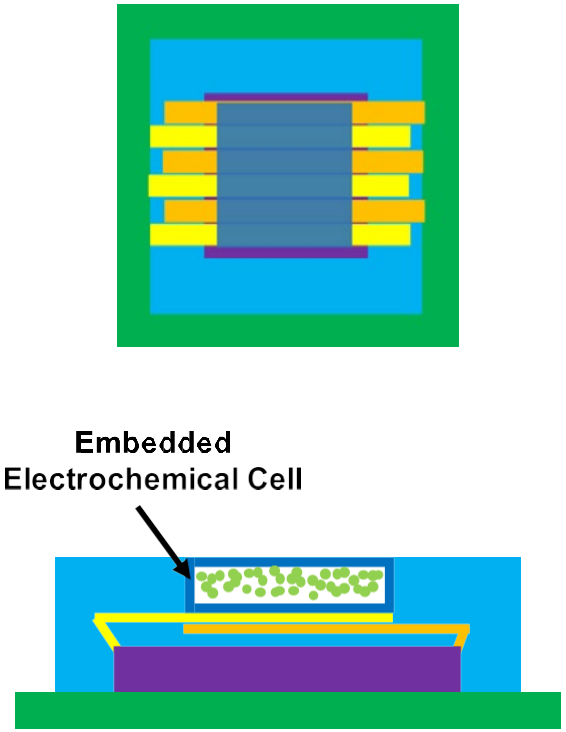
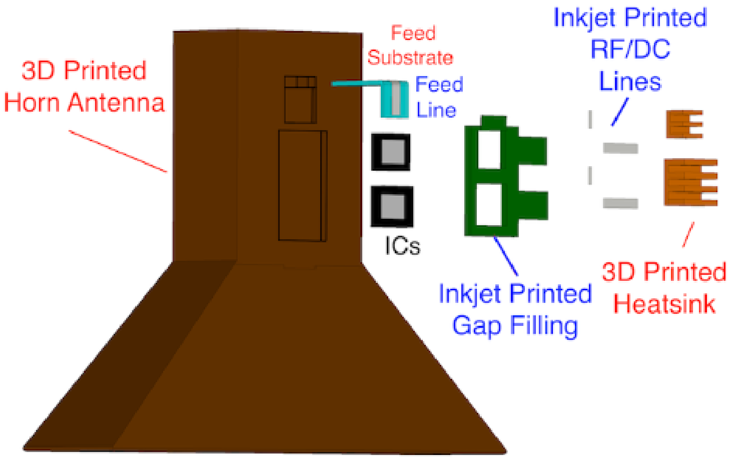
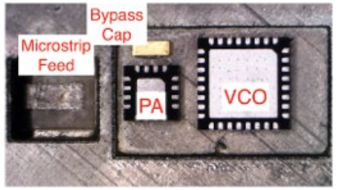
Top View



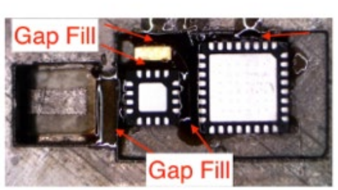
(f)

System On Antenna (SOA)





(a)



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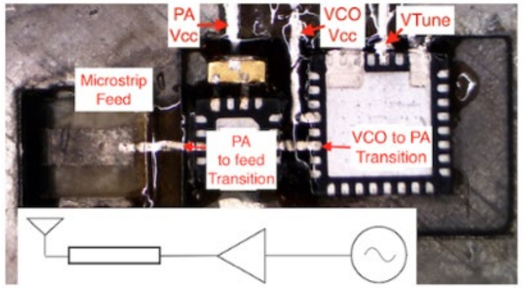
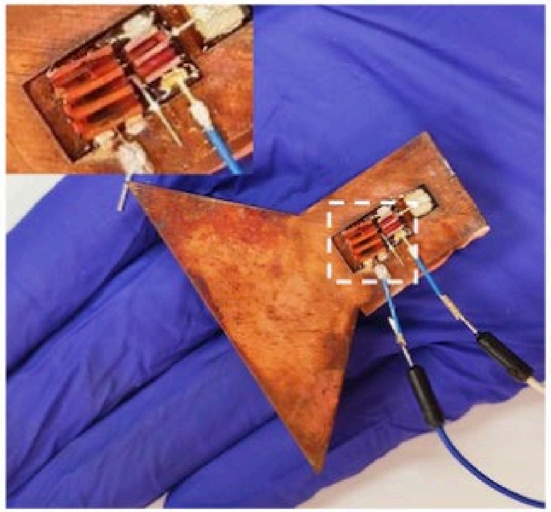
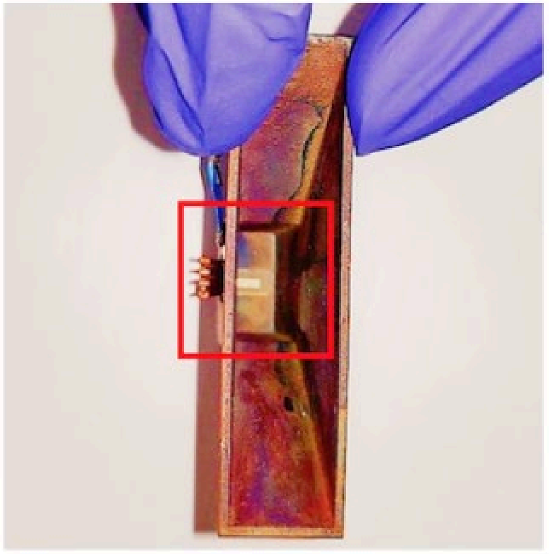


(c)

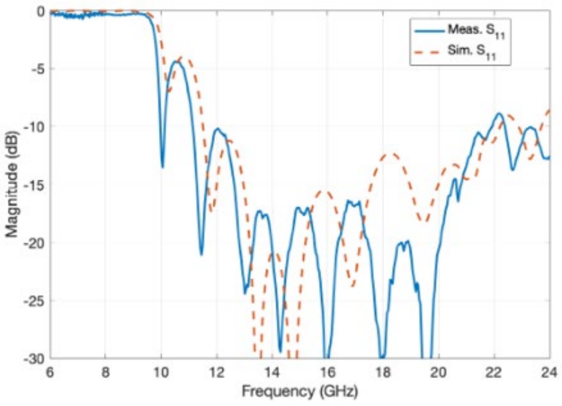


(a)



System On Antenna (IEEE IMS2020)

- RF Beacon with integrated VCO and amplifier
- Performance is nearly identical to simulated horn antenna
- Frequency shift observed showing accurate VCO tunability



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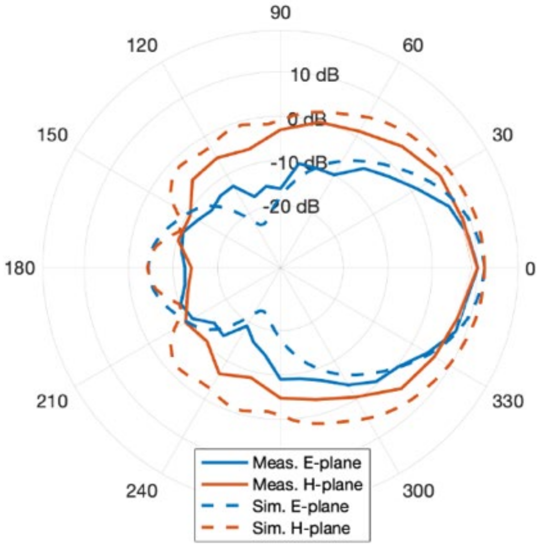

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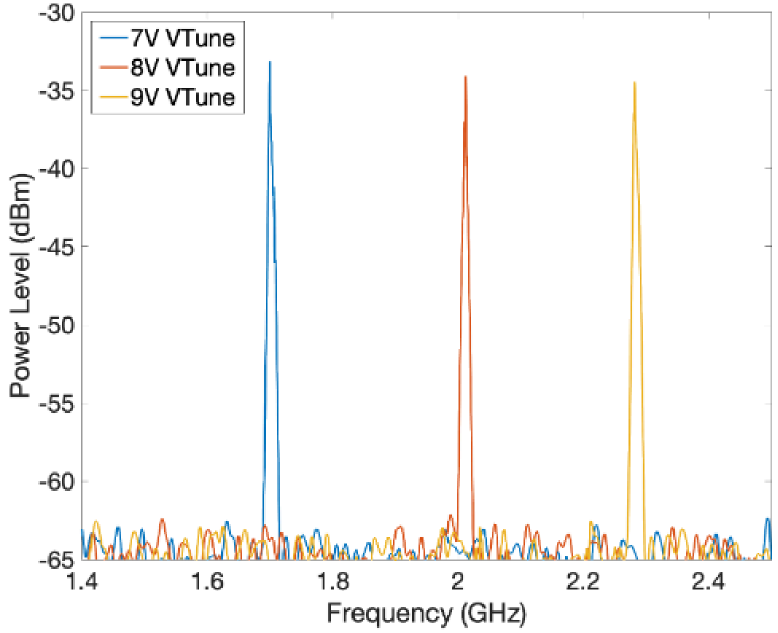
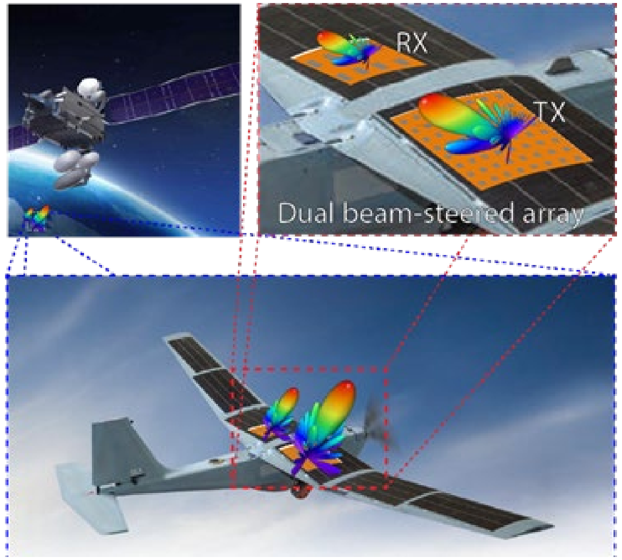
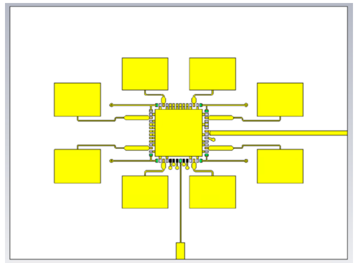


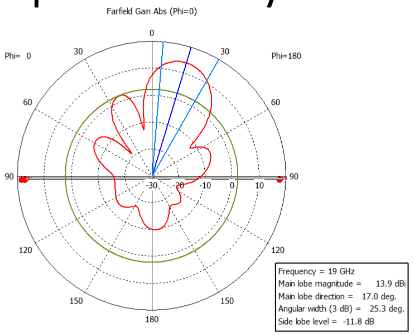
Fully Printable Phased Array Tiles

- Independent **beam-steerable** flexible planar TX and RX antenna array systems
- Frontend ICs with built-in phase shifters to steer the array of each tile, with **individually controlled radiating element**
- Corporate feed network connects **removable tiles** to build a larger array
- **Flexible tiles and feeding network** can be conformally wrapped around curved surface

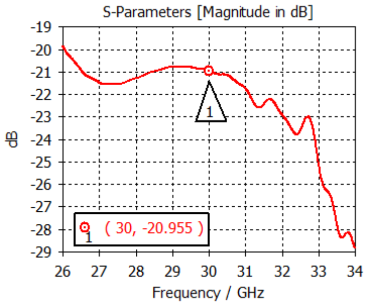


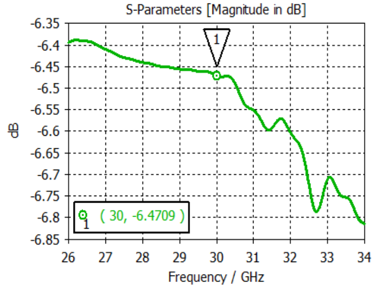


Rx phased array tile

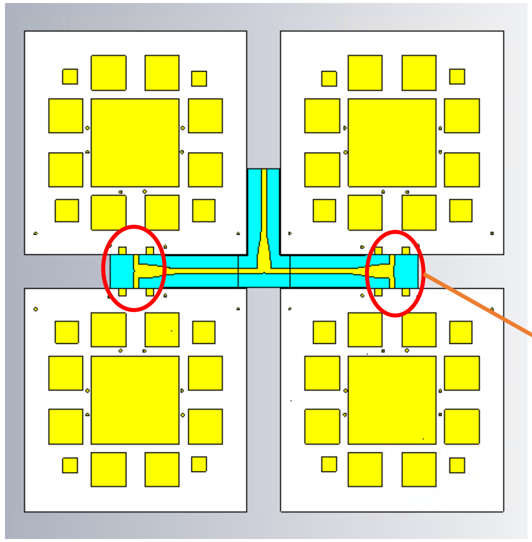


Beam steering



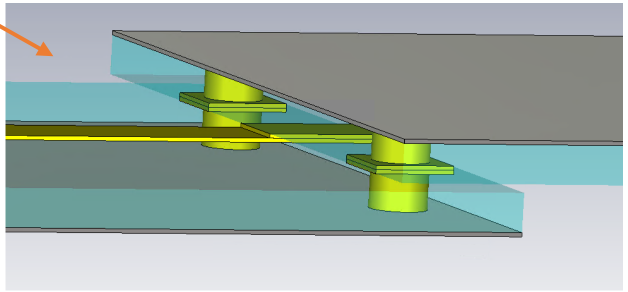


Simulation results of 4 tiles

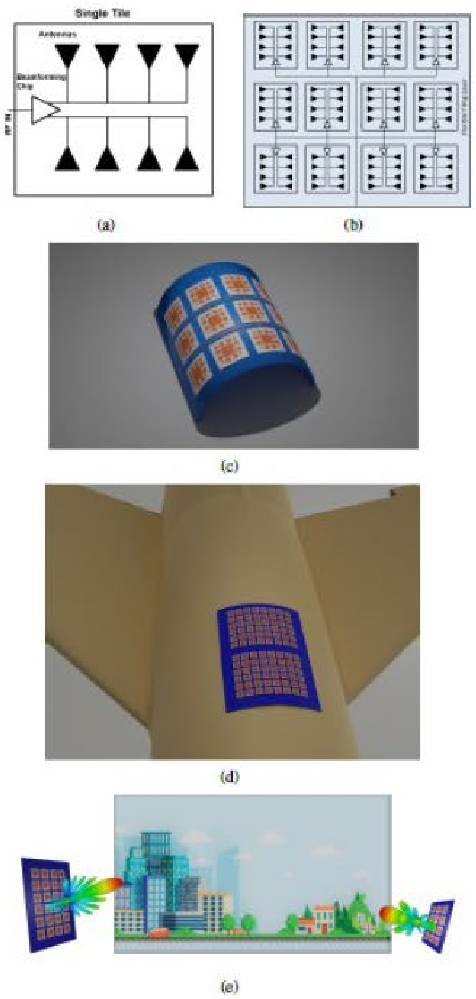


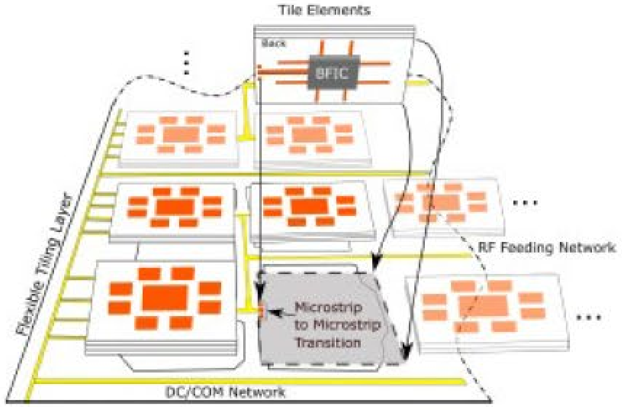
Tx phased array tiles connected by corporate feed

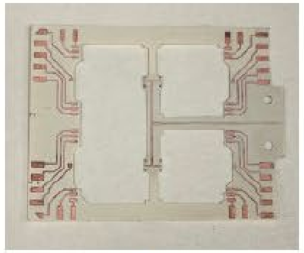
Interconnect of microstrip-to-microstrip transition

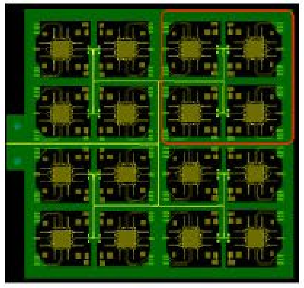


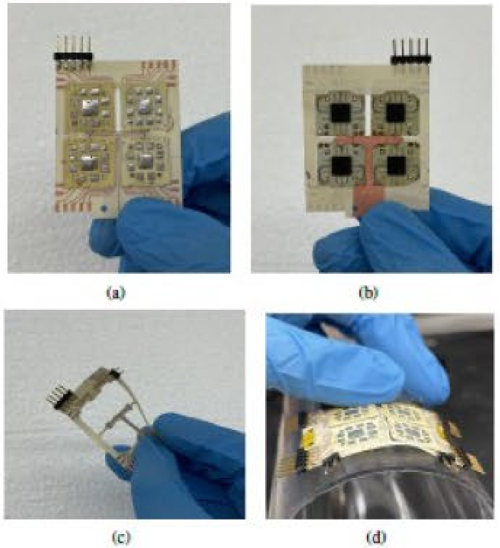
Tile-by-Tile Reconfigurable Intelligent Surfaces

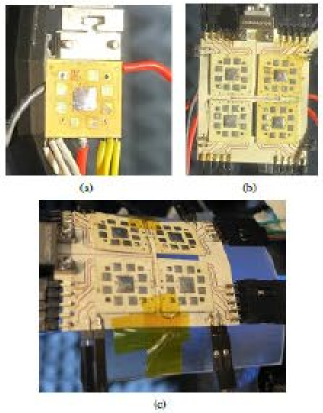





(a)



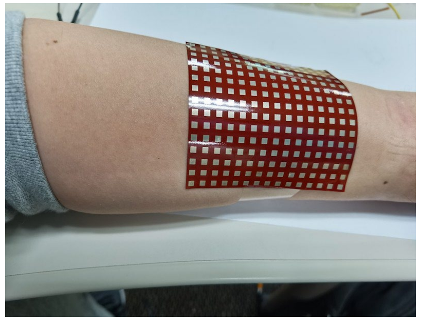


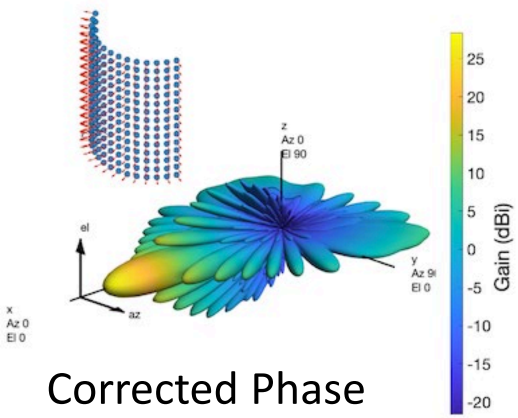


Self-Calibrated “Flex-compensating” Flexible Arrays

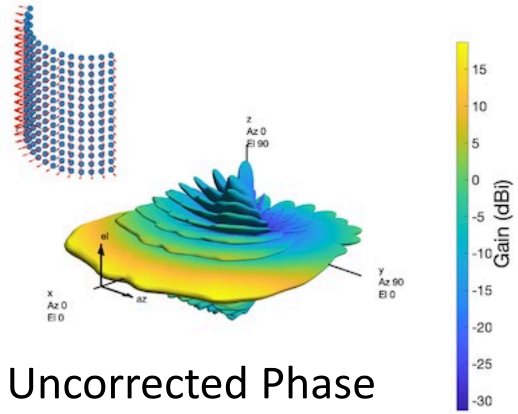
- Conformal applications of arrays allows for superior integration in wearables, aerospace and communication platforms.
- However, phase error causes gain degradation -> Needs Correcting

Requires a way to adaptively know the current bending condition in order to accurately correct for bending





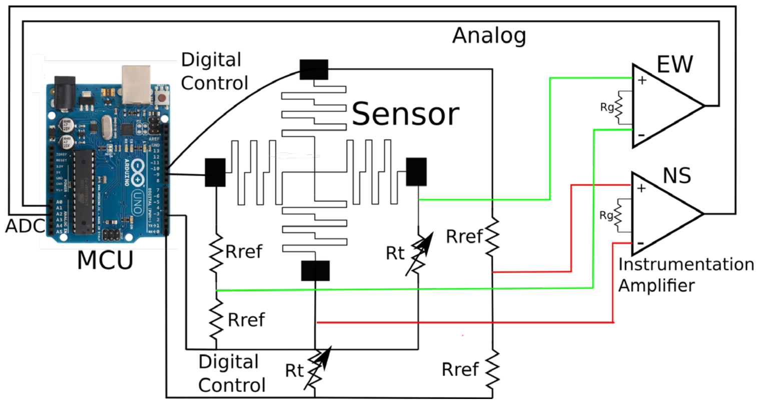
Corrected Phase

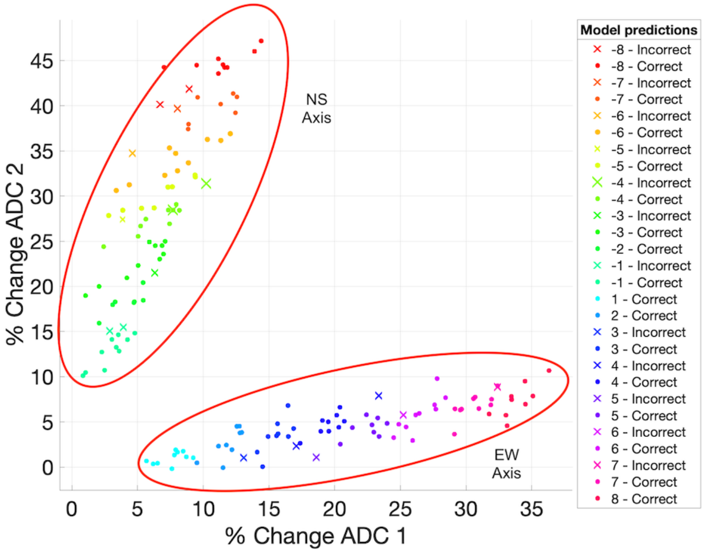


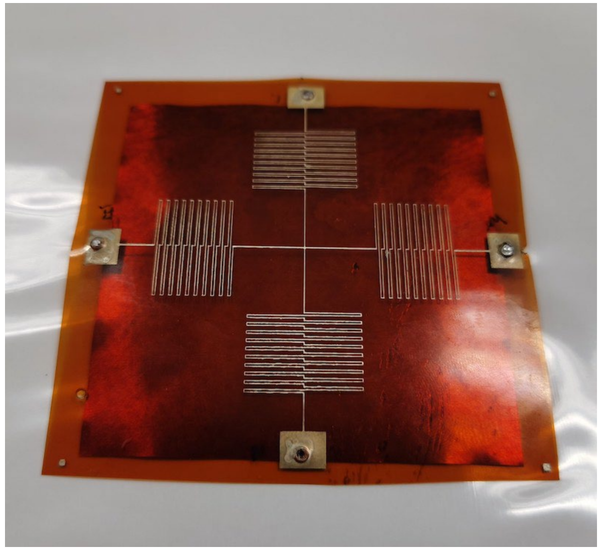
Uncorrected Phase

Self-Calibrated "Flex-compensating" Flexible Arrays

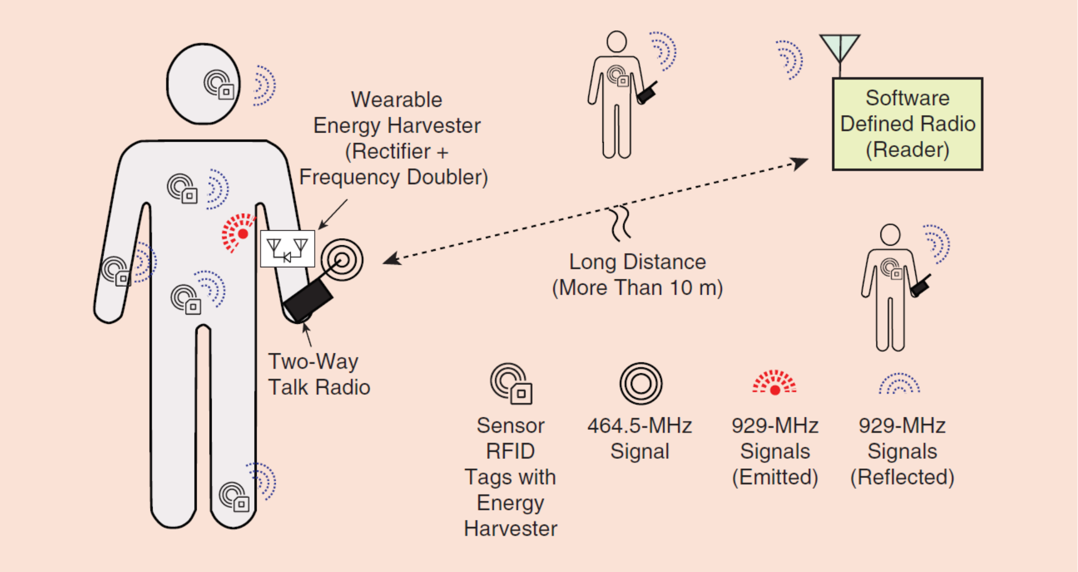
- Utilize inkjet printed resistance sensors -> Resistivity changes with bending
- Classification algorithm: Linear Discriminant Analysis to classify bend radius and orientation ON THE FLY
    - Using LDA: 90% accuracy and only 0.071dB in gain error

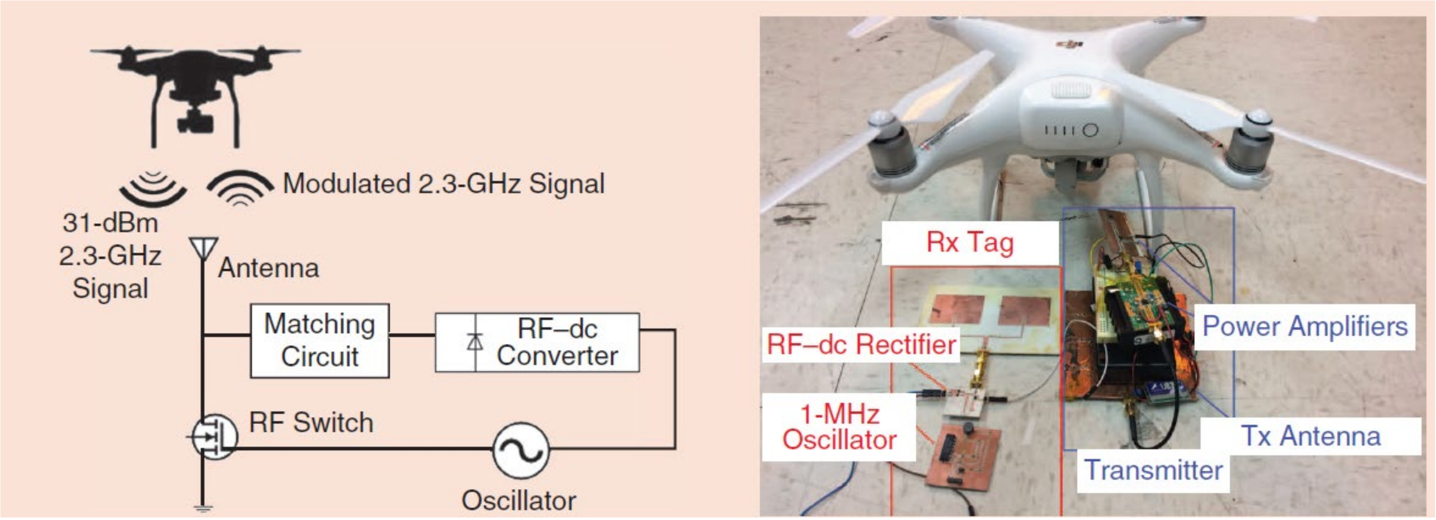


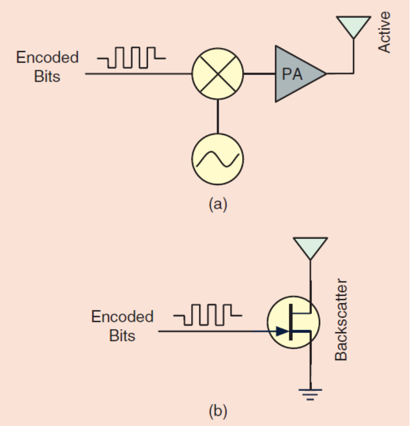


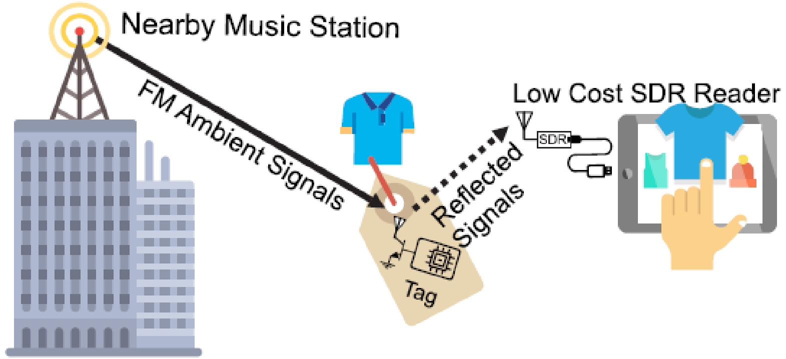


Backscattering: A "Zero-Power" Enabling Technology



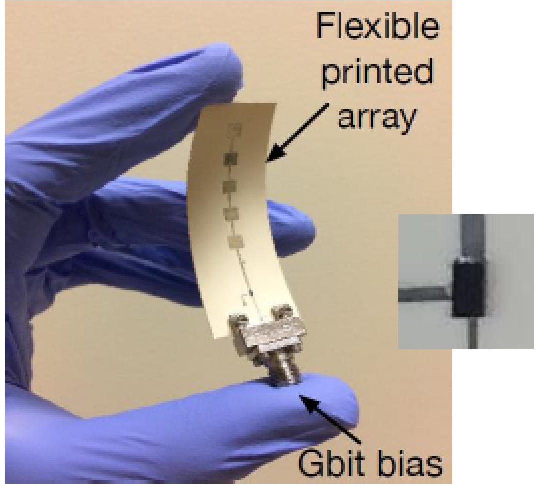


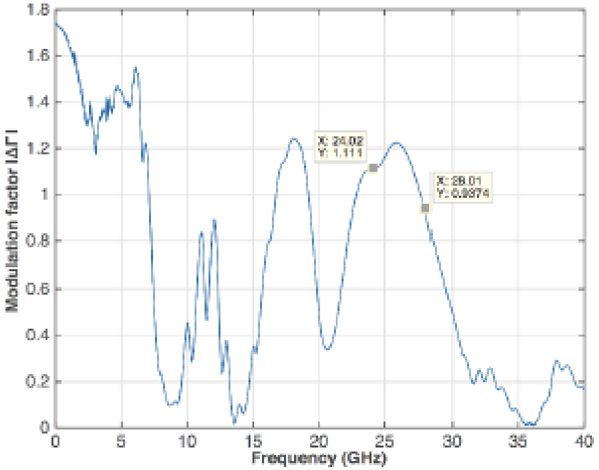




- Gigabit/sec backscattering data rates
- <0.15pJ/bit power efficiencies
- 1km+ interrogation range
- Fully scalable/ultra-low cost

Gbps Millimeter-wave Backscatter





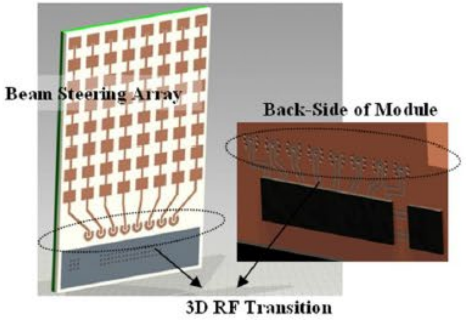
- Printed **flexible** 24-28 GHz tag
- Ultra low-loss substrate
- **First time reported Gigabit** backscatter data rates (> 4 Gbps)
- Extreme energy efficiency < 0.15 pJ/bit
- **3-4 orders of magnitude** beyond current RFIDs

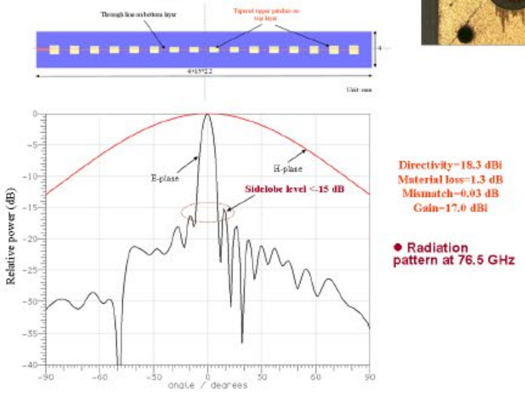
J. Kimionis and M.M. Tentzeris, "Millimeter-wave Backscatter: A Quantum Leap for Gigabit Commu- nication, RF Sensing, and Wearables," in IEEE MTT-S International Microwave Symposium (IMS) 2017, Honolulu, HI, USA, Jun. 2017.

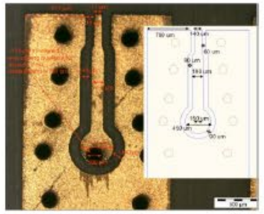
“Smart Material Embedded” mmW Radar Systems

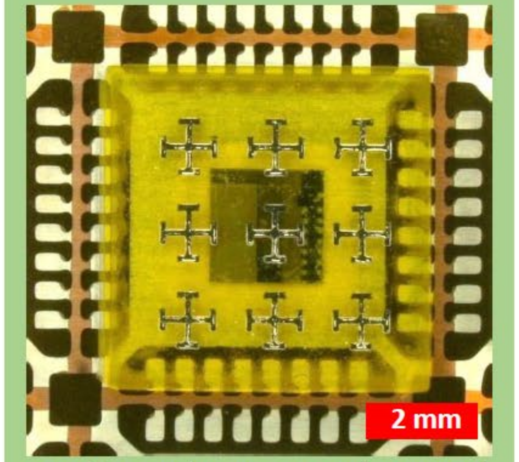
Automotive Radar / Post-Process On-Package Printing

- Use inkjet printing to fabricate metallic structures on top of 3D-printed encapsulation
  - Decoupling capacitors
  - Antenna arrays
  - Frequency selective surfaces (FSS)





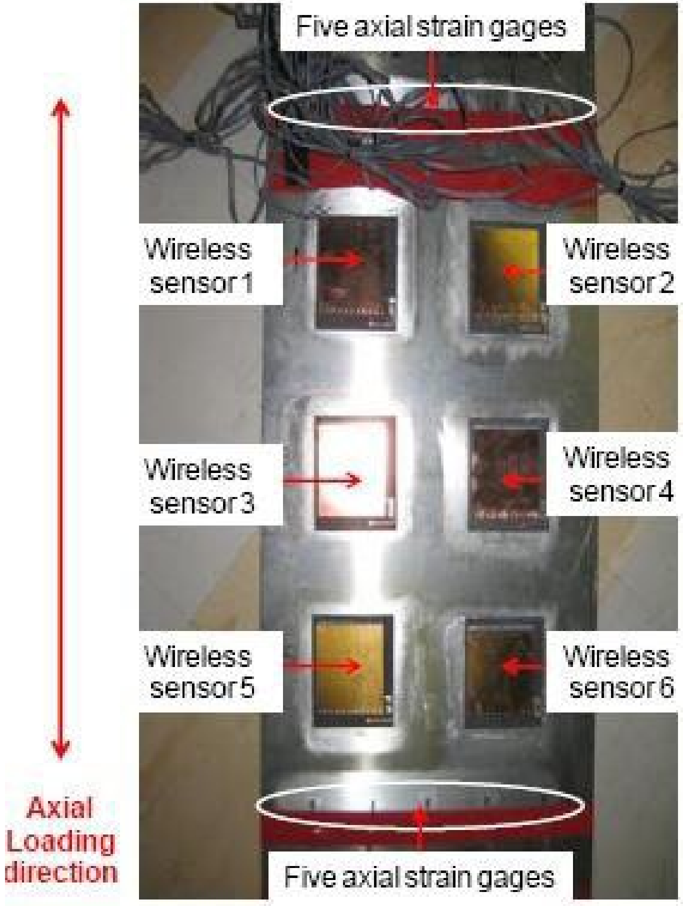




Periodic Jerusalem Cross FSS inkjet-printed onto 3D-printed encapsulation

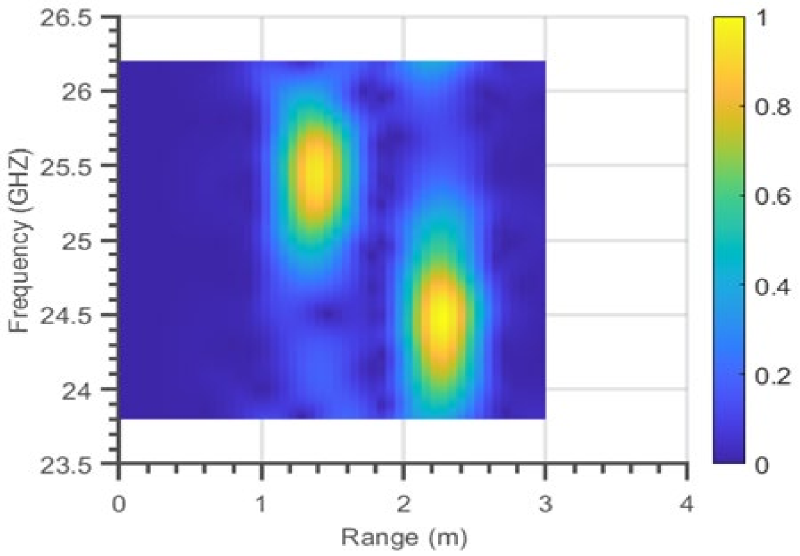
"Zero-Power" Smart Skins for Structural Health Monitoring

- Capability to detect cracks and <20 u-strain
- Range extended to 10 meters through the use of Solar Power

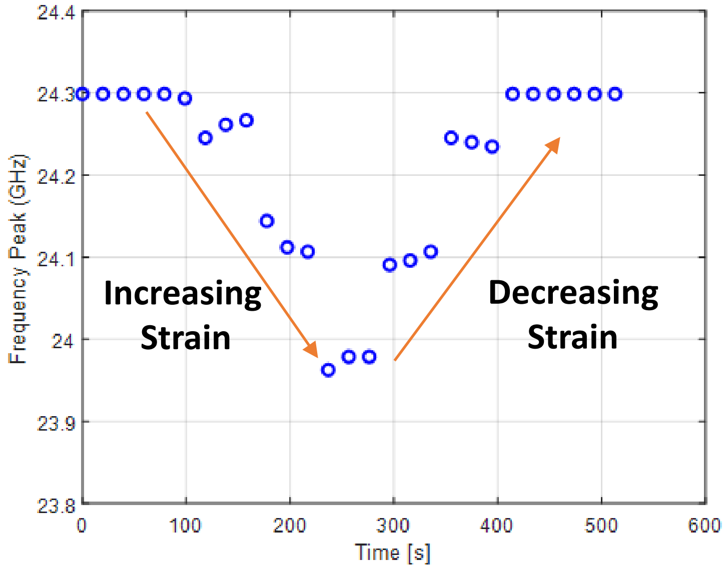


(a) Sensor instrumentation on the aluminum specimen

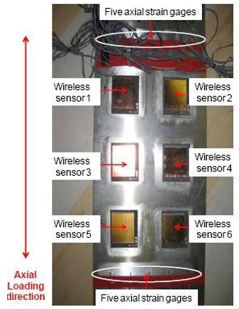
mmWave smart skins for structural health monitoring (SHM)



Frequency multiplexing allows dense implementation and discrimination in range



Sensor able to capture strain profile while embedded in composite material



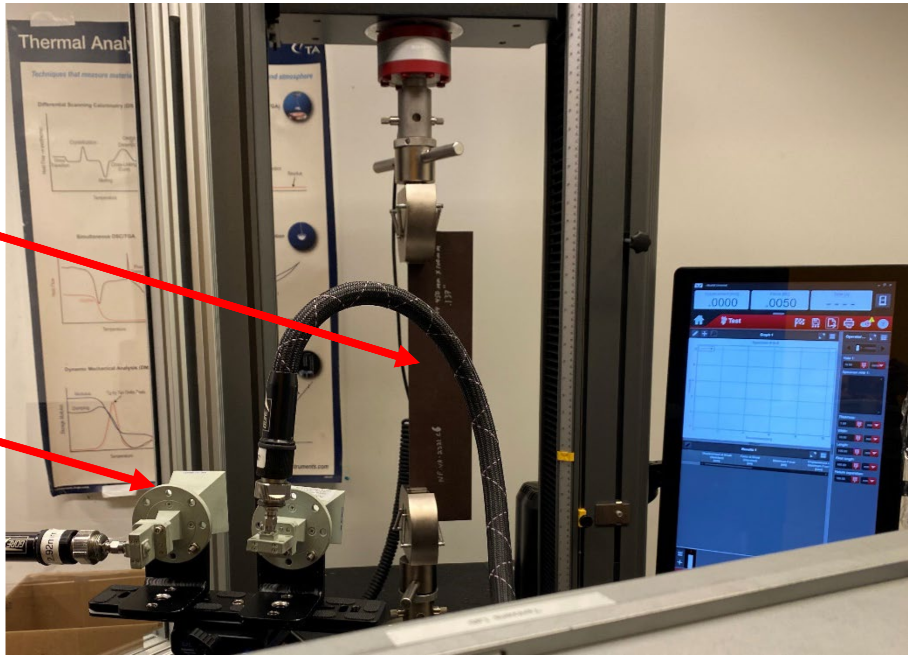
(a) Sensor instrumentation on the aluminum specimen

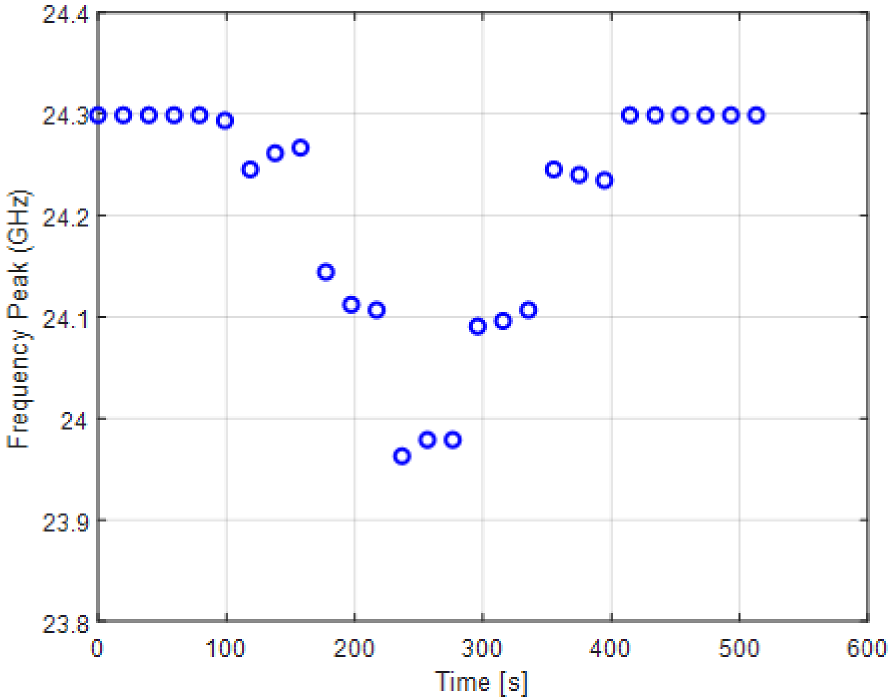
mmWave smart skins for structural health monitoring (SHM)

- Strain was applied in fixed steps of strain from 0 to 4400 u-strain and interrogated at a range of 1 m off-axis.
- Linear change in frequency with an estimated sensitivity of ~73.86 kHz/u-strain.
- Sensor displayed a large dynamic range for sensing strain and recovered to original frequency.

CF Sample

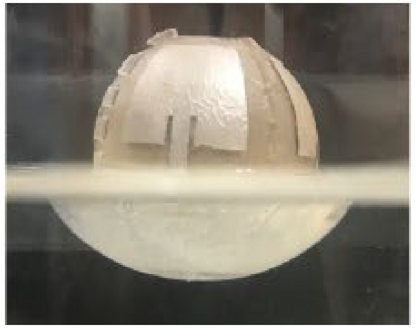
Horn Antennas

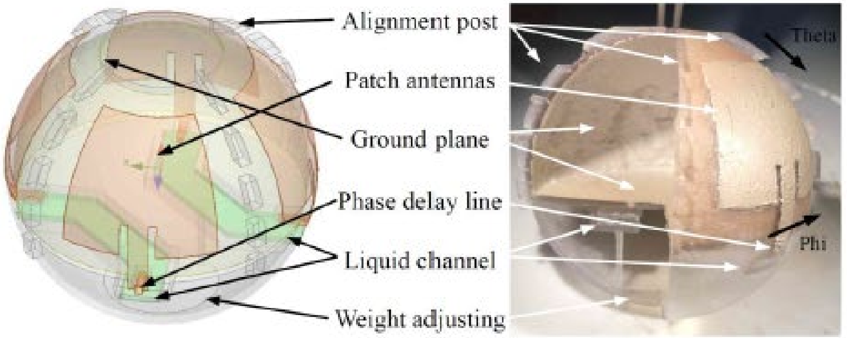




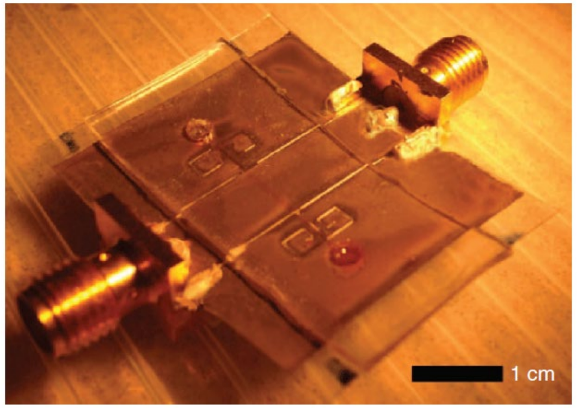
Smart Floating Balls

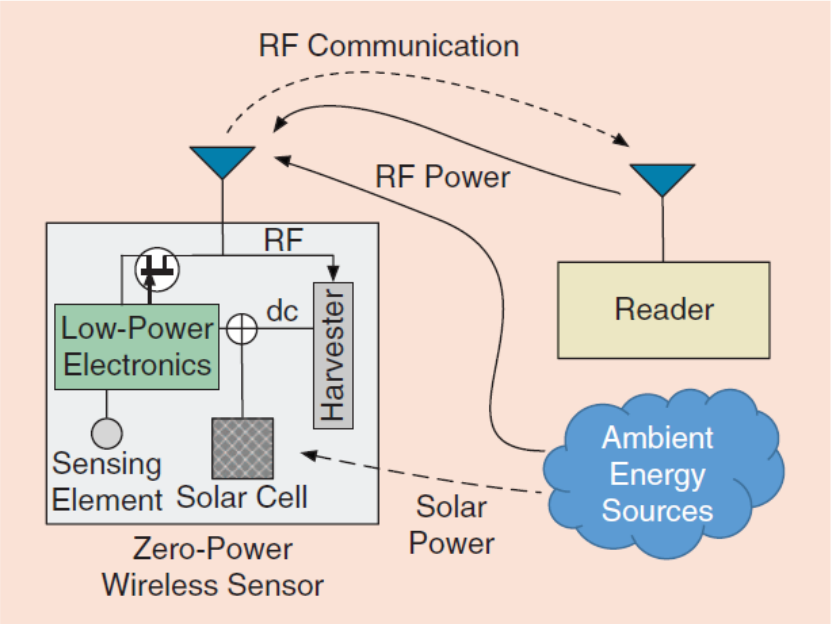
- Phase configuration chipless RFID
- Shadowing balls to save water by reducing evaporation in reservoirs
- Water quality monitoring for contamination, such as oil and gas wastewater (low permittivity)

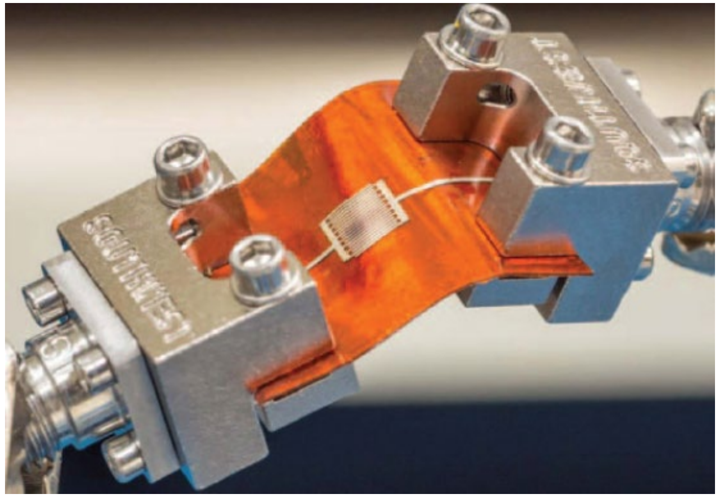


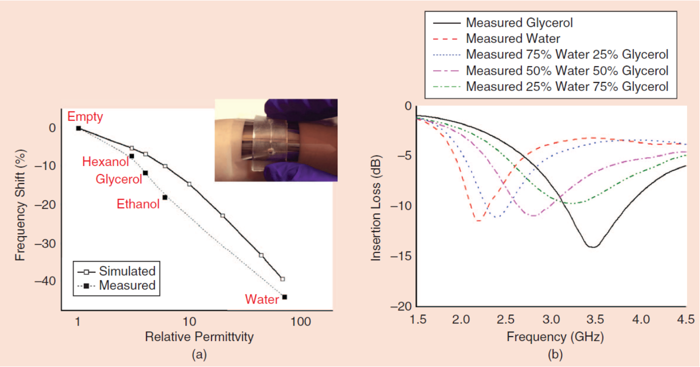


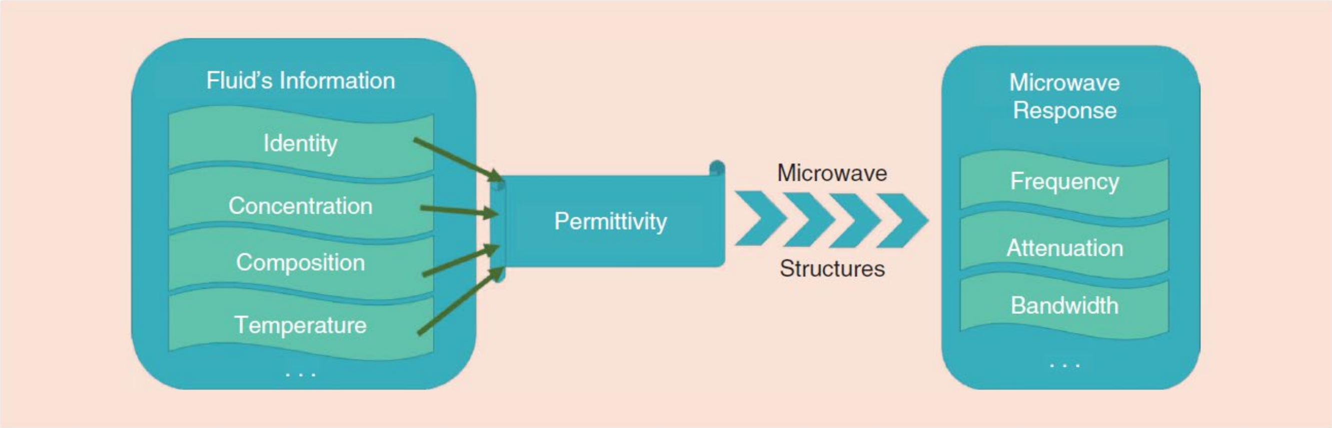
"Zero Power" 3D/Inkjet-Printed Wireless Sensors



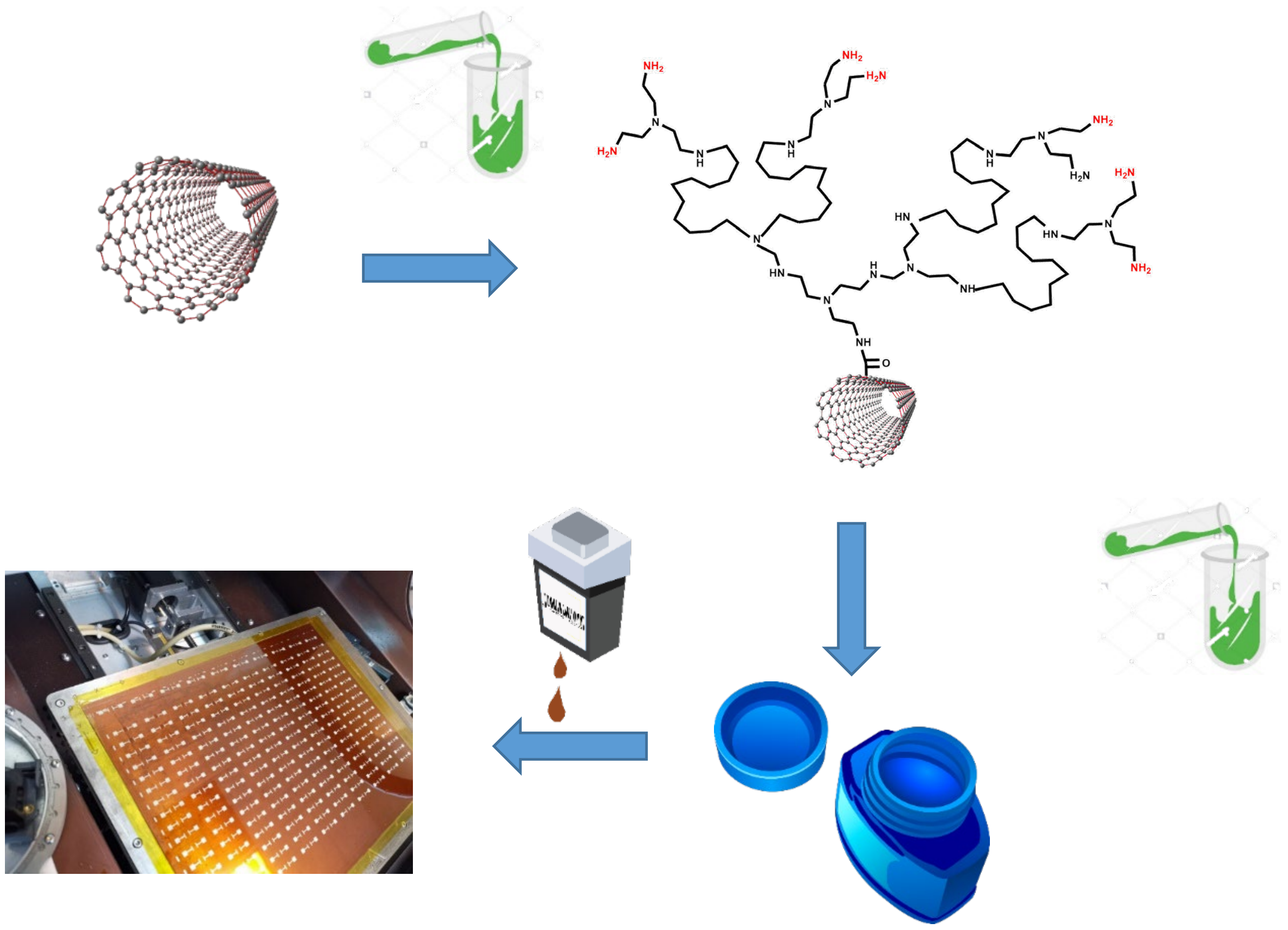


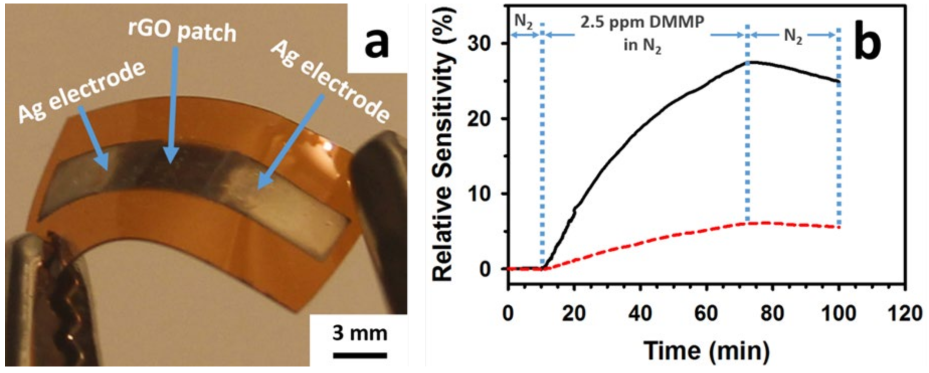




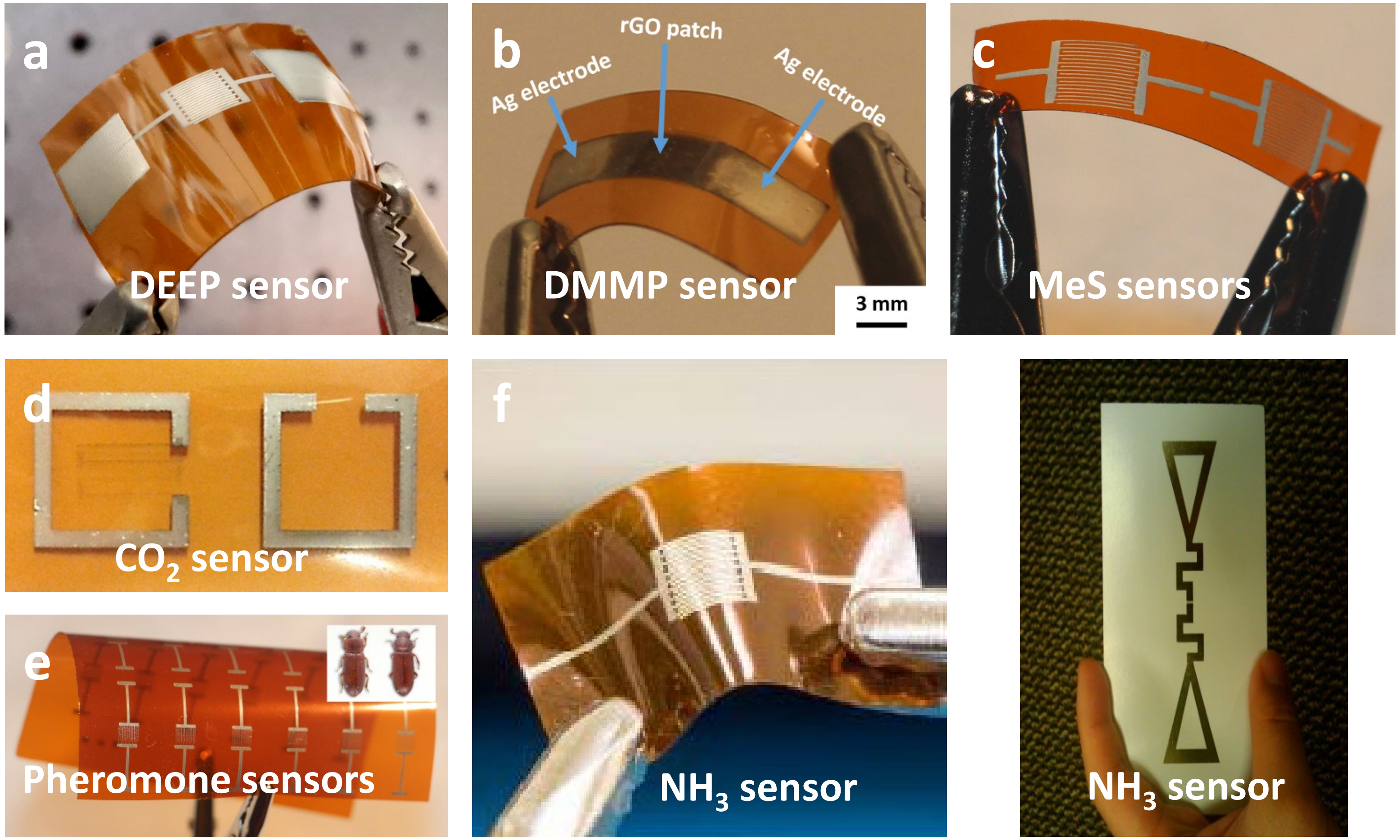


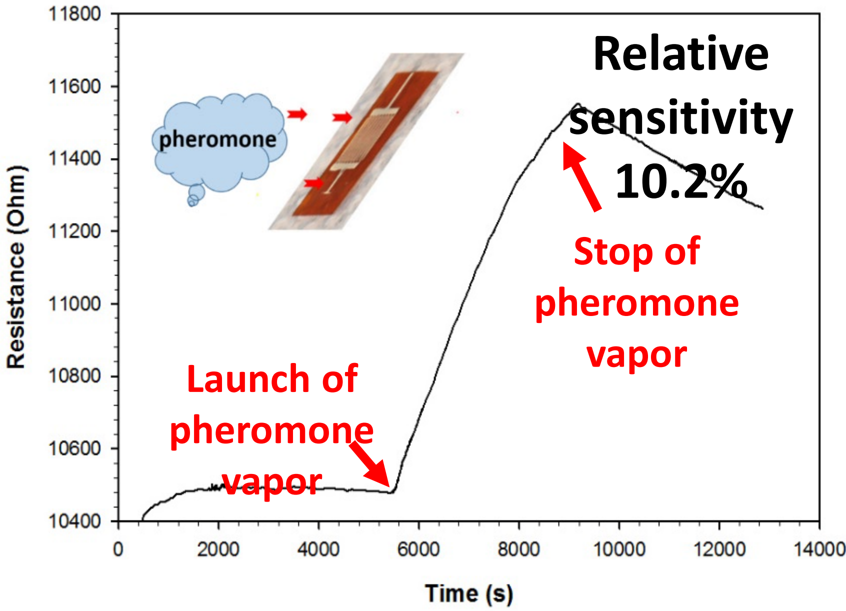
Fully Inkjet-printed chemical/biological sensors





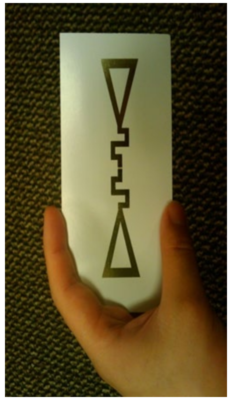
Inkjet-printed chemical/biological sensors

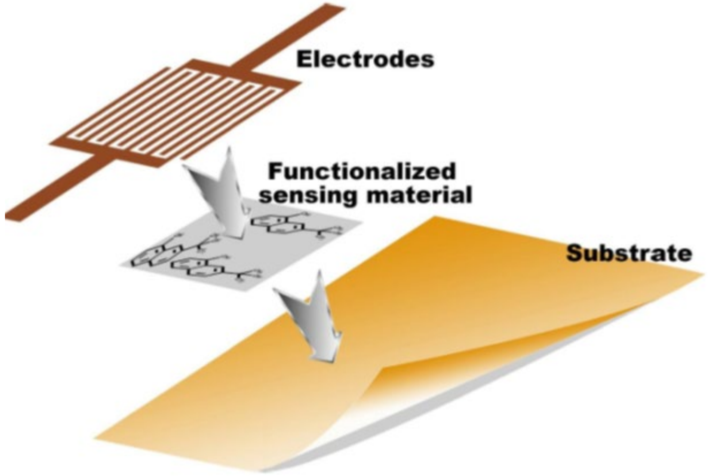


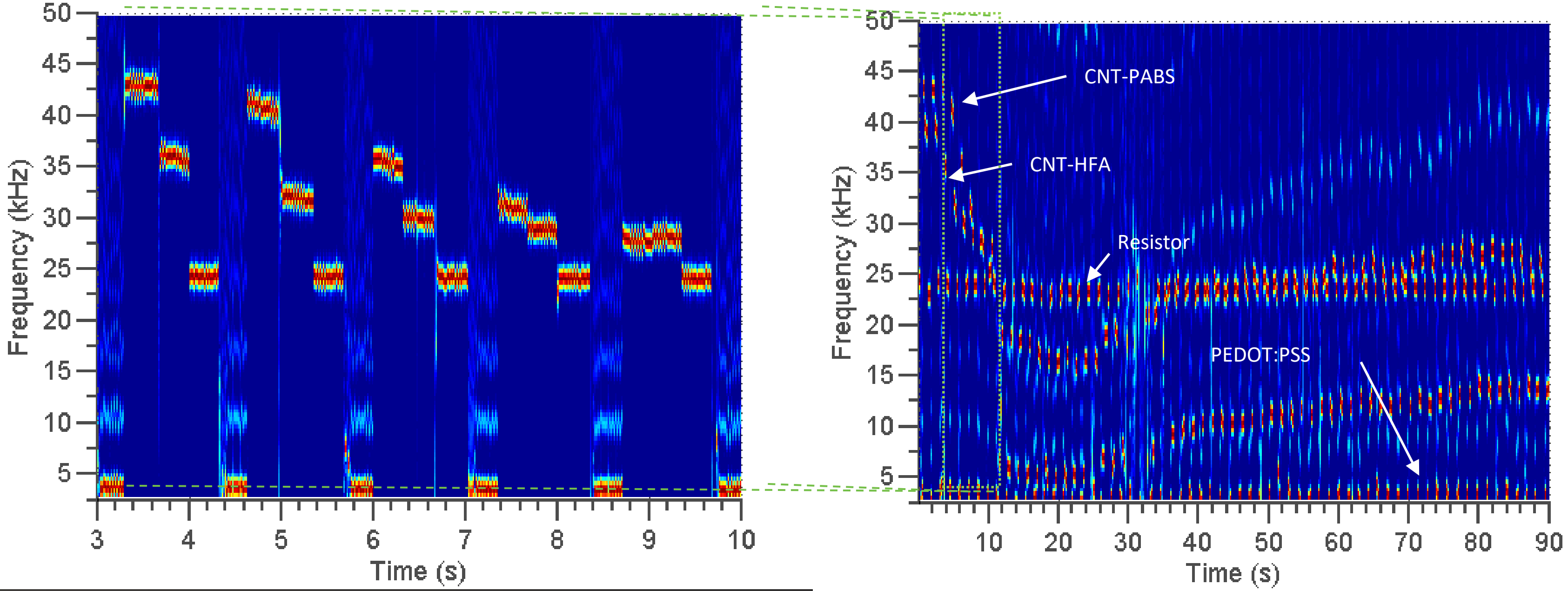


Zero-Power Wireless 3D/Inkjet-printed "Electronic Nose"

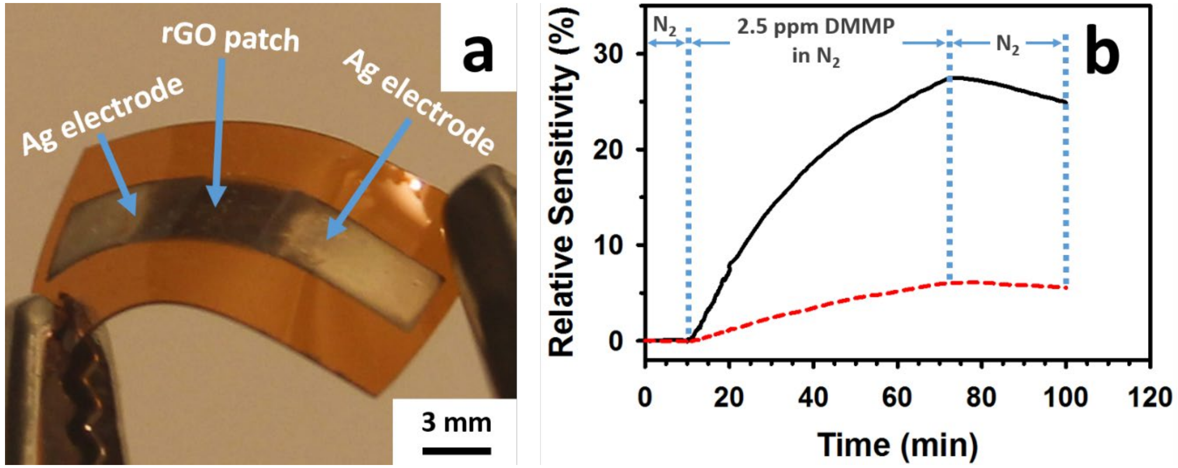
- Real-time multi-agent selective "chipless" sensing down to 50ppb at 50m+ range in seconds
- Simultaneous detection of:
  - Organophosphate
  - Ammonia
  - Humidity
  - Temperature



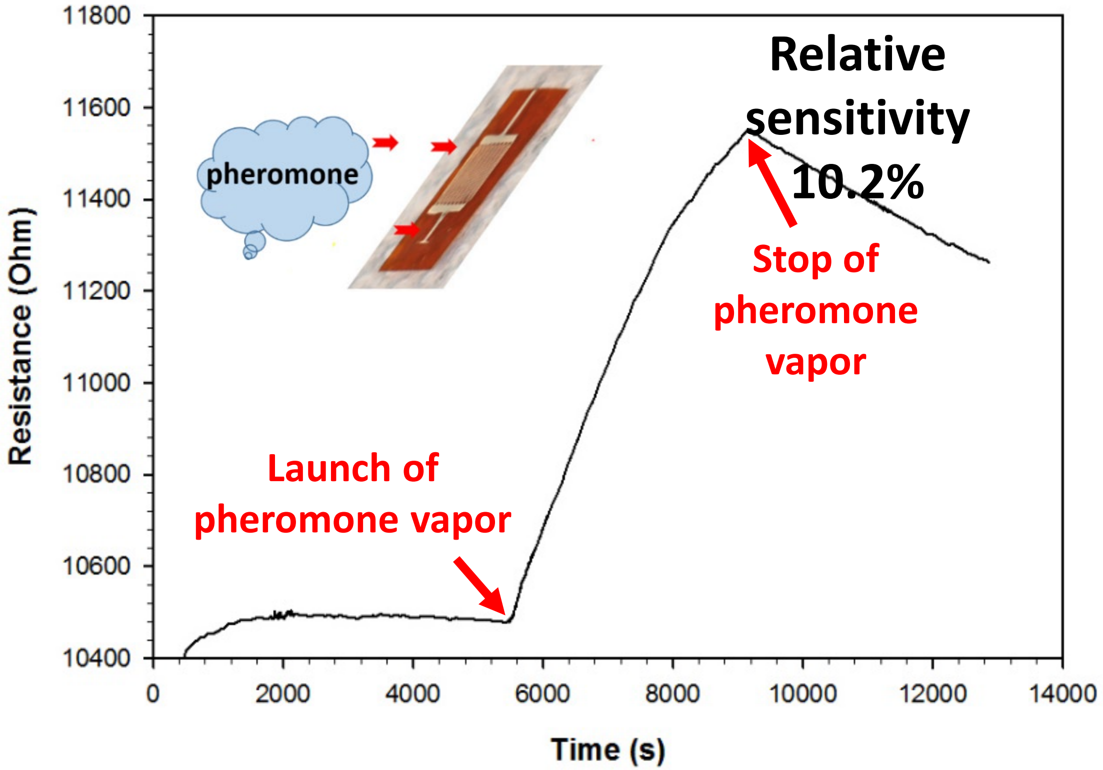


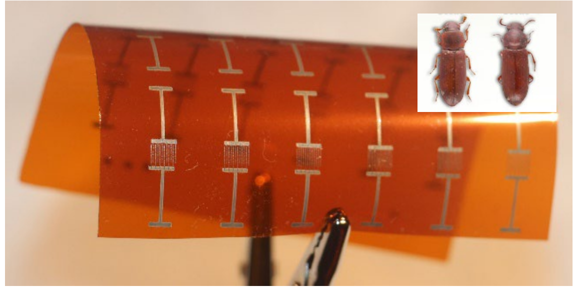


Graphene-based DMMP sensors



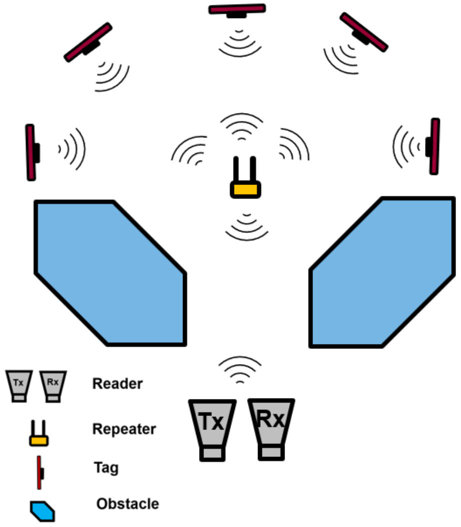
Smart Agriculture Pheromone sensors

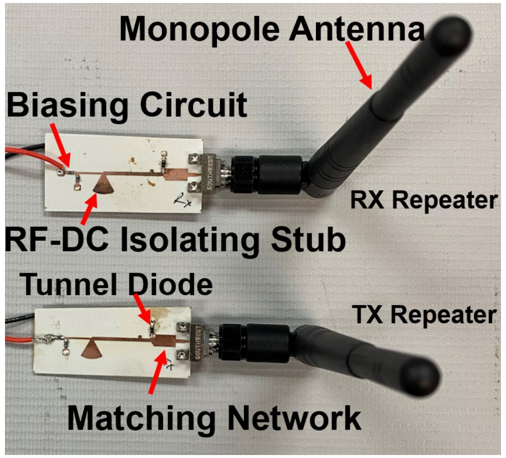




NLOS Interrogation of RFID-enabled Sensors: A 2-way repeater with uW Consumption

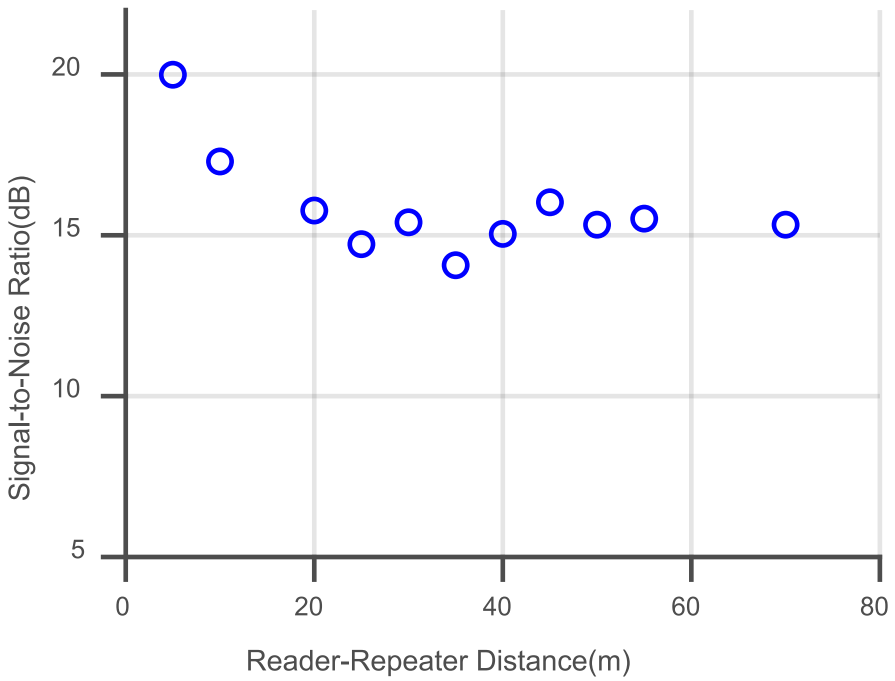
- Device provides more than **4.55X** read range extension in the interrogation of 5.8GHz semi-passive RFID tags
- Enables non-line of sight interrogation thus increasing the feasibility of large scale wireless sensor networks
- Achieves both while consuming a meager 40µW (**over 1000X less than state of the art**)
- Low voltage of operation at **<0.2V** enables energy autonomous wireless sensor networks

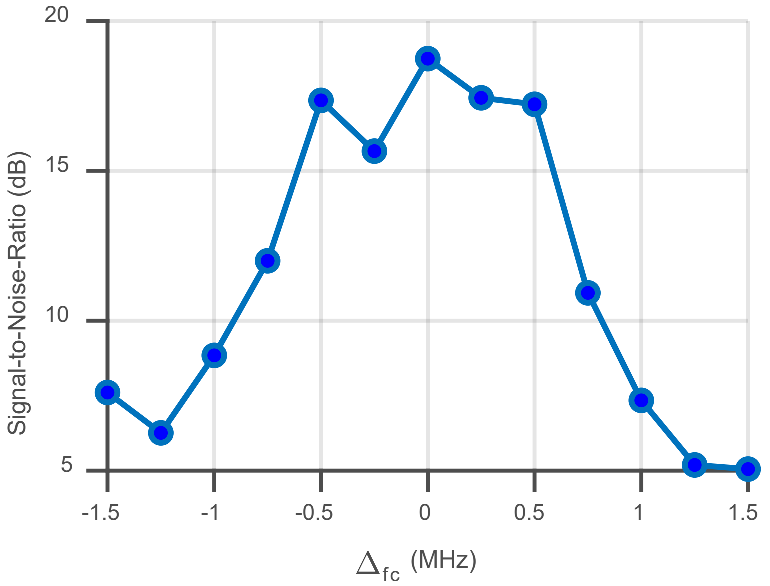




	Repeater Power Consumption	Operating Frequency	Operating Voltage	Max Gain
This Work	**40µW**	**5.8GHz**	**0.2 V**	**50dB**
[1] A.G.Dimitriou, IEEE Journal of RFID, 2020	9300mW	900MHz	15V	51.6 dB
[2] J. Song et. al IEEE T.A.P, 2012	240mW	2.4GHz	3 V	50dB
[3] M. Kashanianfard et. al IEEE T.A.P, 2017	270mW	2.4GHz	1.7 V	73dB

NLOS Interrogation of RFID-enabled Sensors: A 2-way repeater with uW Consumption

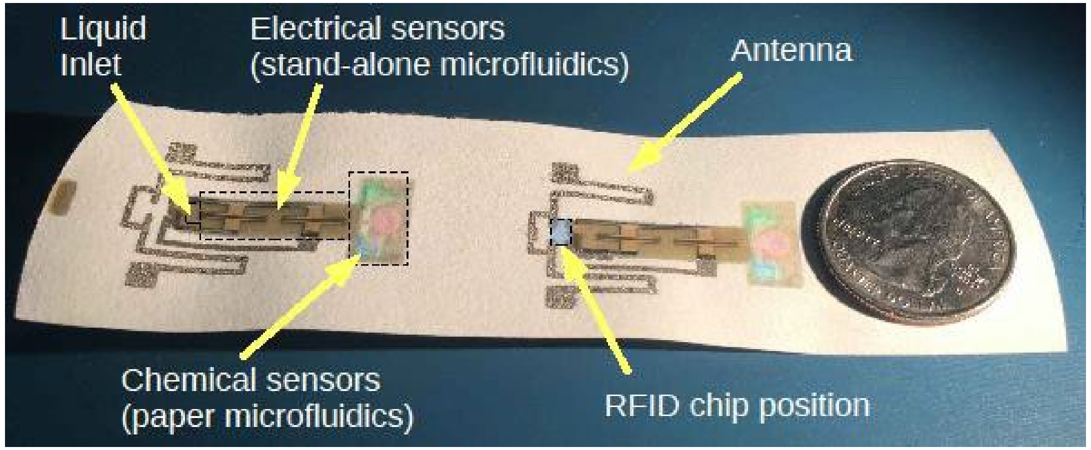


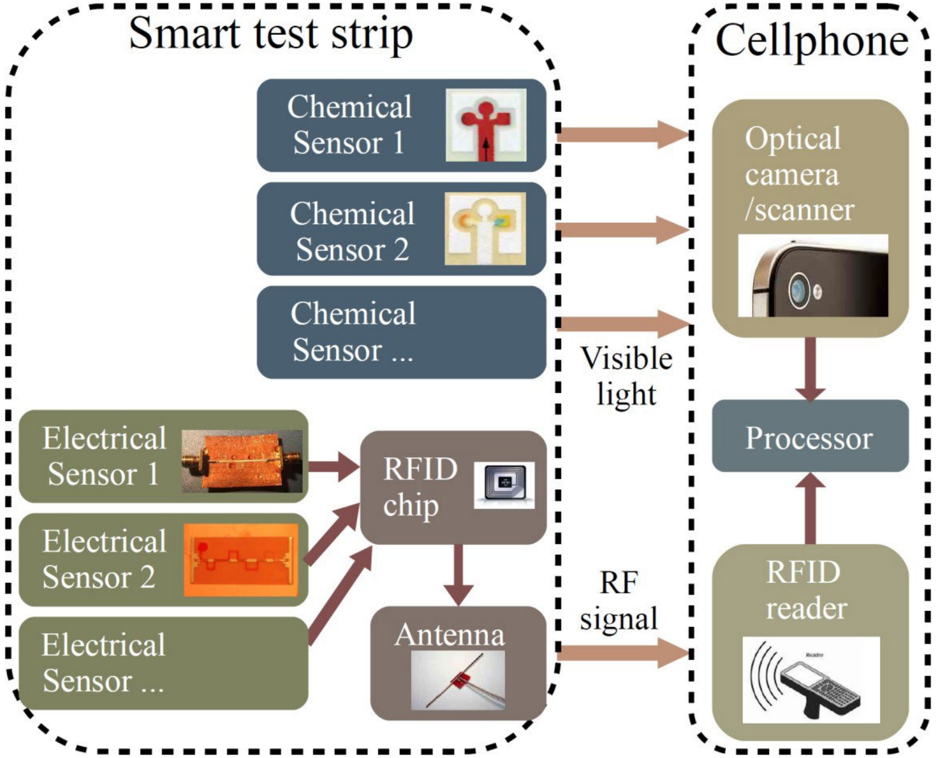


Stable Signal-to-Noise Ration over long distances (80m+)

Smart Test Strips Through Inkjet-Printed Microfluidics

- Zero-Power wireless comprehensive liquid sensing
- Completely inkjet-printed RFID + paper microfluidics
- On-demand sensors addition





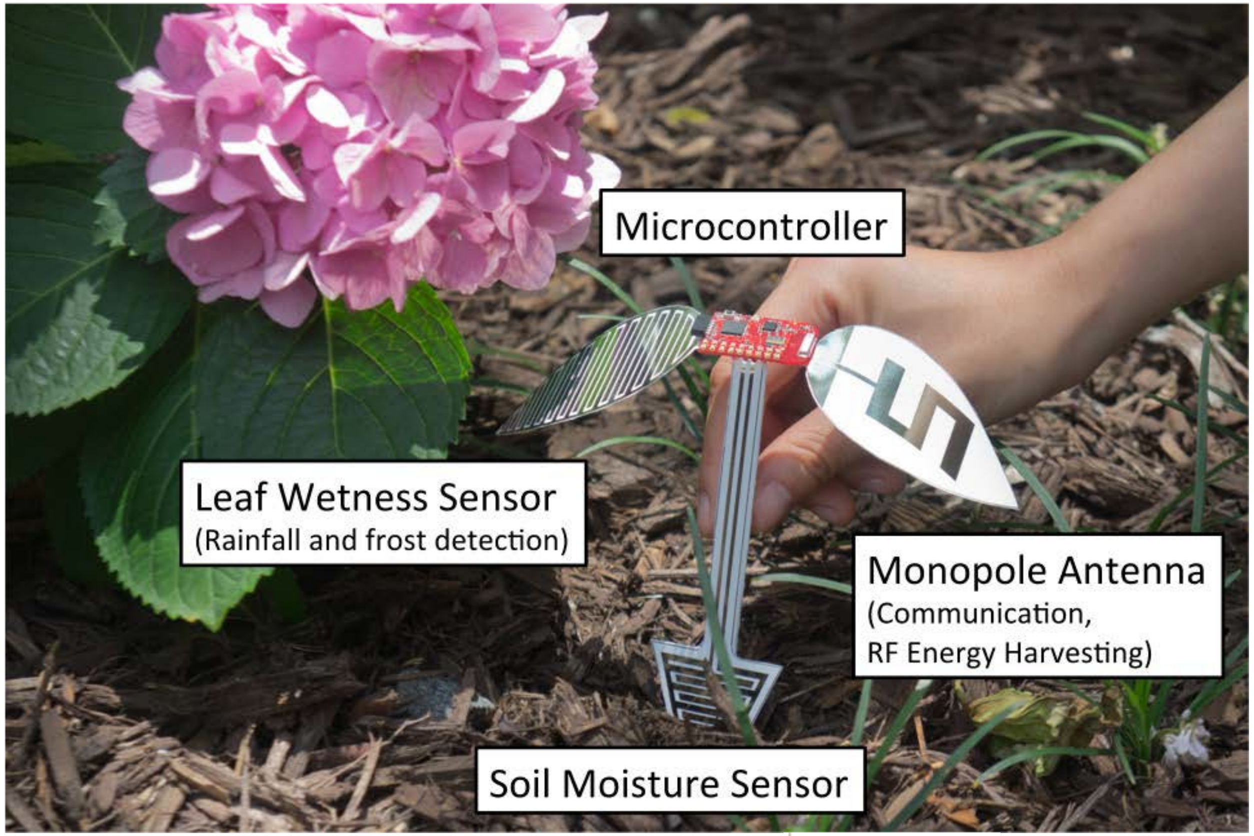
Inkjet-Printed Soil Moisture and Leaf Wetness Sensor

Features:

Inkjet-printed capacitive sensor for soil moisture and rain detection

Applications:

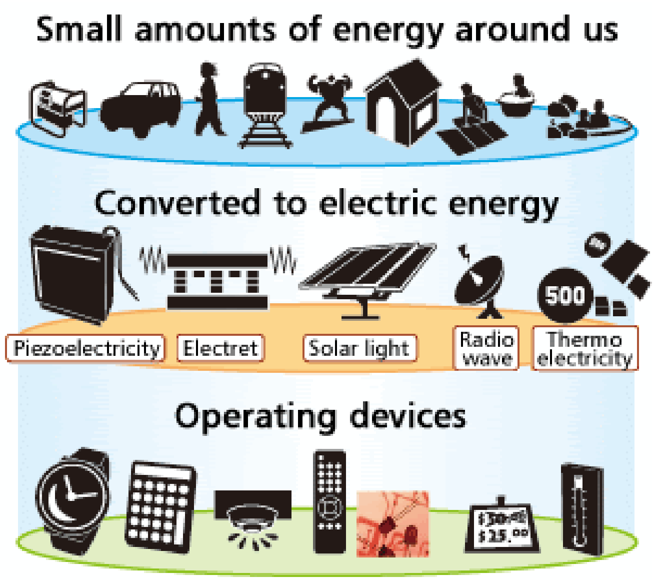
Irregation optimization, quality control of high-value fruit, and land-slide detection in mountains



NEDO 東京大学 THE UNIVERSITY OF TOKYO Georgia Institute of Technology

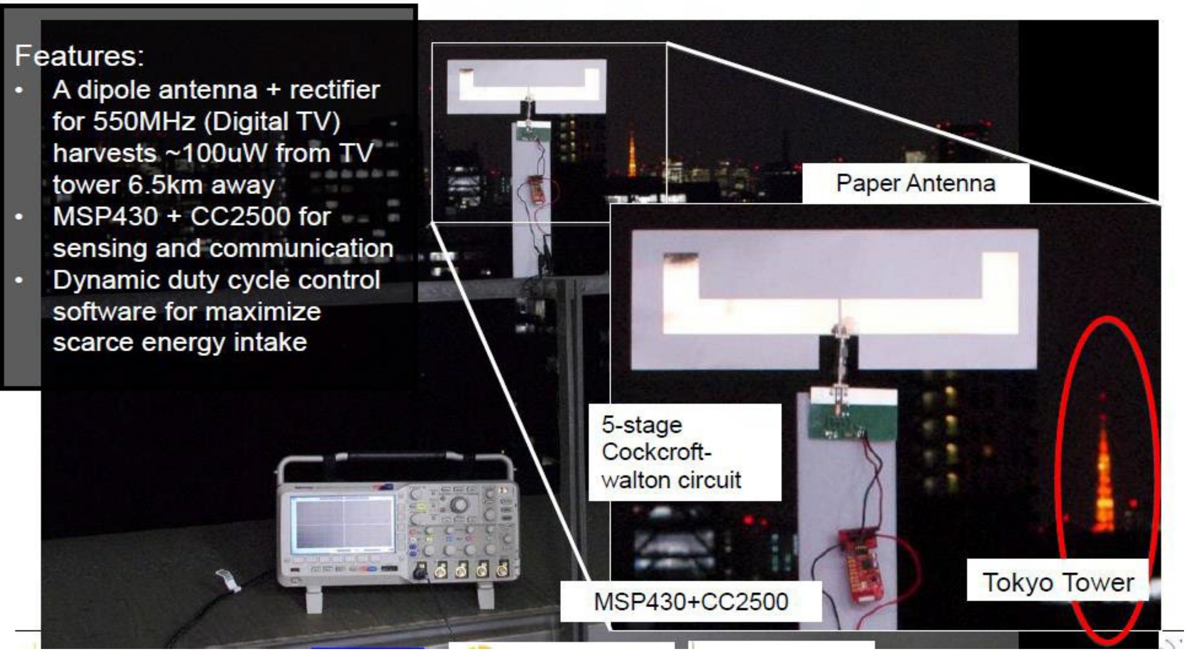
"Zero Power" = Ambient Energy Harvesting

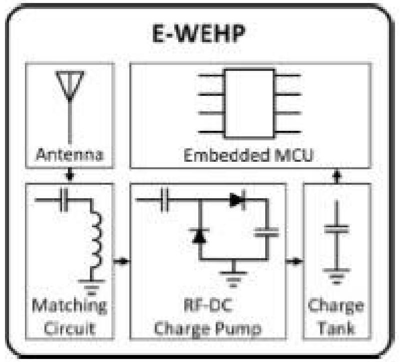
http://www.lsr.com

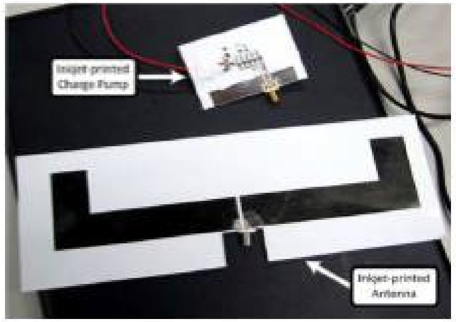


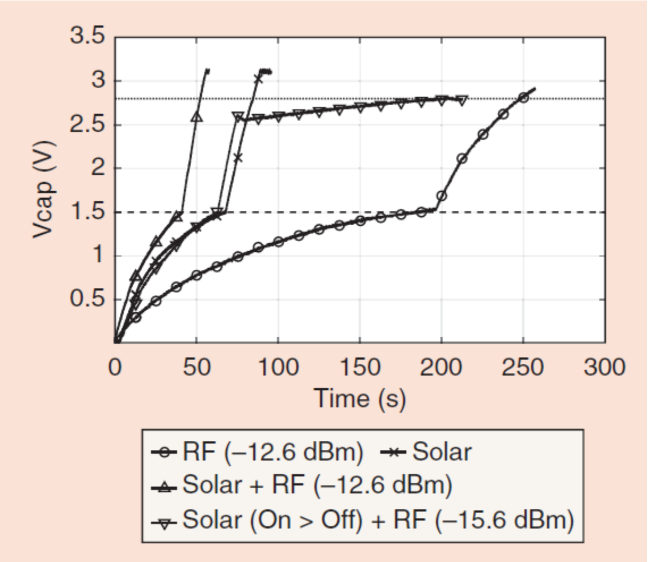
Energy from Thin Air? “Agnostic” Ambient Multiform Energy Harvesting

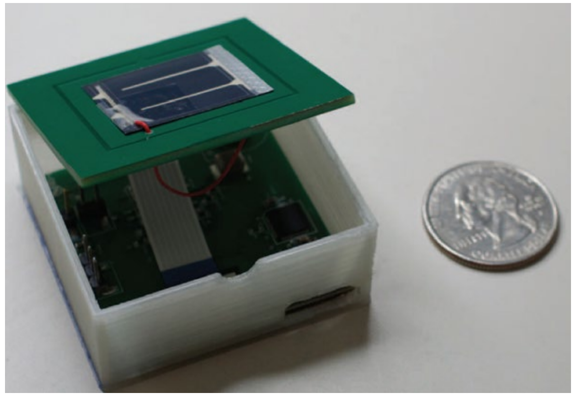
Features:
- A dipole antenna + rectifier for 550MHz (Digital TV) harvests ~100uW from TV tower 6.5km away
- MSP430 + CC2500 for sensing and communication
- Dynamic duty cycle control software for maximize scarce energy intake

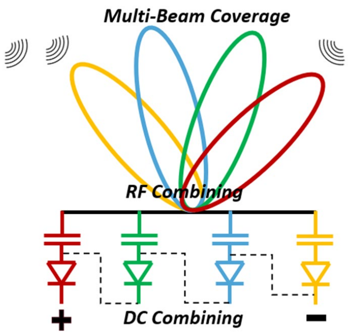


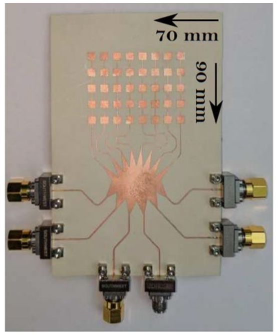


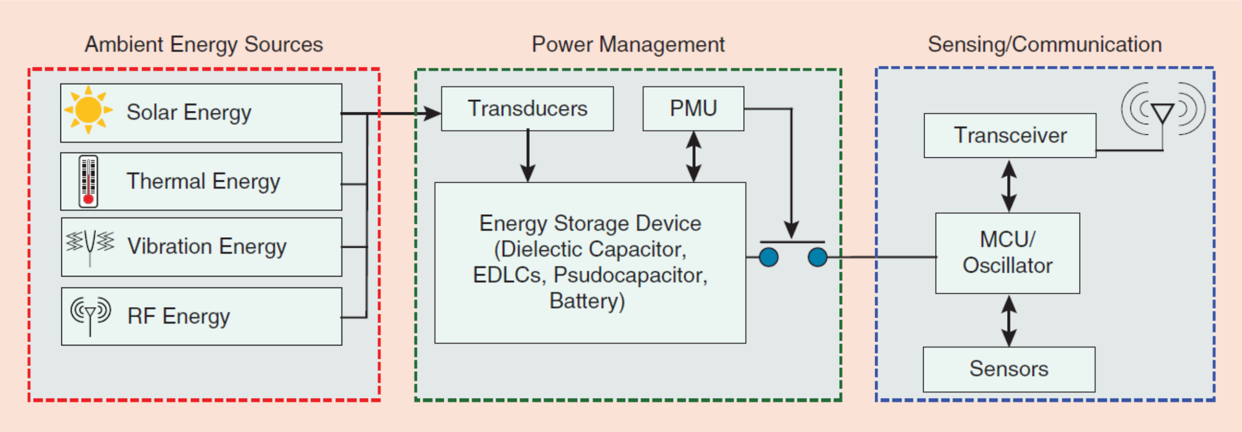






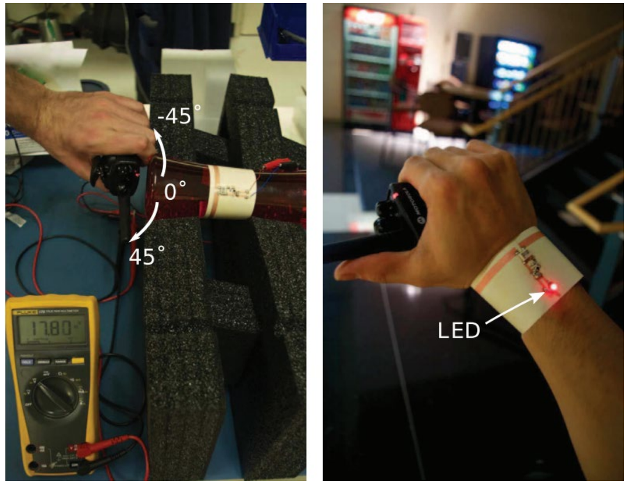




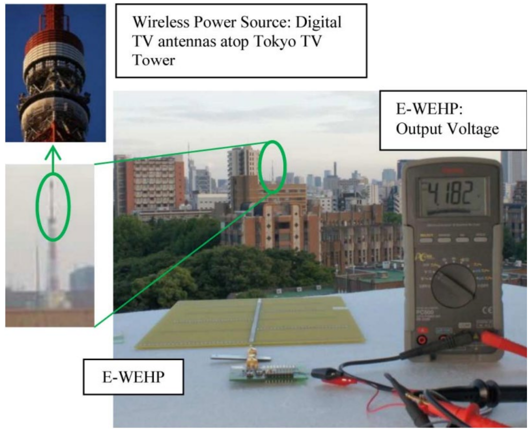


Additive manufacturing for Ambient energy harvesting

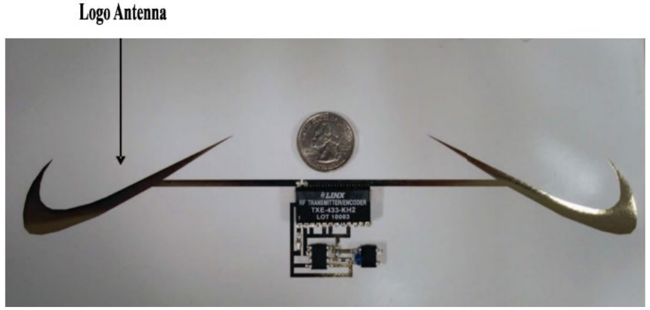
Wearable flexible near-field RF EH



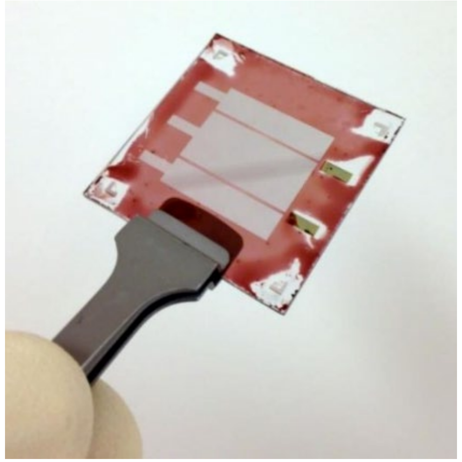
Autonomous EH system for TV signals



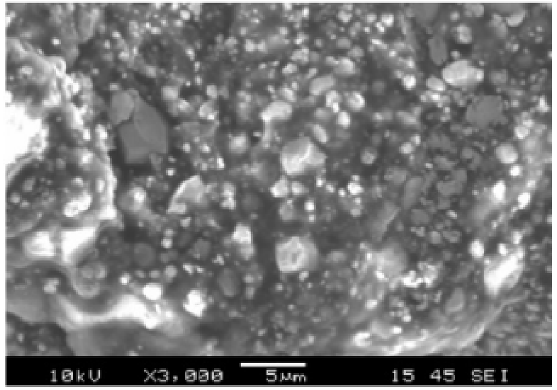
Printed wearable piezoelectric EH for shoes



Printed organic photovoltaic on flexible substrate



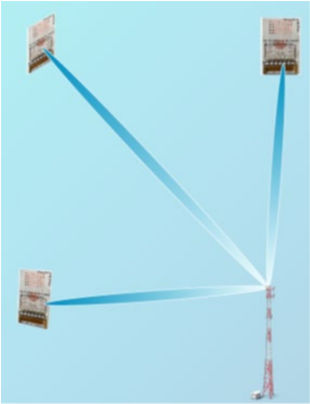
Printed piezoelectric material on flexible substrate

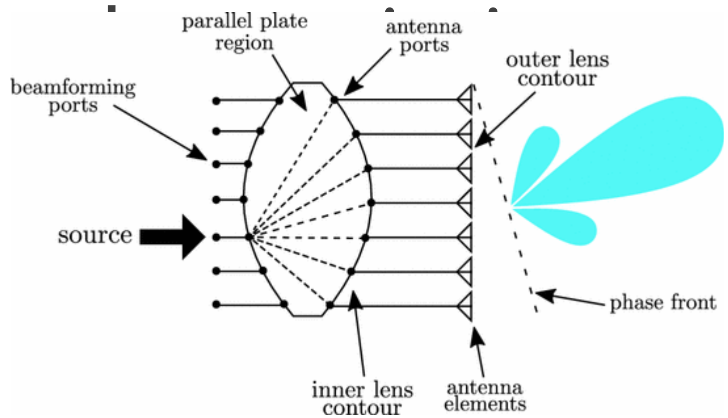


Wireless Charging of Wireless Sensor Modules Using 5G

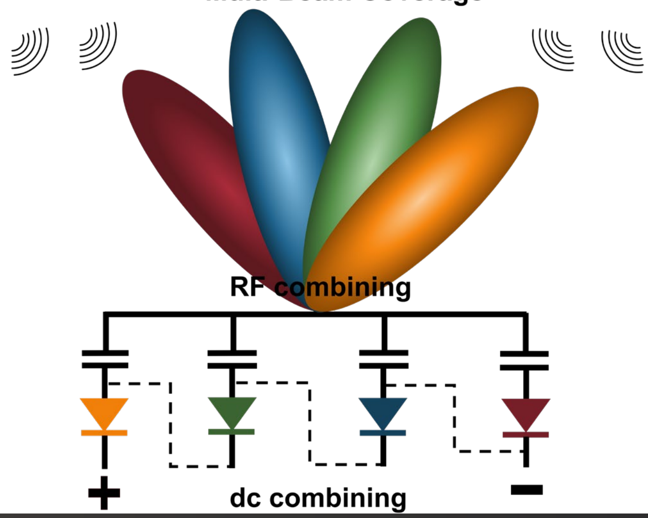
Rotman Lens for mm-wave harvesting

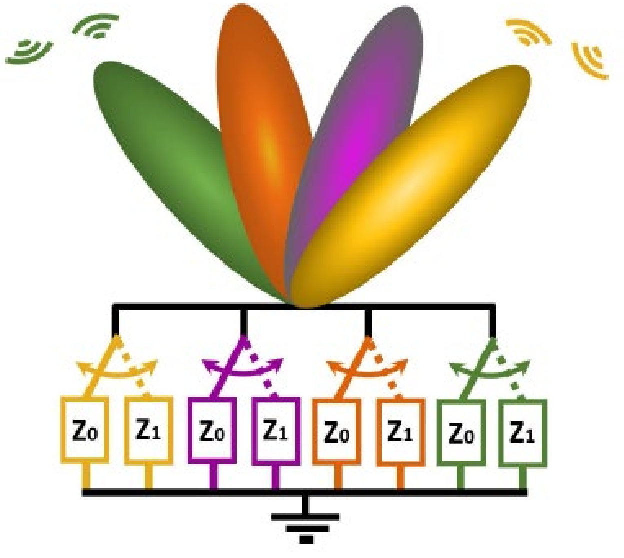
Breaking the High Gain and Large Beamwidth Trade-off at mm-Wave Frequencies





- Electrically large antennas
- High gain and lack of isotropic behavior
- Use of BFNs





Wireless Charging of Wireless Sensor Modules Using 5G

How does it work

Dual Combination: RF + DC

Scavenge mm-Wave Signals

Antenna arrays connected to the antenna ports of the Rotman lens scavenge the mm-wave energy from all directions.

STEP 01

RF Combine and Focus

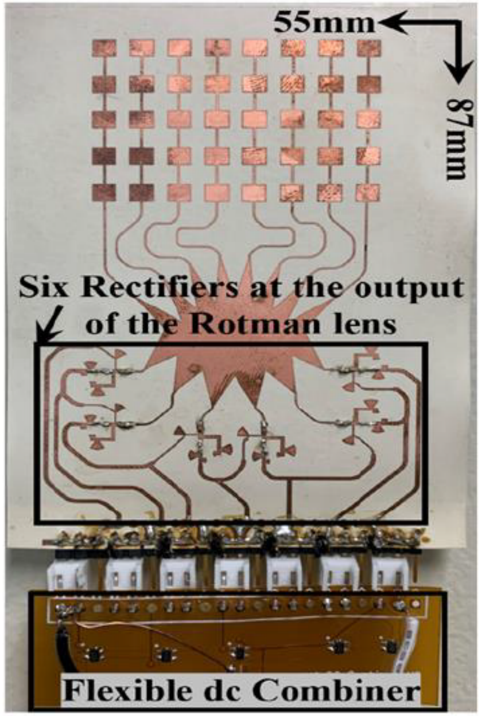
The Rotman lens combines internally all the mm-wave signals collected by the antennas and focuses them to one beam port on the opposite side, where a rectifier is connected.

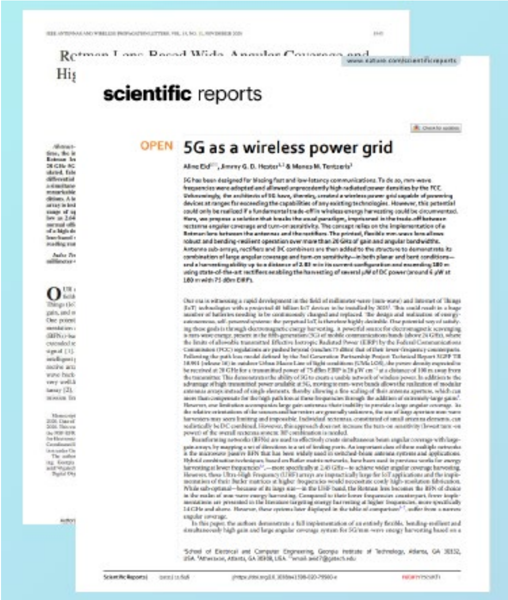
STEP 02

Rectify and DC Combine

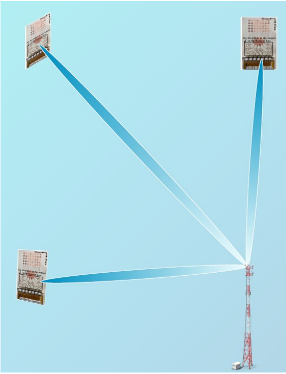
The rectifiers connected at the beam ports of the Rotman lens convert the mm-wave energy to DC power. The DC combiner enables an efficient voltage extraction irrespective of the direction of the incoming signal.

STEP 03




scientific reports

OPEN 5G as a wireless power grid

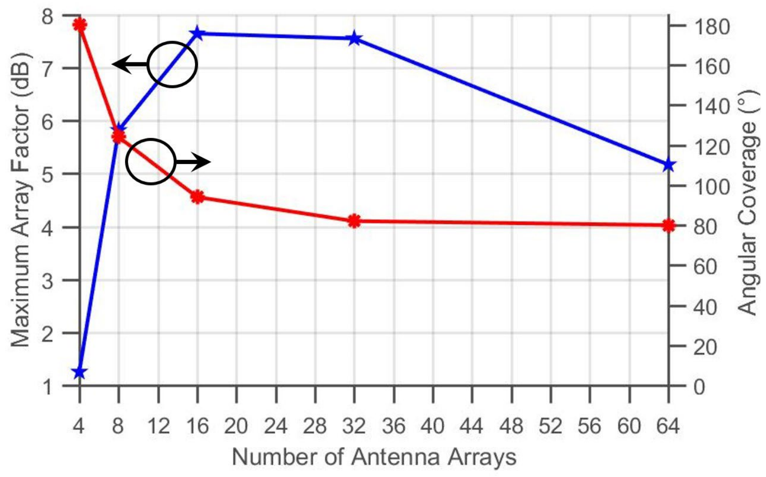


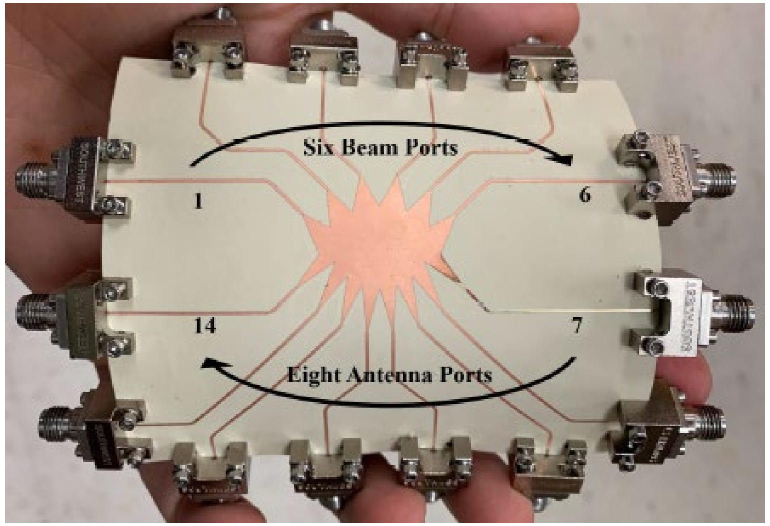
Wireless Charging of Wireless Sensor Modules Using 5G

Scalable and Broadband Structure

Optimal compromise (Na=8, Nb=6):

- High array factor of 5.95 dB
- 120◦ total angular coverage



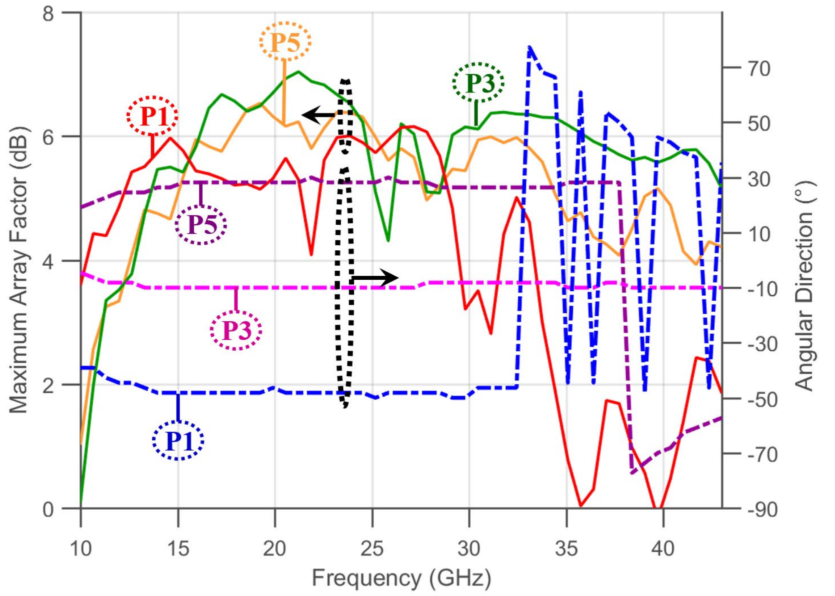


P1, P6: Edge Beams

P2, P5: Secondary Beams

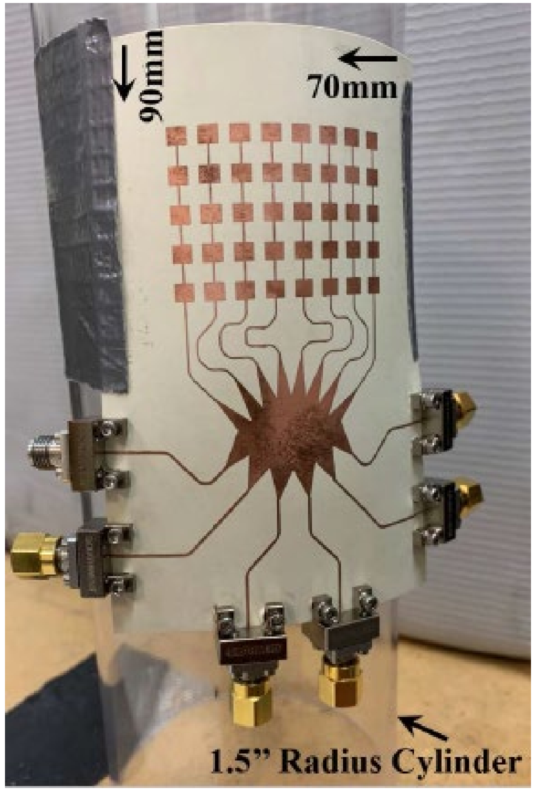
P3, P4: Center Beams

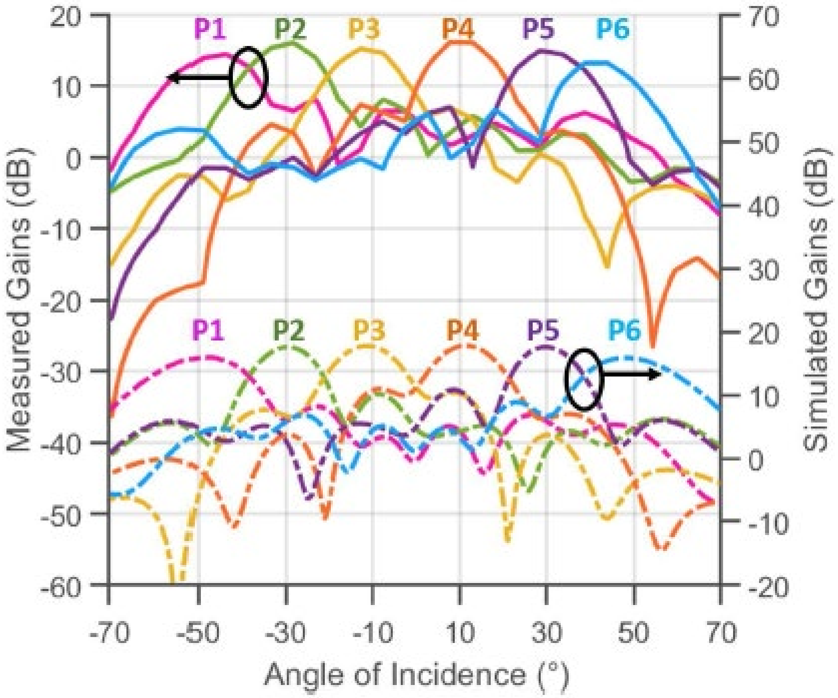
- Beamwidth and array factor maintained over a large **bandwidth exceeding 20 GHz**

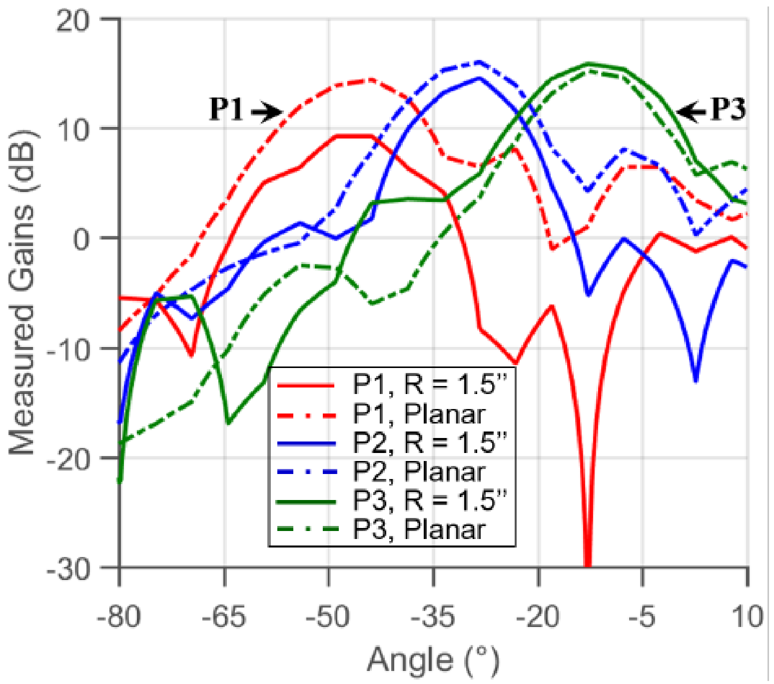


Breaking the trade-off

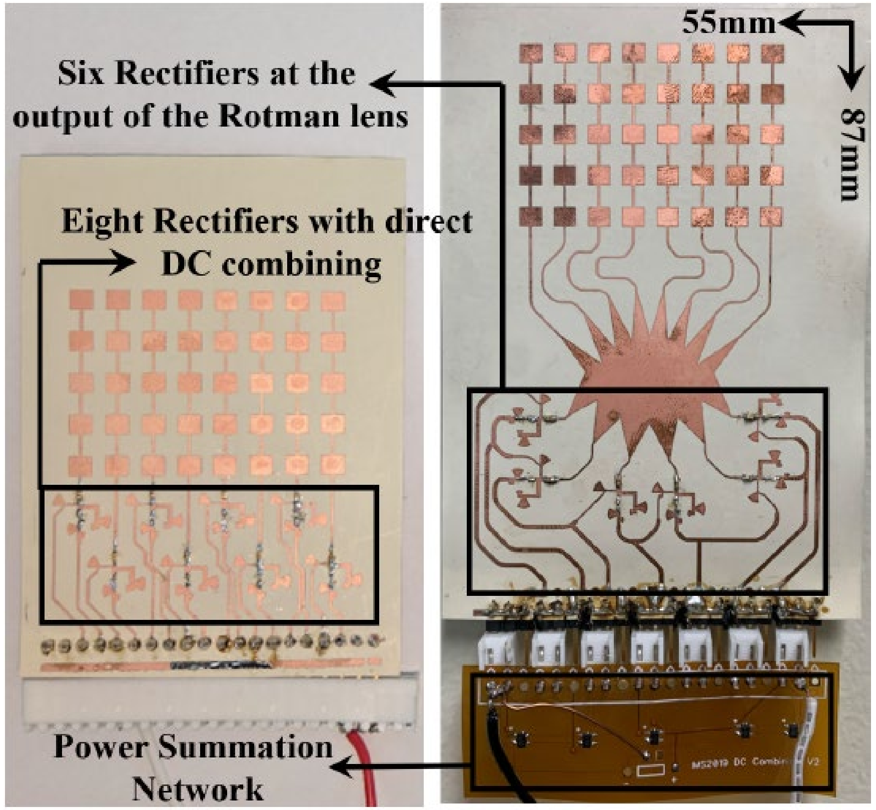
- Eight serially-fed patch antenna arrays added
- **Simultaneous 17dBi gain and 110° angular coverage at 28GHz**
- **Minor** gain deterioration under severe bending



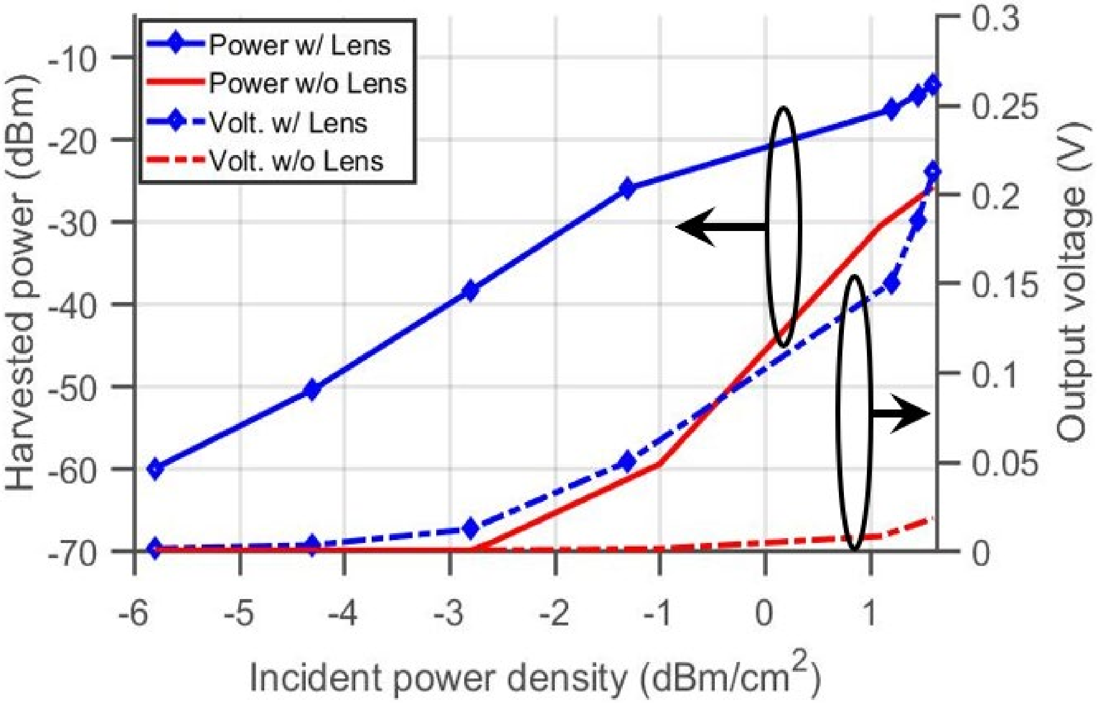




Comparison of this "Direction Agnostic" Solution vs. a Standard Array



Sensitivity of the Systems



- **6dB lower turn-on power density**
- Higher efficiency at all measured power densities
- **21-fold increase** in harvested power

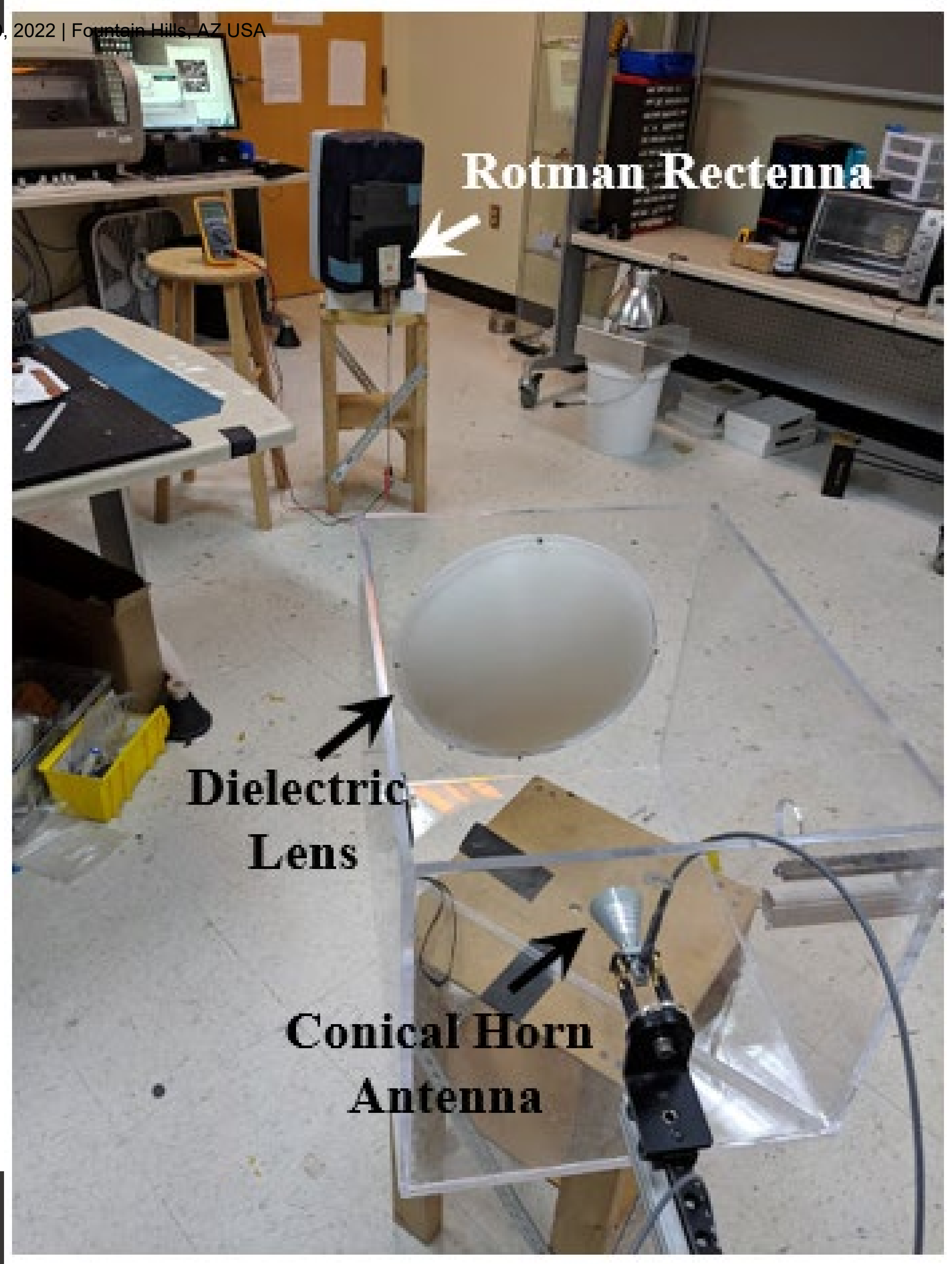
Long-Range
mm-wave Harvesting

- **Longest reported range of 2.83m** under open load conditions and transmitted **54dBm EIRP**

6μW can be harvested **at 180m**

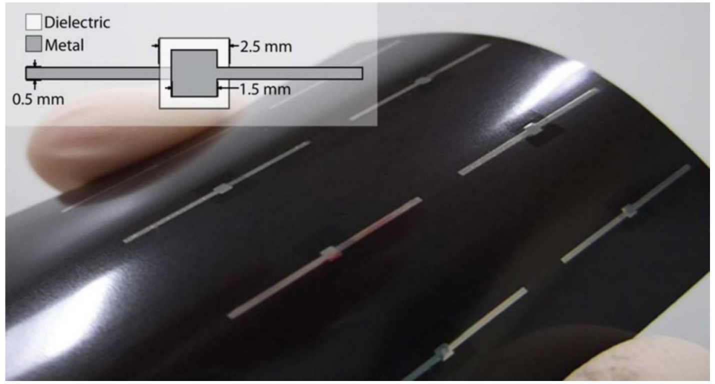
Assumptions:

1. **75dBm EIRP**
2. Rectifier's sensitivity of **-30dBm (PCE ~ 5%)**
3. **3GPP TR 38.901** (release 16) in outdoor Urban Macro Line of Sight conditions (UMa LOS)

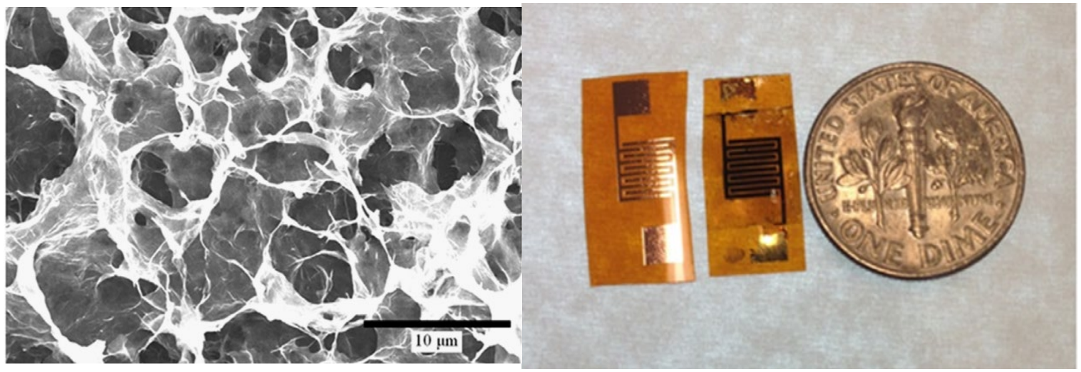


Additive manufacturing for Energy storage

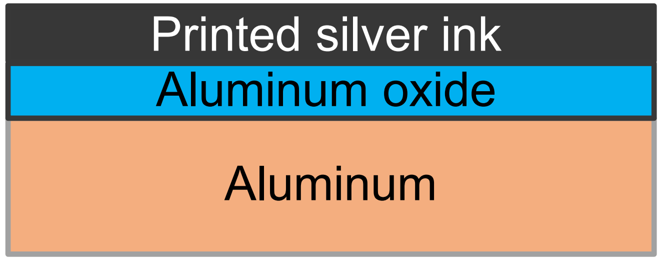
Fully printed dielectric capacitor



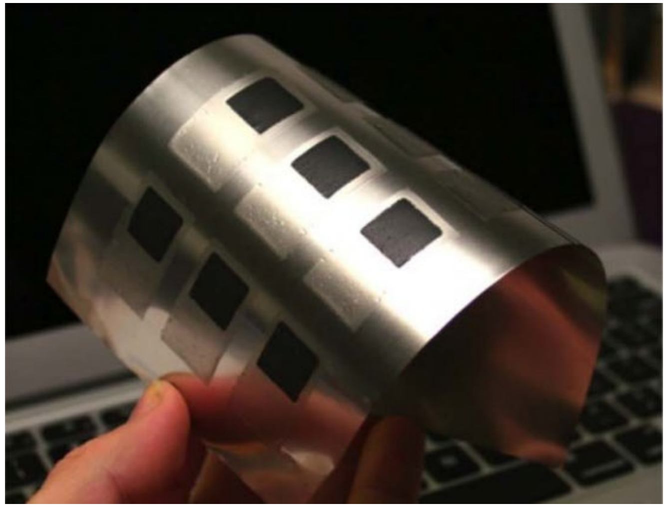
Printed pseudocapacitor (supercapacitor) using graphene oxide (GO)



Printed electrical double layer capacitor



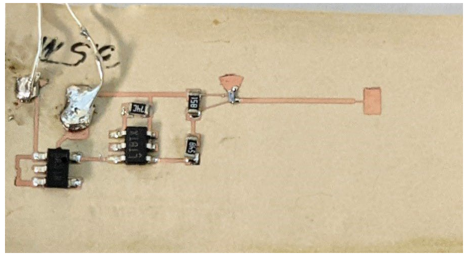
Additively manufactured flexible battery

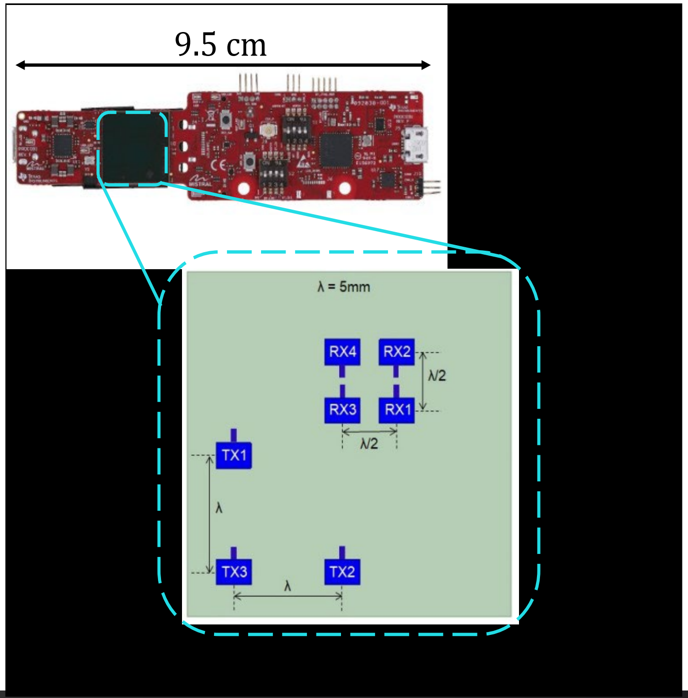


Can we achieve low-cost miniaturized "sub-cm" Micro-localization using 60GHz mmIDs?

- **60 GHz mmWave systems enable high fidelity microlocalization and compact system components.**

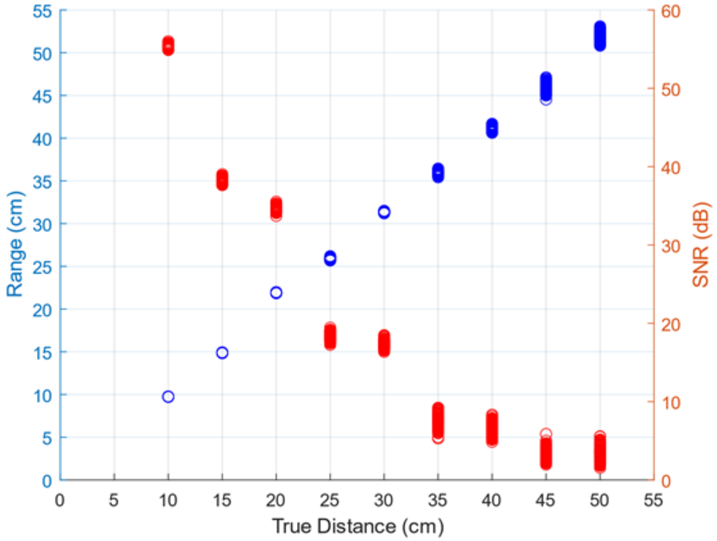
- **Millimeter-wave Identification (mmID) is a natural choice that provides a ultra low-cost compact microlocalization IoT applications.**





Can we achieve low-cost miniaturized "sub-cm" Micro-localization using 60GHz mmIDs?

- **The low-cost, mmID localization system provides 5 mm accuracy up to 0.5 m from the reader.**
- **The angle-of-arrival of the mmID provides 1.79 ° an angular accuracy.**
- **With further development of the reader and mmID tag, the theoretical reading range over 45 m enabling medium and long range microlocalization applications in robotics, wearable, and human computer inferface applications.**



True AoA	Mean of Estimated AoA	STD of Estimated AoA
-40°	-38.91°	1.19°
-20°	-21.74°	0.65°
0°	0.65°	0.58°
20°	21.79°	0.83°
40°	39.82°	1.52°

Is it possible to achieve interrogation ranges of 1km+ for <20uW tag consumption?

Van-Atta reflect-array: Advantages

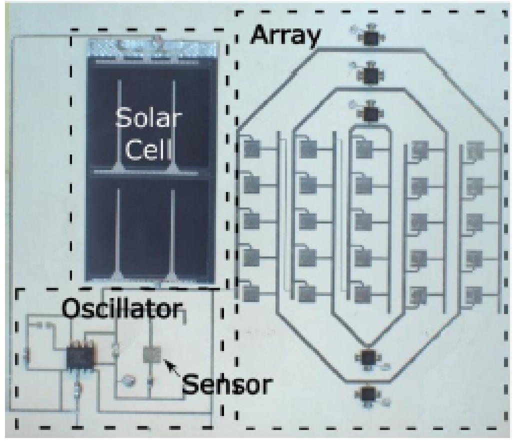
- Unique combination of properties
  - Arbitrarily high RCS (fully scalable)
  - Largely angle independent monostatic response
  - Cross-polarized response

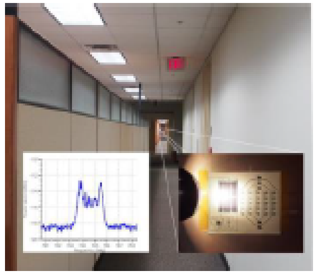
- Reader system consequences
  - High frequency operable (unused bands)
  - High gain, compact, reader antennas (long range)
  - Narrow beamwidth reader antennas (clutter isolation)

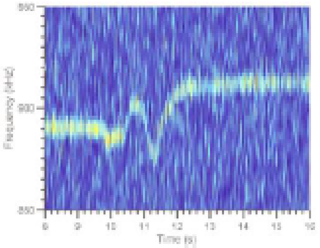
- Operational advantages
  - **Unprecedented (angle independent) reading range (1km+)**
  - Extremely high clutter-induced-interference isolation
  - Compactness

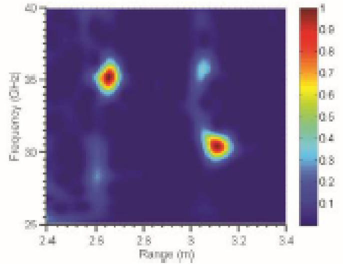
Printed, flexible, backscatter-modulation Van-Atta sensor km-Range "patch" structure

- 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 (20uW)
  - Almost immediate integration of any of our printed gas sensors
    - Several on the same platform, in the future
    - Great resolution (below 0.5m)







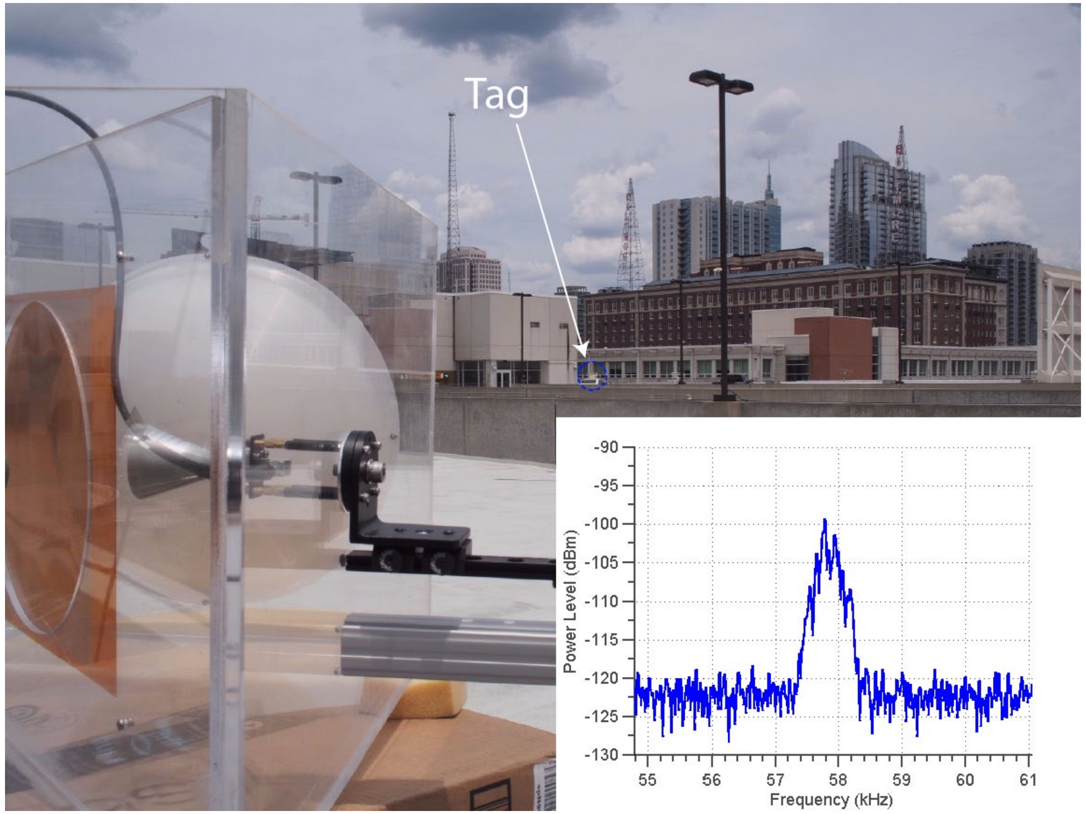


J.Hester and Manos M. Tentzeris, "A mm-Wave Ultra-Long-Range Energy-Autonomous Printed RFID-Enabled Van-Atta Wireless Sensor: at the Crossroads of 5G and IoT", *IEEE International Microwave Symposium (IMS)*, 2017, accepted

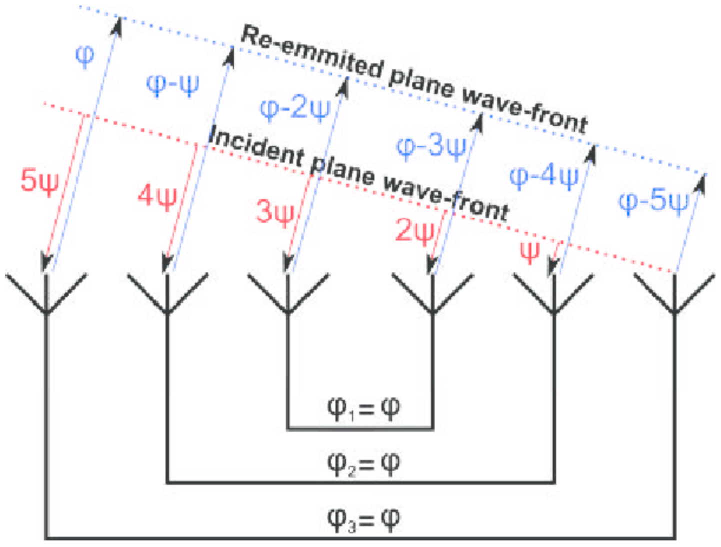
J.Hester and M.M.Tentzeris, ``Inkjet-Printed Flexible mm-Wave Van-Atta Reflectarrays: A Solution for Ultralong-Range Dense Multitag and Multisensing Chipless RFID Implementations for IoT Smart Skinsâ€IEEE Transactions on Microwave Theory and Techniques, Vol.64, No.12, pp.4763-4773, December 2016.

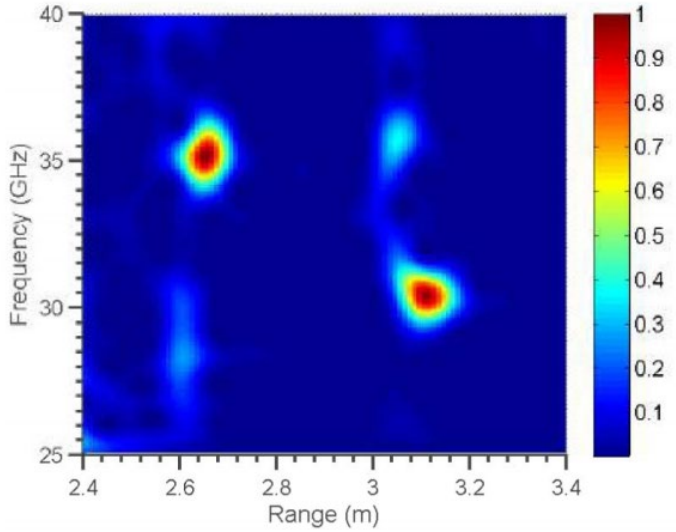
Long-range measurement

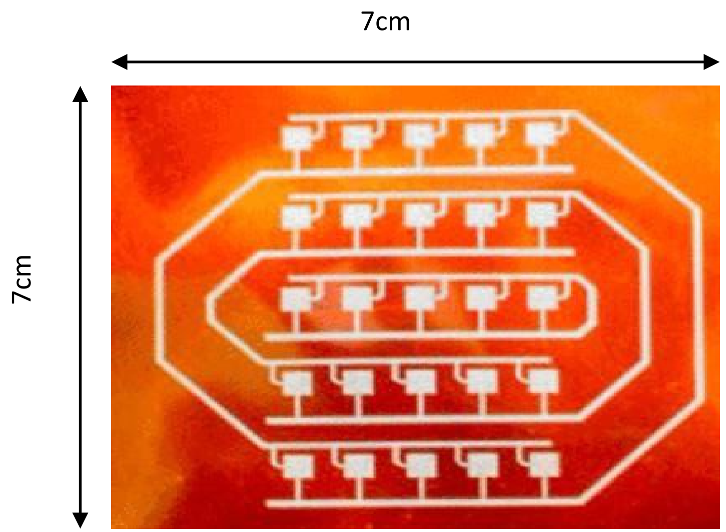
- Set up outdoors at a distance of 90m
- Power consumption of 20 μW during operation
- Energy autonomous, even indoors
- Tag was detected with a SNR of 22dB
  - Enables 250m range
- Outdoor light was used to power the mote
- Longest demonstrated range for a backscatter node



Smart Skin": the backscattering tag is also the wireless strain sensor!



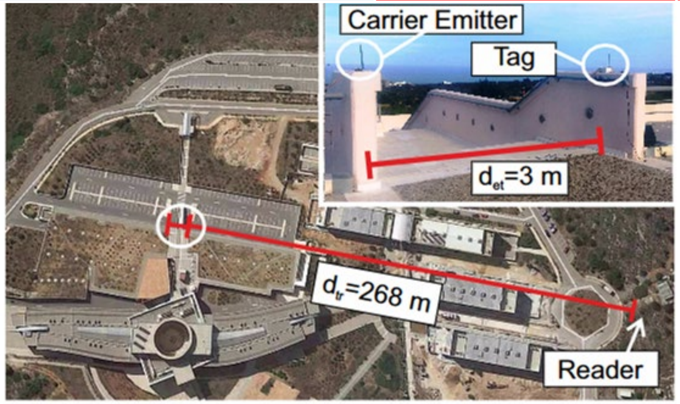


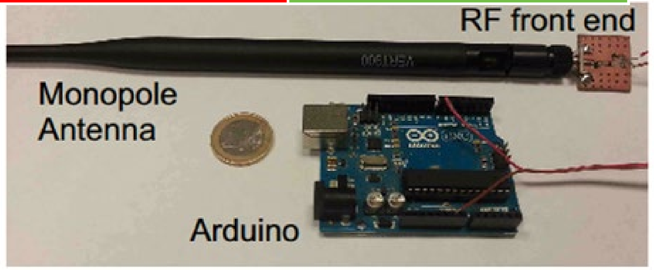


High gain, mmWave retrodirective antenna structure can be frequency and spatially multiplexed to enable dense SHM implementation

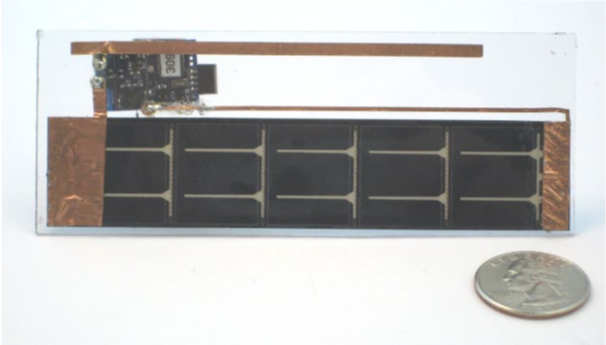
Comparison to the State Of The Art

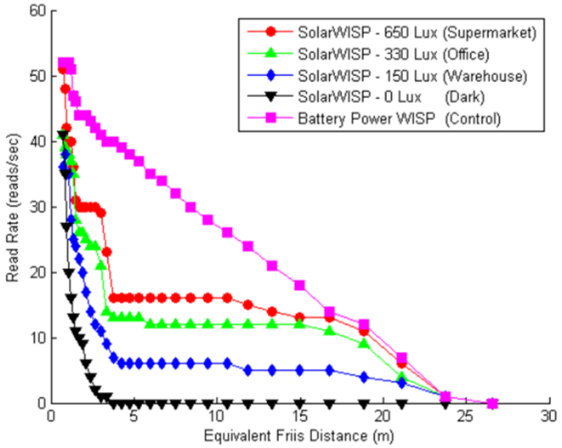
Metrics	[1]	[2]	This work [Atheraxon/GT]
EMrange	28.5m	25m	250m
Area	48cm^2	27cm^2	50cm^2
Can be isolated from support	No	No	Yes
Flexible	No	Yes	Yes
Printed	No	No	Yes
Spatial multiplexing	No	No	Yes
X-pol response	No	No	Yes
Sensing-enabled	No	No	Yes





[1] G. Vougioukas, S. N. Daskalakis, and A. Bletsas, "Could battery-less scatter radio tags achieve 270-meter range?," in 2016 IEEE Wireless Power Transfer Conference (WPTC), 2016, pp. 1–3.





[2] A. P. Sample, J. Braun, A. Parks, and J. R. Smith, "Photovoltaic enhanced UHF RFID tag antennas for dual purpose energy harvesting," in 2011 IEEE International Conference on RFID, 2011, pp. 146–153.