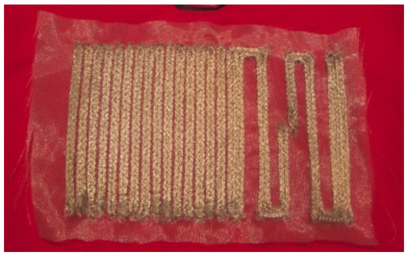
Conductive Textiles for Wearable Electronics

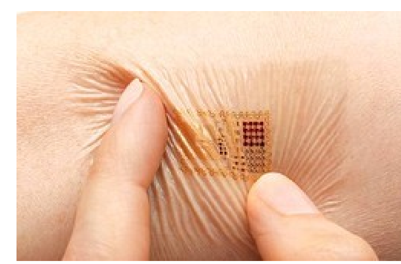


John L. Volakis

Dept. of Electrical and Computer Engineering

Florida International University

E-mail: jvolakis@fiu.edu



FLORIDA INTERNATIONAL UNIVERSITY

Motivation for Wearable Applications

Assist government with non-interrupted assistance on the battlefield

Medical applications: continuous monitoring of patient vital signs

Enabling body-integrated electronics

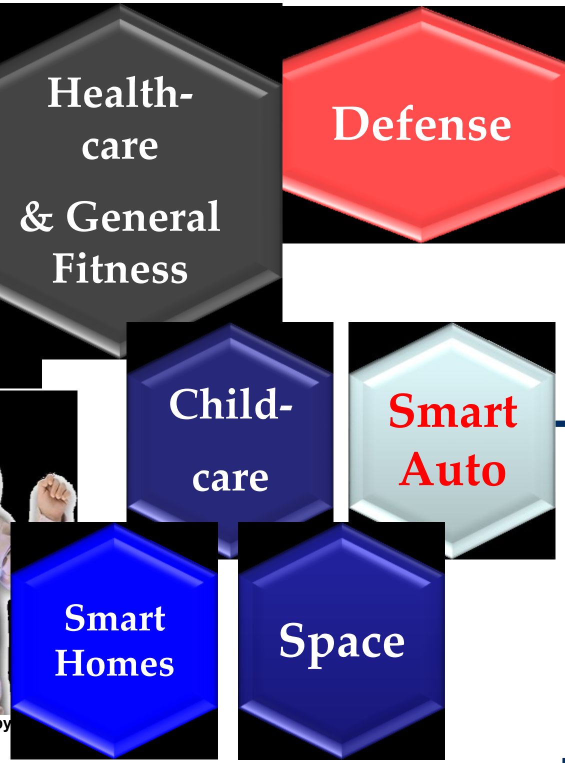
Internet of Everything: constant connectivity between objects and humans

Assisting elderly, infants, disabled, pets etc.

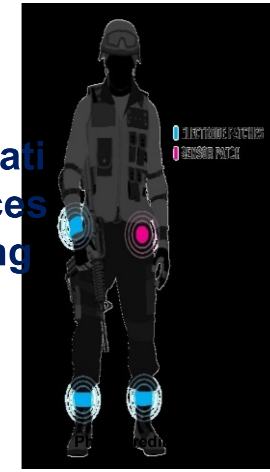
multi-billion wearable market with lots of potential

Textile Electronics and their Potential

- Concussion-detecting helmets
- Performance metrics (heart rate, oxygen levels, etc.)



- Integrated communication interfaces and sensing tactical gears



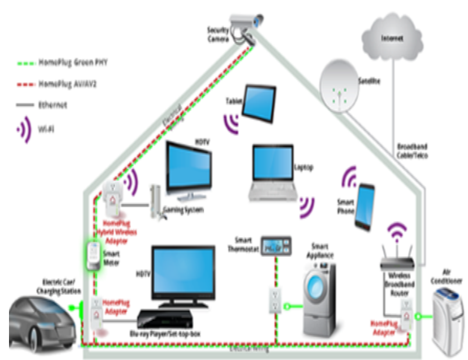
- Sleep monitoring
- Location tracking
- Performance matrix tracking

Photo credit: MonBaby

- Sensors/ Antennas integrated in Car-seats/belts
- Enhanced WiFi/ GSM connection

- Integrated sensors in curtains, seats, carpets
- Security / Emergency

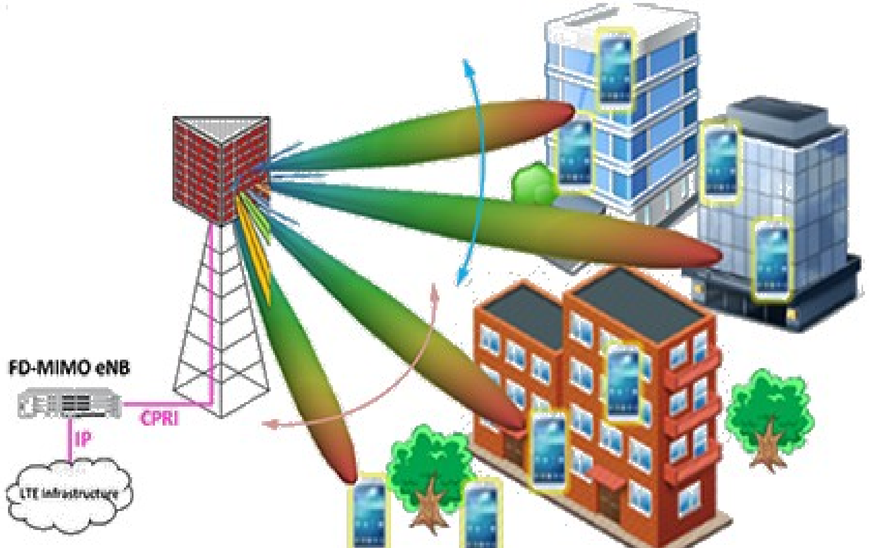
Photo credit: Ant Yradar



- Sensor-enabled Space Suits

Photo credit: NASA

Outlook and Research Areas in 5G, 6G, and Beyond/RF Communication Systems



Source: Samsung

New Market Demands

- Amazingly Fast
- Great Service in a crowd
- Super Real-time & reliable communications
- Ubiquitous "things" Communicating

Source: https://www.extremetech.com/extreme/176093-v2v-what-are-vehicle-to-vehicle-communications-and-how-does-it-work

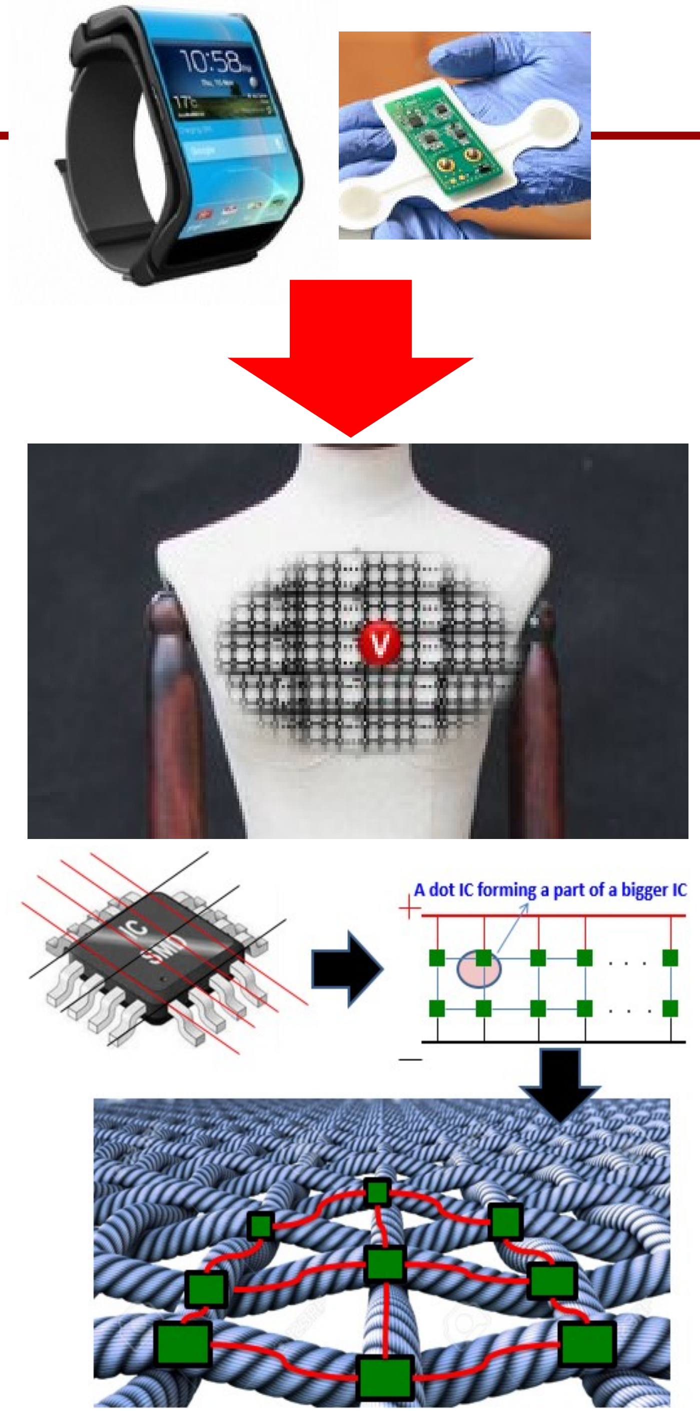
Areas of Research:

1) Ultra-Wideband (UWB) systems
2) RF front ends: frequency agile, very small size, weight area, and power efficient (SWAP)
3) Advanced techniques to address spectrum coexistence and improve spectral efficiency and interference mitigation
4) Communication in contested environment
5) Millimeter-wave systems
6) RF-digital Transceivers
7) Integrating Machine Learning and Artificial Intelligence in RF design

FIU

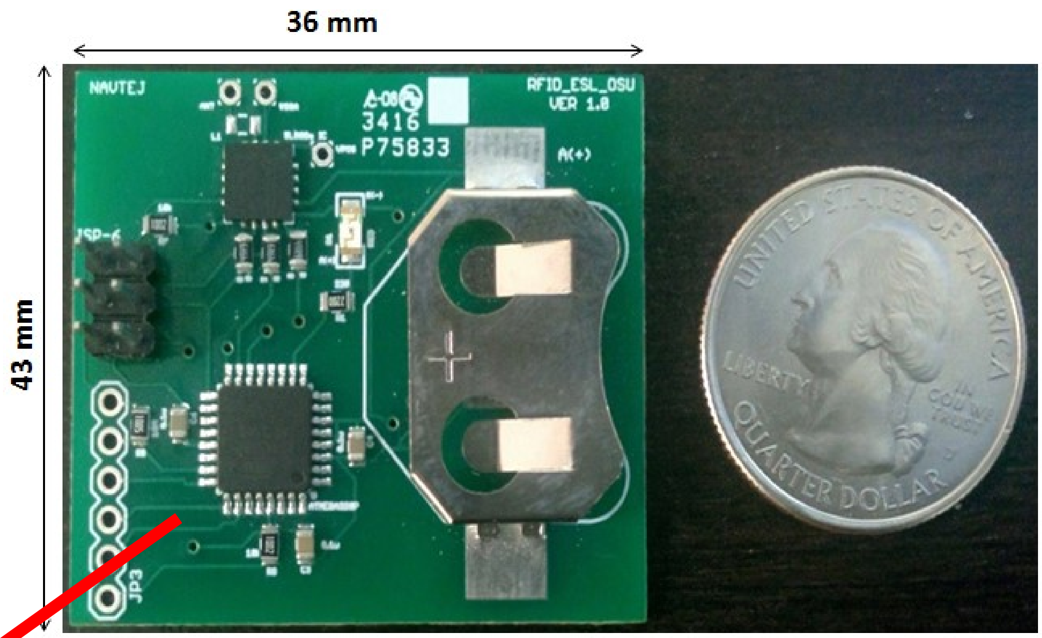
Ensuing Concept

- **Create textile-based electronics for integration into clothing or fabrics. Goal is to enable communications, IoT and sensing without using handhelds or discrete accessories.**
  - **Current Wearables are lumped accessories**
- **Can we create electronic surfaces that include circuits and IC components and which are part of our clothing.**
- **Can we power these electronics using remote power harvesting.**

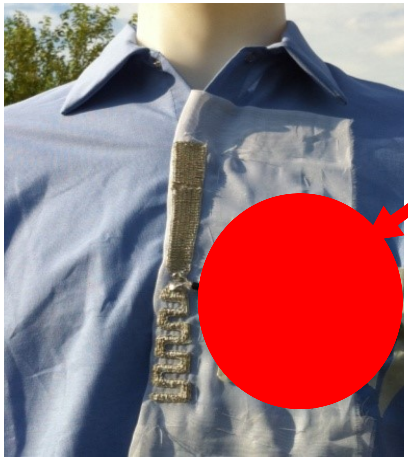


Transceiver Board on Textile Surfaces

- Decompose chip into smaller components (0.5 to 1 mm) and insert them across the textile grid.
- Employ our electronic textile grids to create circuits and connections around the chips.
- Create matching circuits and connections to multitude of sensors, including wireless sensors
- Distributed flexible batteries
- Eventually, power harvesting surfaces



UHF RFID reprogrammable tag circuit board

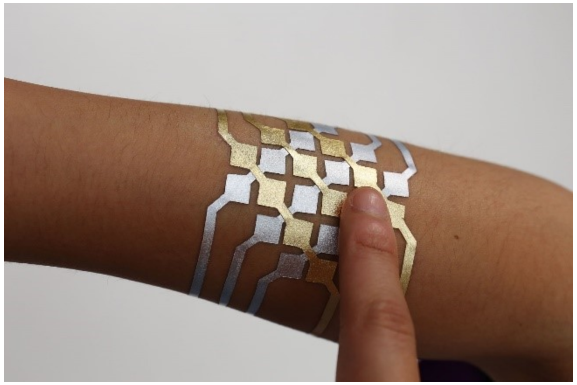


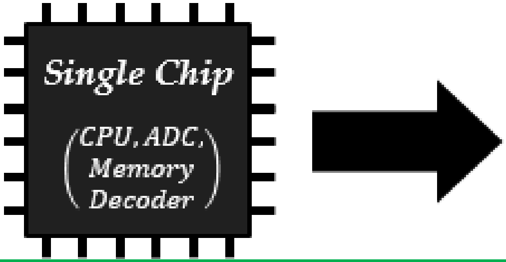
Entire chip & Board is printed on textile surface

Board Features

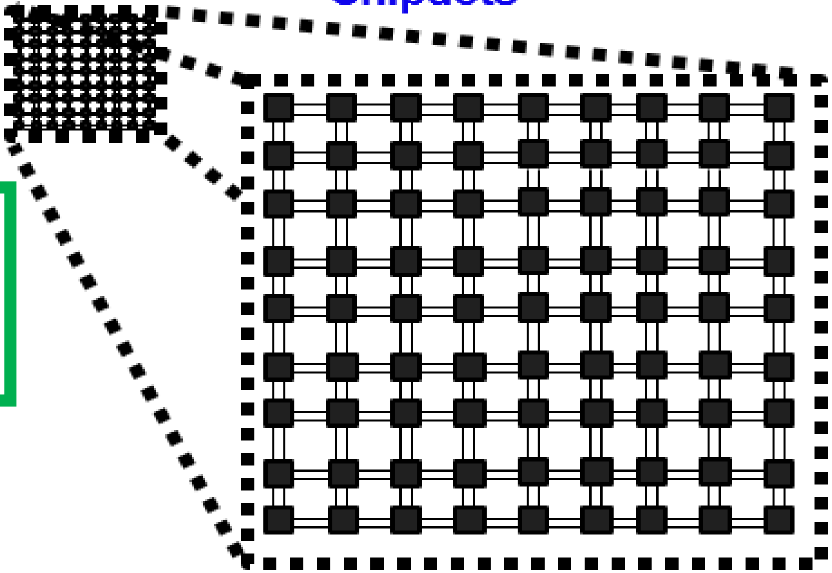
- Multiple sensors
- Data Processing
- Data Logging
- Reprogrammable on board
- UHF RFID EPC Class 1 Gen 2 compatibility
- Interface to externally designed Antenna

Future Electronics will be Wearable





Textile Embedded Chipdots



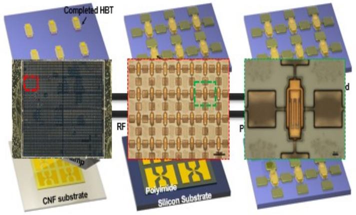
Wearables:

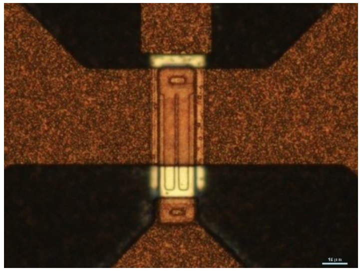
- 37% annual growth
- 300 million devices to ship

- **Morgan Stanley projects a $1.1T market for IoT and wearables.**

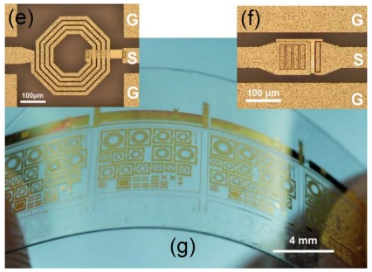
Flexible Electronics are at their Infancy

(similar to transistors before microprocessor chips)

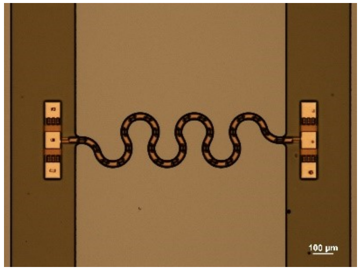




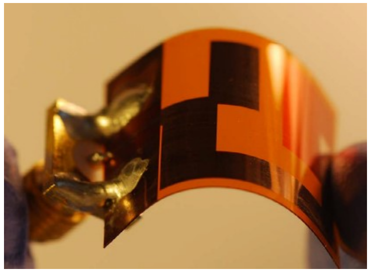
RF transistor



Inductors & Capacitors



Transmission Line

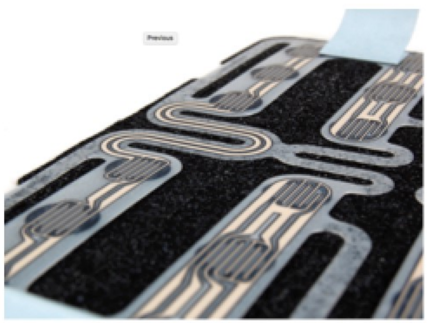


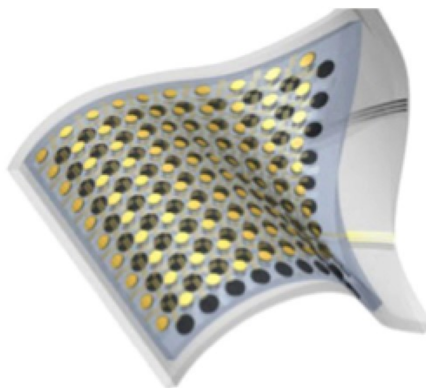
Antenna

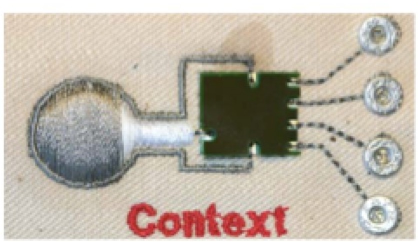
Slide from
Prof. Jack Ma (Wisconsin)

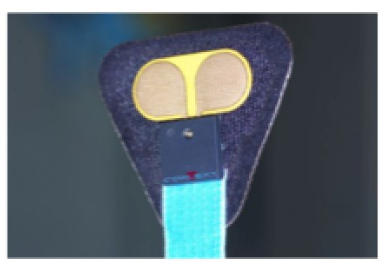
Expanding Frontiers in Biosensing

- Wireless sensors embedded into clothing for continuous monitoring of human physiology *unprecedented spatial density* will provide new modes of diagnostics for healthcare delivery and research.









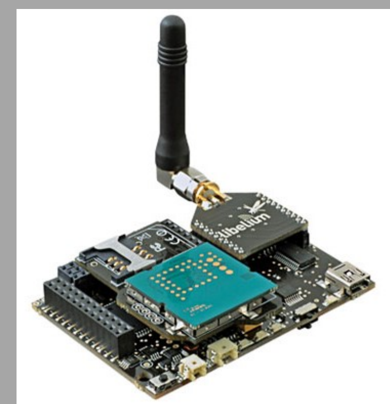
Current state of art- Medtronic ECVUE, all electronics are external, limiting use to clinic

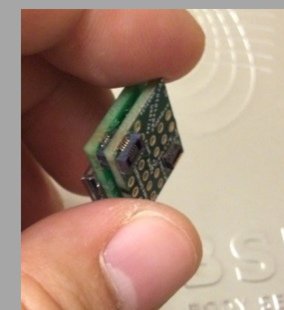
Will be Challenging

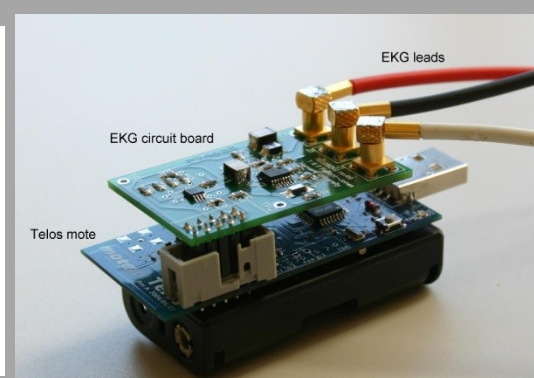
Courtesy of UC-San Diego

Traditional Sensors and Electronics

Existing sensors and electronics are rigid, breakable, bulky, and obtrusive.

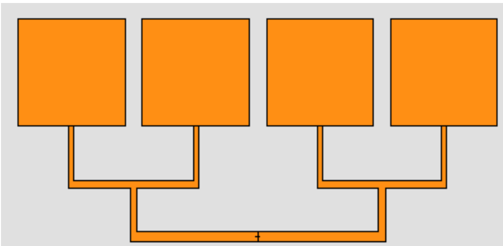






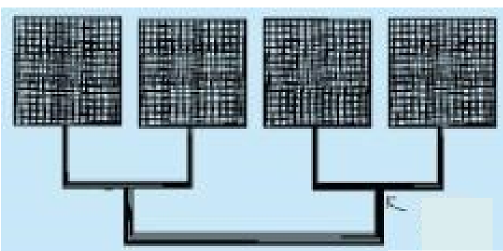
Our Embroidery Technology

HFSS model

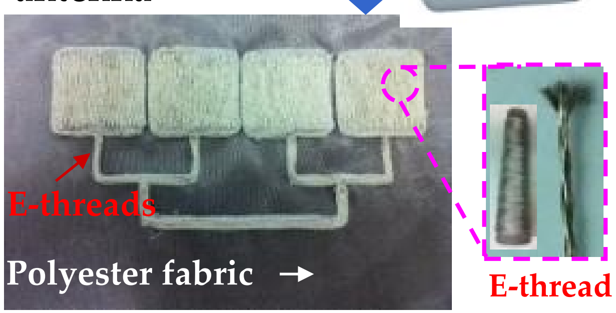


Export to specific computer program

Digitization



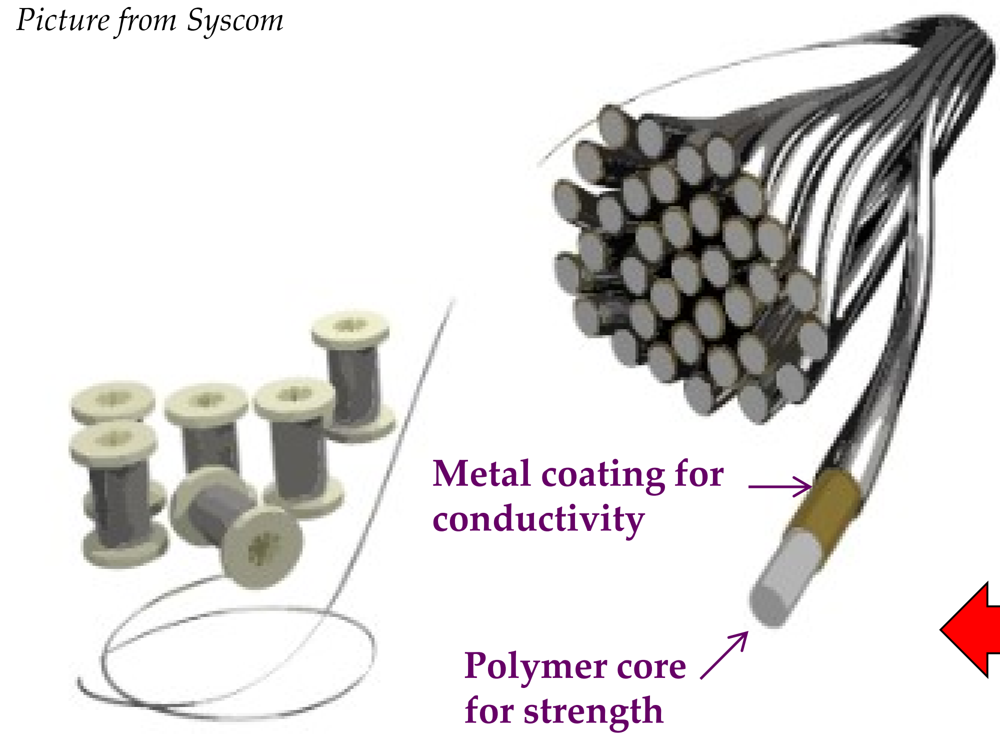
Embroidered antenna



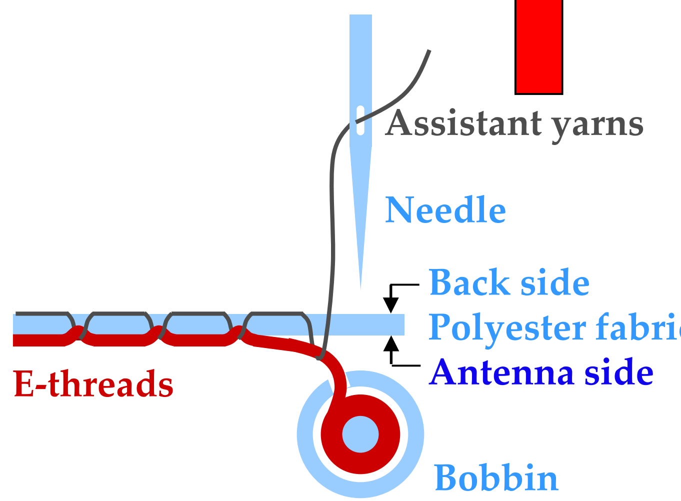
Threads Used for Antenna Embroidery

Assistant Yarn: Regular non-conductive thread.

E-threads: Metal-coated polymer threads, bundled into groups of 7s to 600s to form threads.

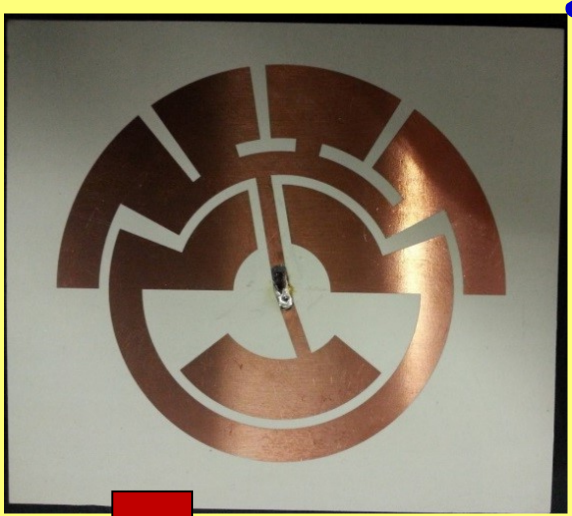


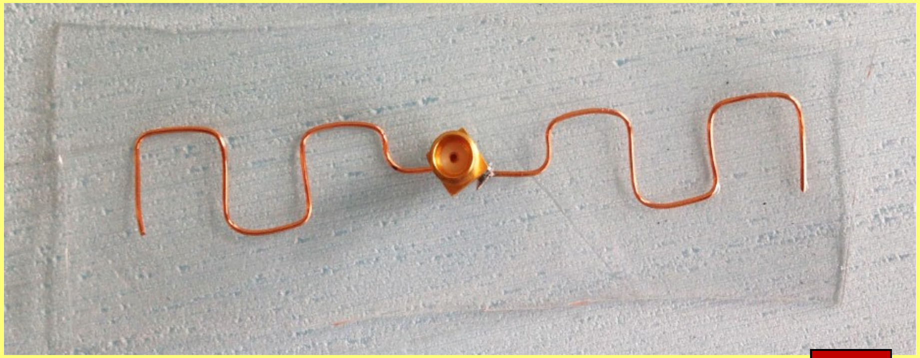
Picture from Syscom



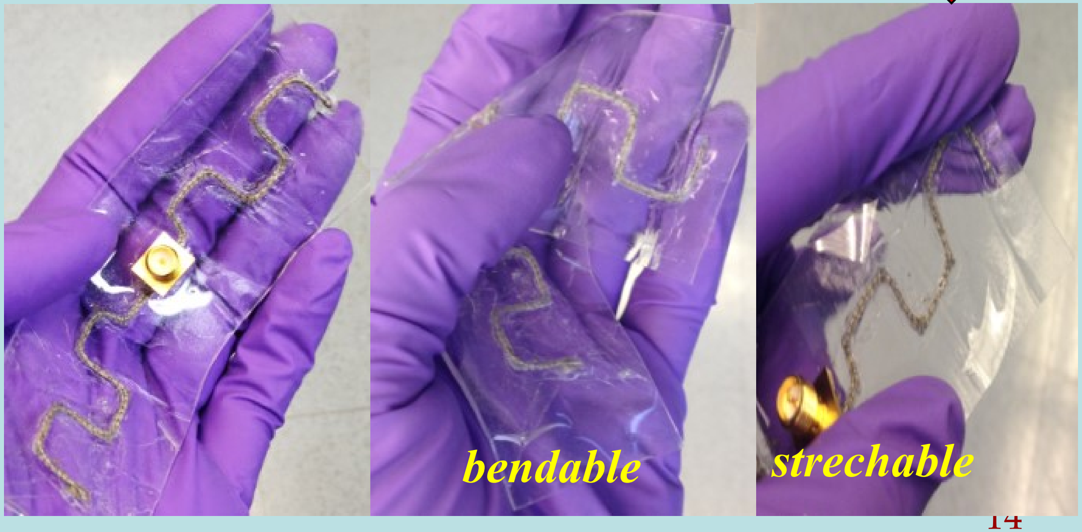
E-Textile Electronics in Our Group

Rigid copper prototypes





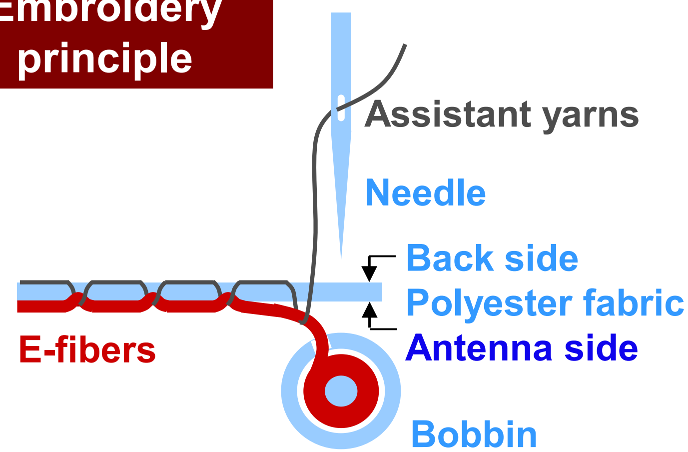
Flexible E-textile prototypes



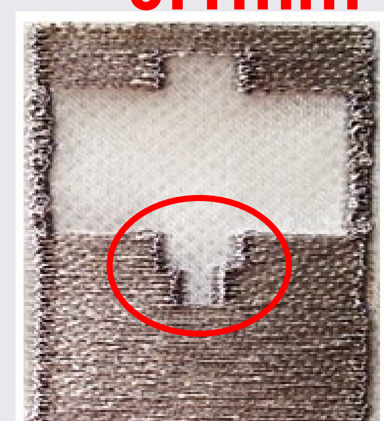
Automated Embroidery of Textile E-threads

- Export antenna design pattern.
- Digitize thread route for automated embroidery.
- Embroider on fabrics using braided or twisted E-fibers (embroidery process uses assistant non-conductive yarns to “couch” down E-fibers).
- E-fibers: Metal-coated polymer fibers, bundled into groups of 7s to 600s to form threads. Each thread may be down to ~0.12mm in diameter.

Embroidery principle

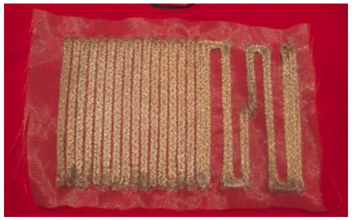


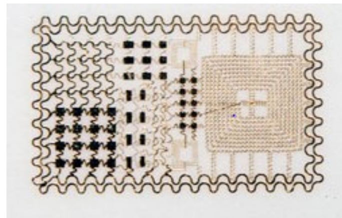
0.1 mm – Precision Achieved in Embroidery

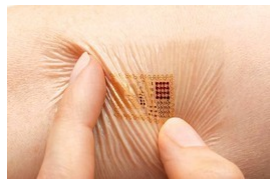
	Former Technology (2013)	Latest Technology (2016)
Provider	SYSCOM, USA	ELEKTRISOLA, Switzerland
# of filaments	664	7
Diameter	0.5mm	~0.1mm
Embroidery accuracy	0.5mm 	**~0.1mm**  
Embroidery density	2 threads/mm	7 threads/mm

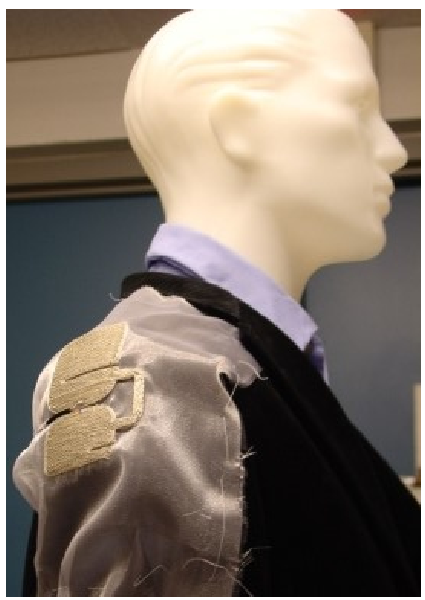
Fabric Electronics for Adaptable Smart Technologies: IoTs, Communications & Sensing (FEAST)

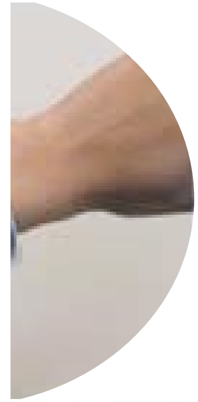
“Printed” on any Fabric





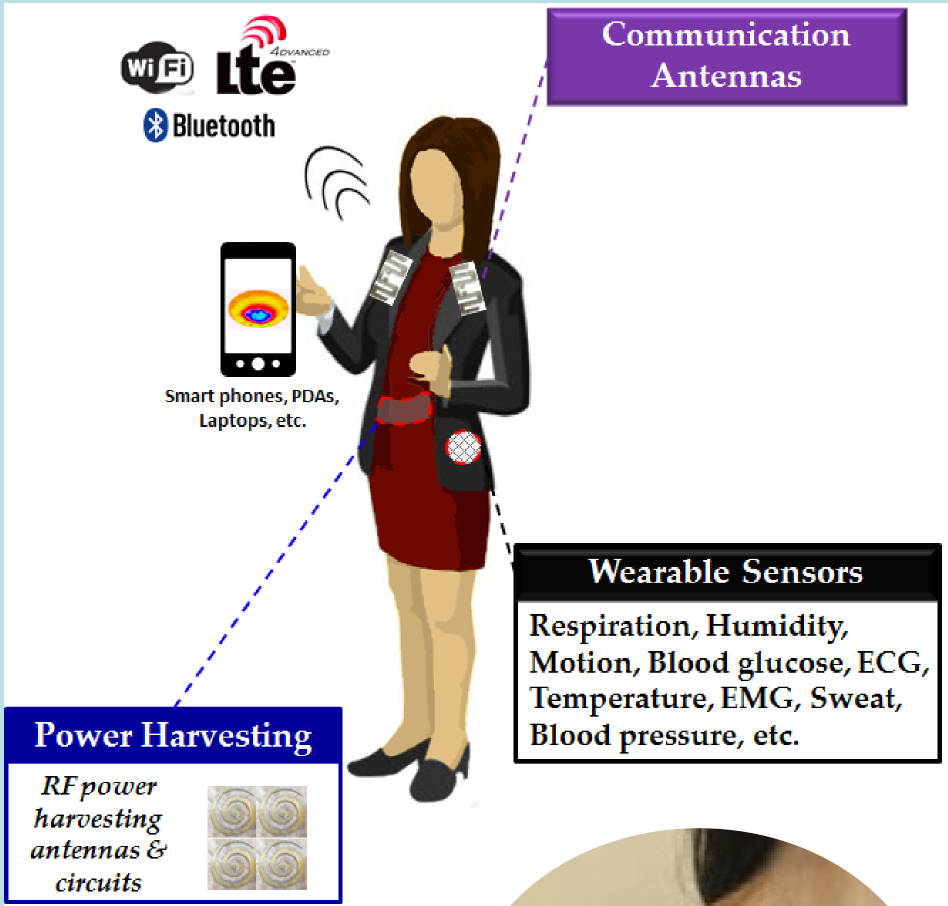






E-Textiles vs. Wearables

E-Textiles



Wearables

Apple Watch: heart rate sensor, GPS and accelerometer used to measure "the many ways you move"

> $350

https://www.apple.com/watch/

Jawbone Activity Tracker: tracks activity, sleep stages, calories, and heart rate.

> $30

https://jawbone.com/

Sensoria Smart Socks: detects parameters important to the running form, including cadence and foot landing technique

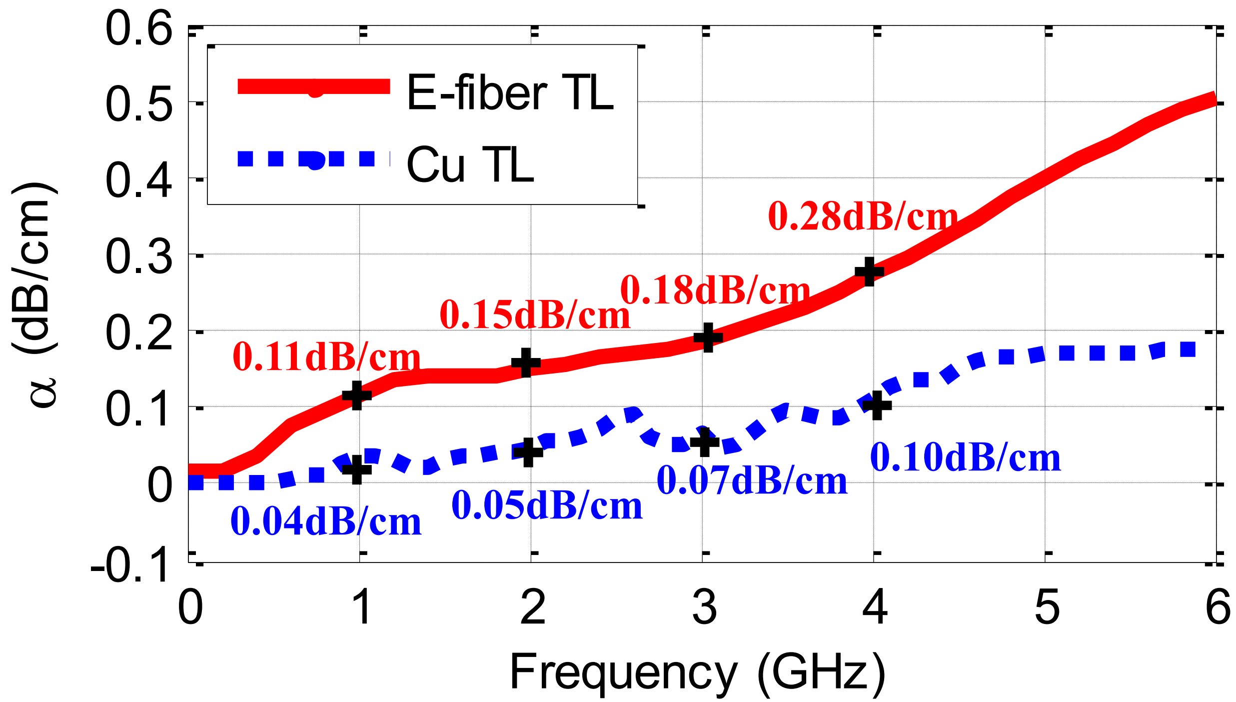
$200

http://www.sensoriafitness.com/

E-Textile Properties

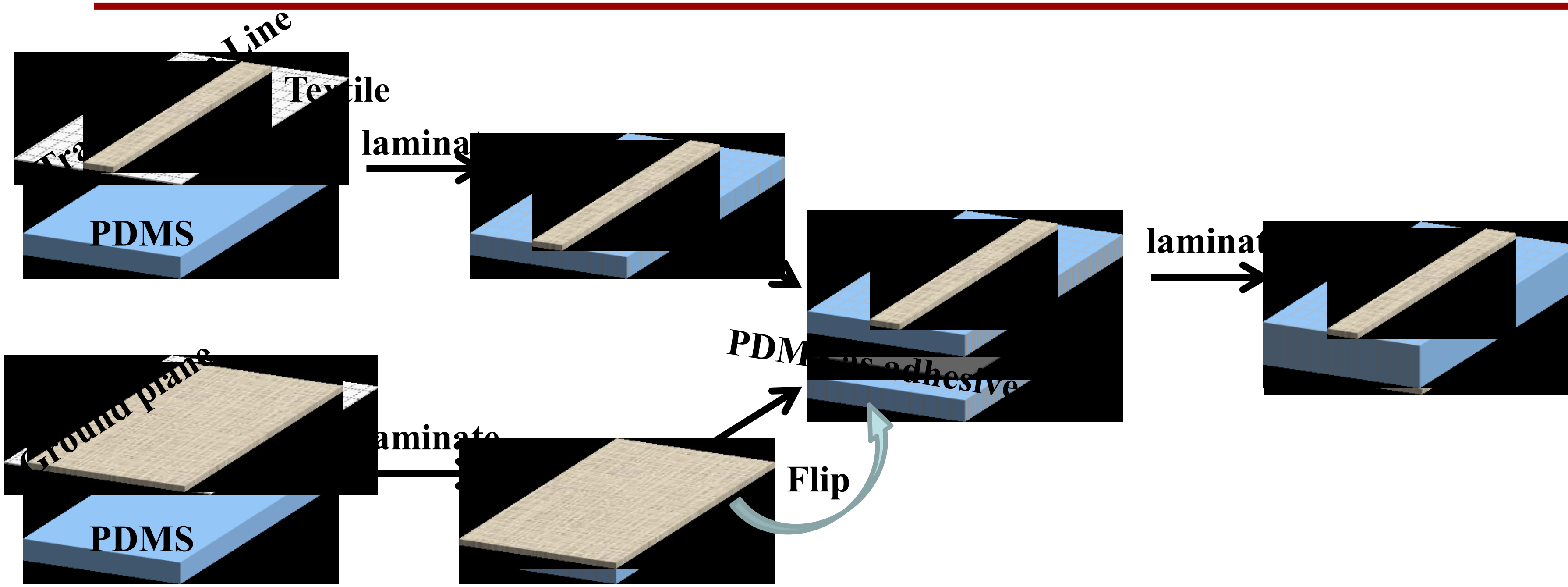
Attenuation Comparison of E-textile and Copper TL

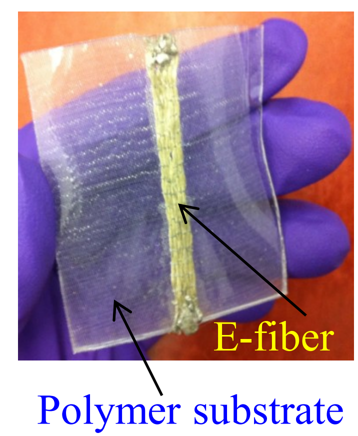
E-fiber textiles are efficient conductive media for RF applications



- Overall attenuations of E-fibers are small, making it an efficient conductive media for RF designs.
- Increased attenuation losses at higher frequencies are due to surface roughness and imperfect metallization of the E-fibers.

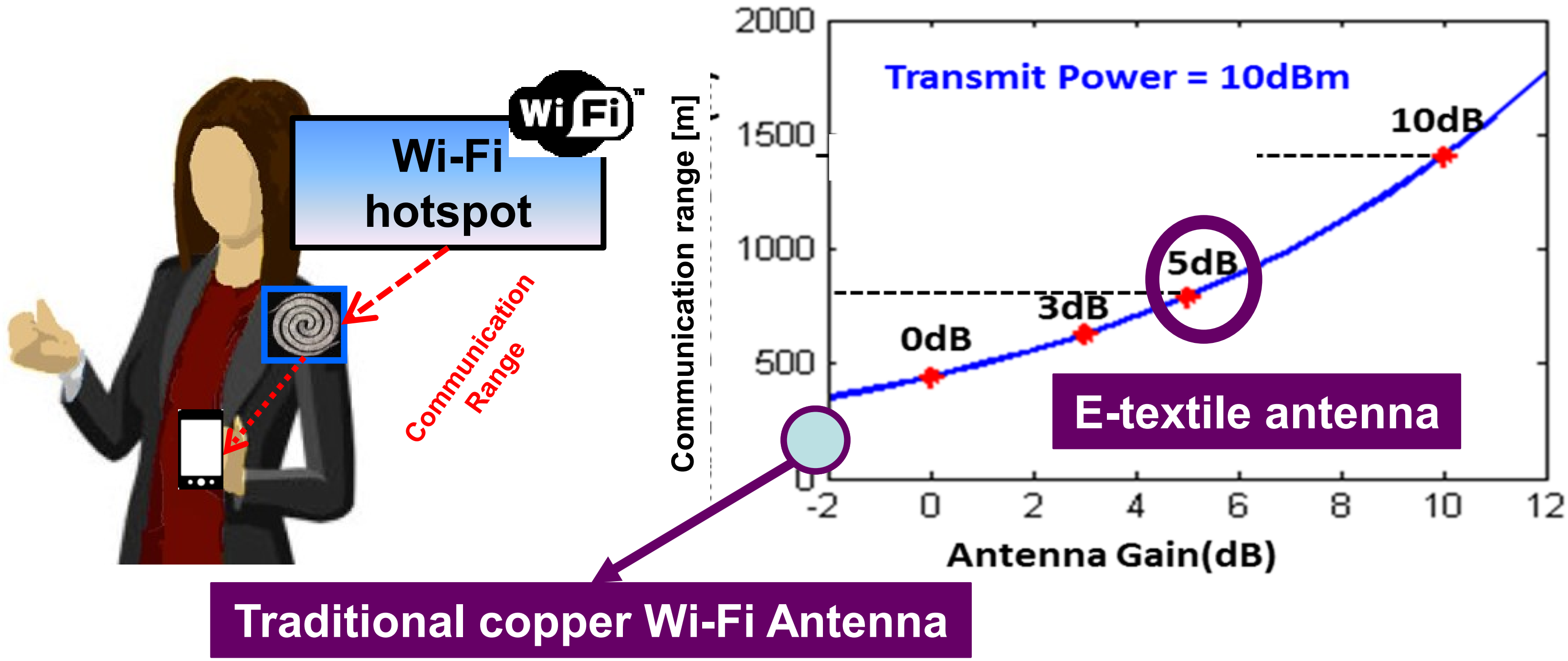
Textile Circuit Assembly on PDMS Substrate





- PDMS: polydimethylesiloxane.
- Elastomeric substrate, mechanically compatible with embroidered textile circuits.
- Tunable dielectric constant of (ε_r~3-13) with ceramic loading.
- Uniform PDMS substrate by casting.
- Partially cured PDMS as lamination adhesive.

E-Textile Antennas Improve the Communication Range vs. Traditional Copper-Based Antennas

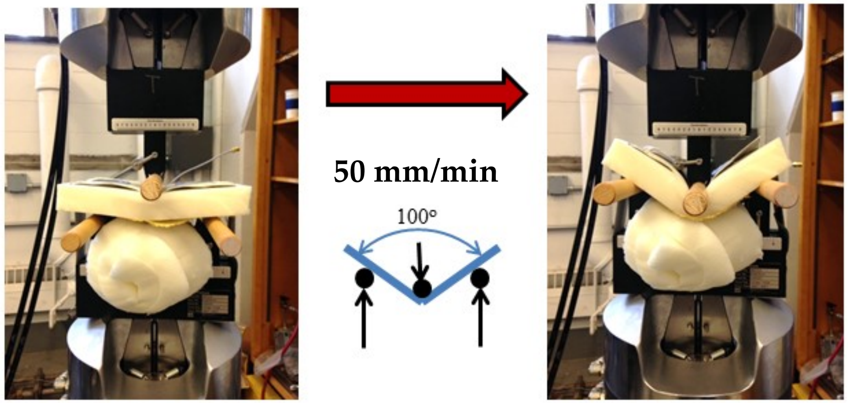


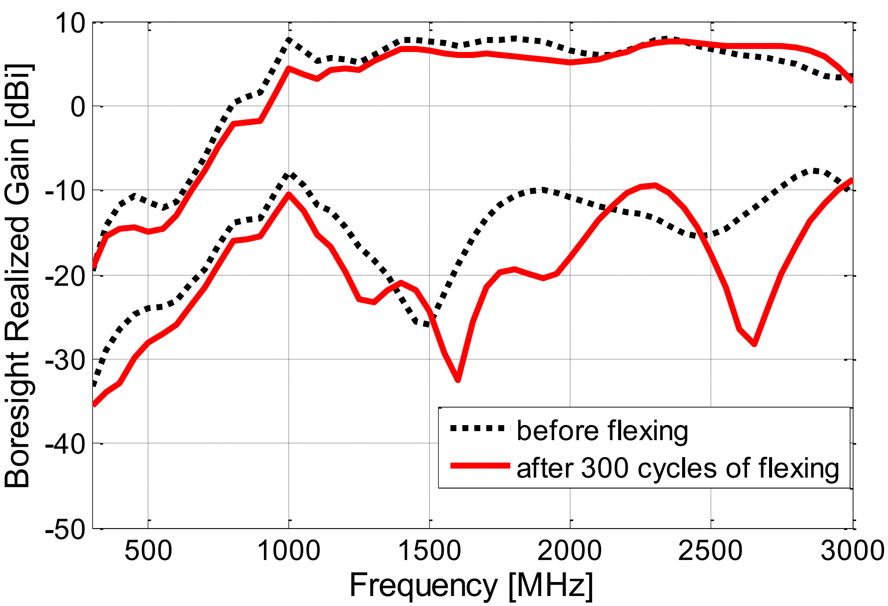
Higher gain E-textile antennas increase max. communication distance (sensitivity).

- *Example: for 3 dB increase in antenna gain, max. communication range increases by ~ 40% (~200 m), assuming a transmitted RF power of 10 dBm.*

Extreme Mechanical and Thermal Tolerance

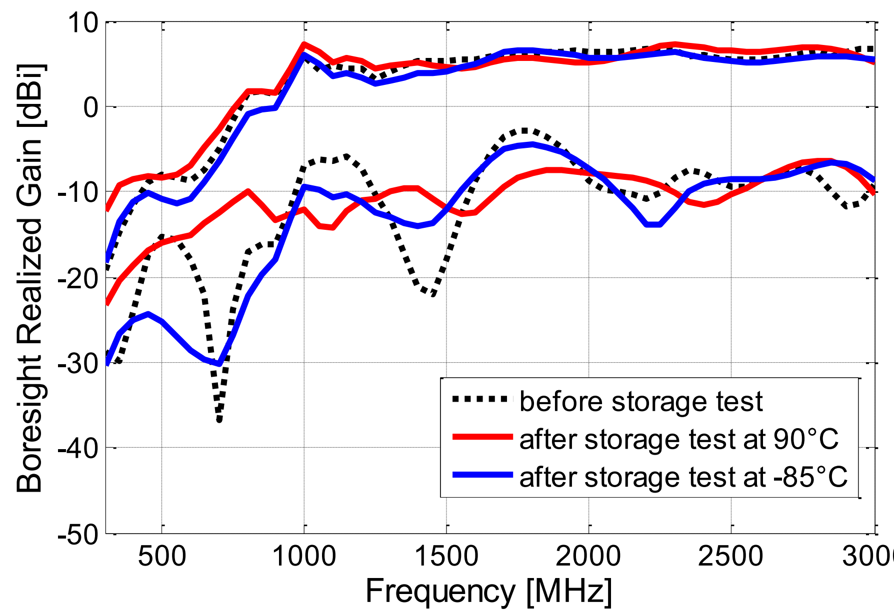
Mechanical Testing





Thermal Testing

- 2-hour hot storage test at 90°C, carried out at the OSU Materials Science Dept.
- 2-hour cold storage test at -85°C, carried out at OSU Biomed. Eng. Dept.



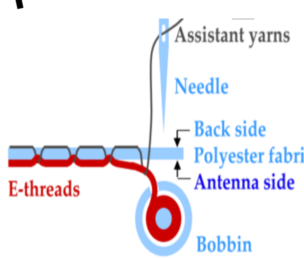
J. Zhong, A. Kiourti, T. Sebastian, Y. Bayram, and J.L. Volakis, “Conformal Load-Bearing Spiral Antenna on Conductive Textile Threads,” *IEEE Antennas and Wireless Propagation Letters*, 2016.

How to Integrate Lumped Components with RF Circuits

Use of conductive thread to make wearable RF antennas and circuits

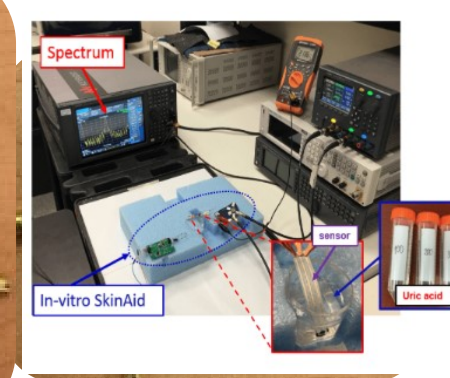
Commercial embroidery machine

Elektrisola-7 conductive thread consisting of strands of silver-coated copper filaments (Cu/Ag50 amalgam)ç



Wearable Sensors and Data-Extraction Circuits

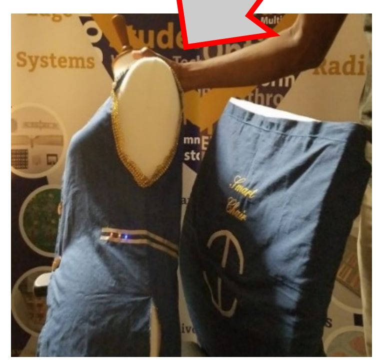
Vital et. al. APS-2019

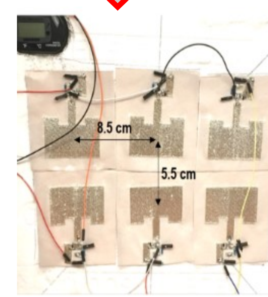


RF Power harvesting jackets for IoT and low-power sensors

Vital/Pawan et. al. IEEE-MTT-2020

Vital et. al. IEEE-TAP-2019



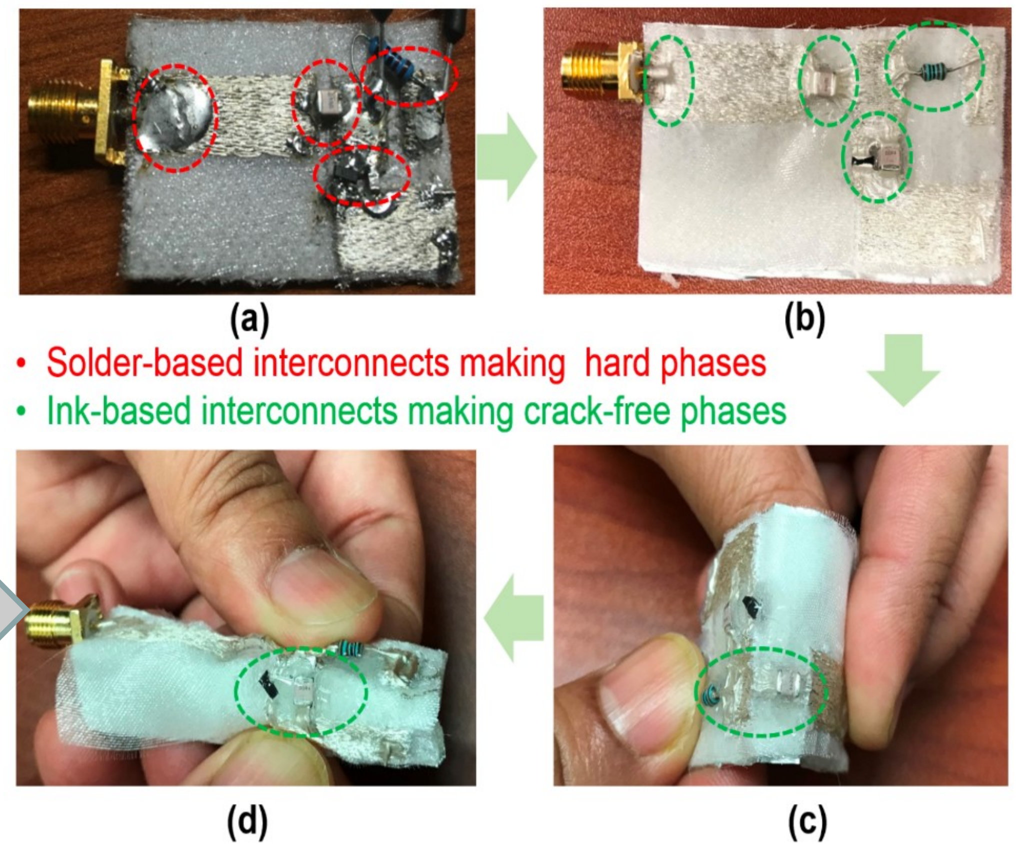


RF Circuits & Wearable Electronics Integration Challenges

Integration of hard and soft components without hard connects is crucial.

Approaches for removing hard interconnects

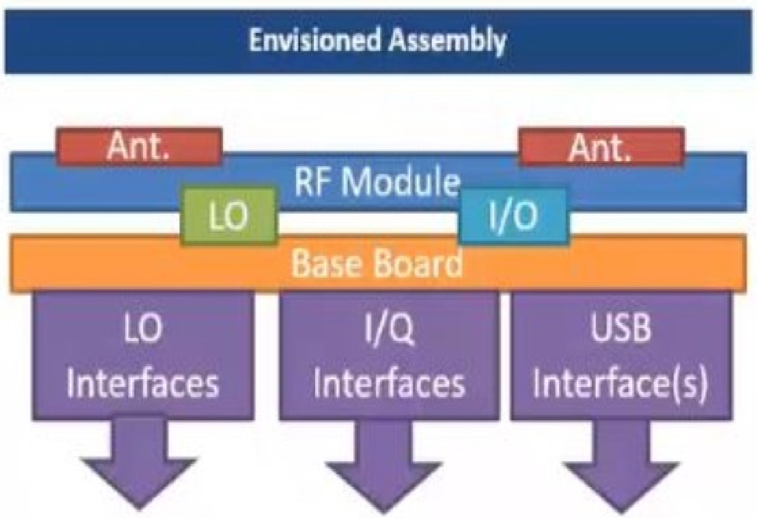
- **Monolithic growth of semiconductor components on flexible surfaces**
- **Using off the shelf components and conductive epoxy**

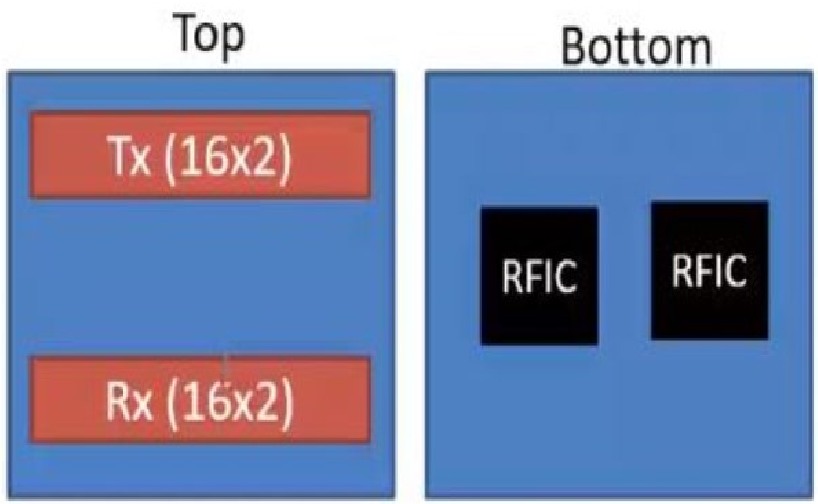


RF to DC power converter implemented using conductive epoxy interconnects and conductive thread embroidery

Stacking-Up Wearable Electronics

Next Step

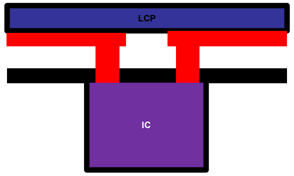


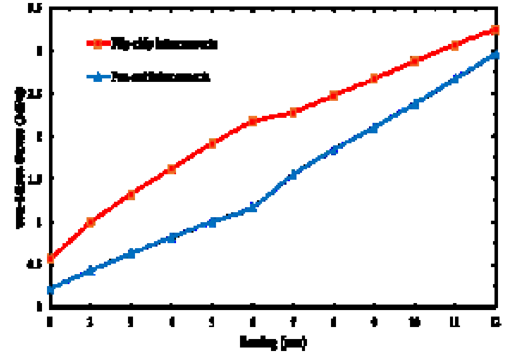


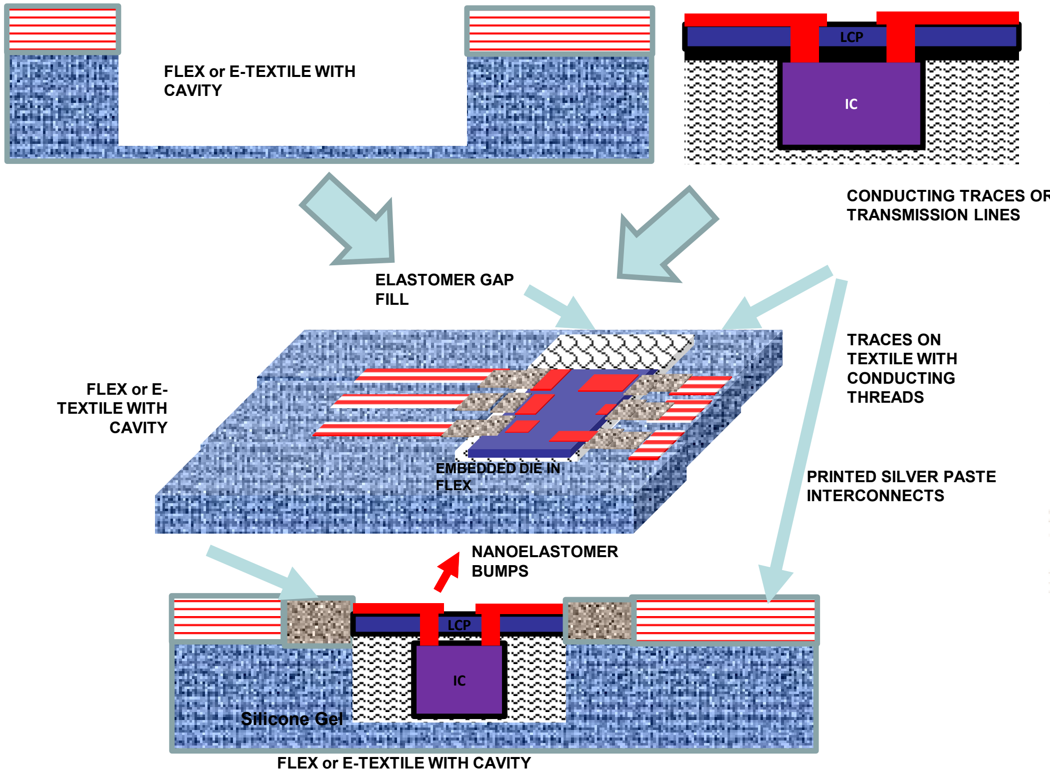
Flex-Textile Hybrid Packaging

- *Textile Fabric is the system package*
- Devices are co-packaged with additively-deposited elastomer traces directly onto textile conductors
- Electrical and mechanical co-design
- Innovative encapsulation for reliability

Thermomechanical modeling:
Flex and textile-embedded packages





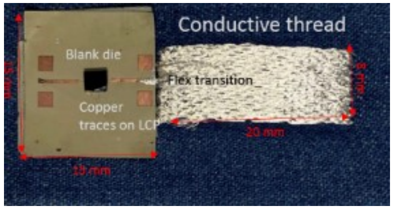


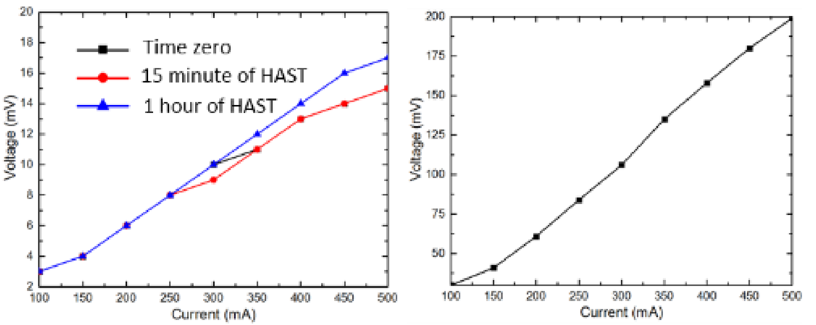
Lower chip-to-flex Interconnect stresses

- Lower flex-to-textile stresses

Fluroelastomer encapsulation

Conductive elastomer adhesives





(a) (b)

Stable resistance under thermal and humidity testing

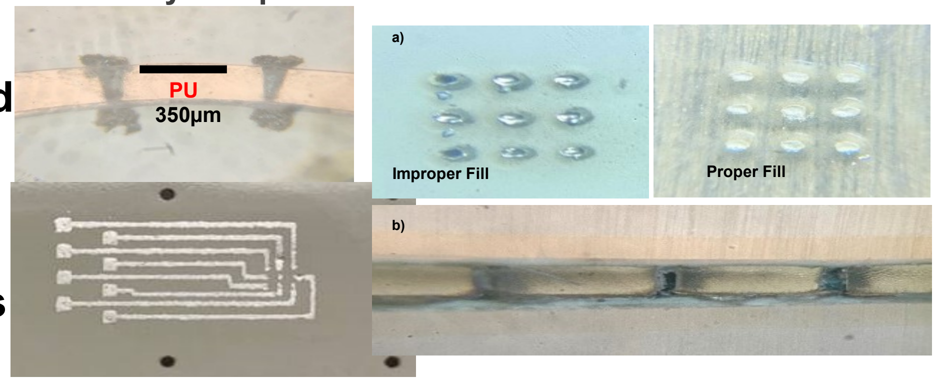
Remateable Connectors is a Natural Next Step

- Remateable flex-to-flex and flex-to-textile Packages
  - End-user or manufacturer can remove and re-assemble

- Examples of use:
  - Textile fabric and on-skin patch interfaces
  - Power harvesting and RF communication
  - Sensor and communication interfaces

- Fine pitch and area-array
- Low-cost additive manufacturing

Area-array fine-pitch for flex-to-flex Z elastomer connectors



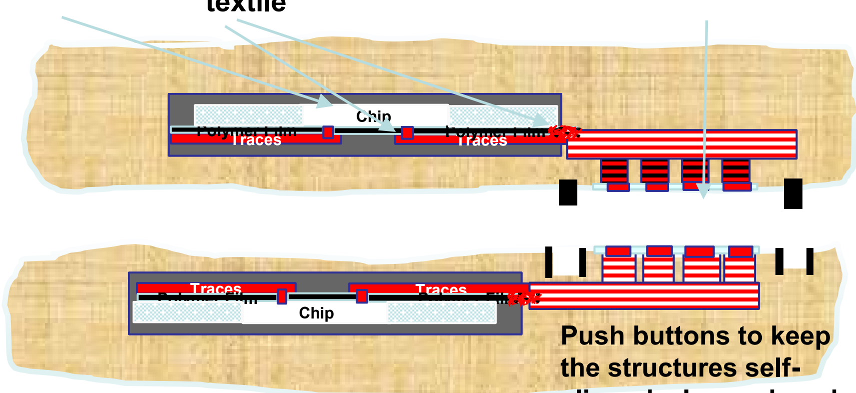
Via-fill of metal-elastomer nanocomposites in elastomer polymer films;

Can be scaled down to 200 micron pitch

Chip in flex

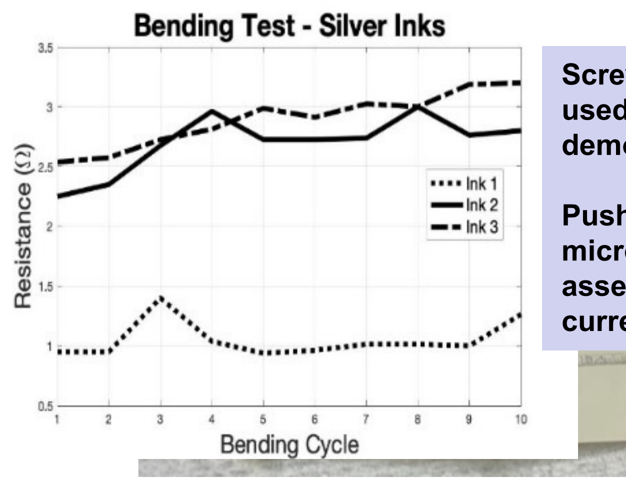
Flex in textile

Remateable Z elastomer interconnect



Push buttons to keep the structures self-aligned, clamped, and under low-resistance contacts

Via Filling and Interconnect Layer Assembly



Screw clamps are used for the first demonstration;

Push-button or micro-Velcro assembles are currently investigated

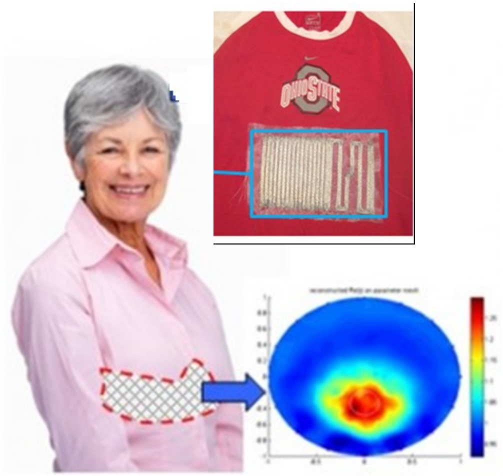
Initial remateability demonstrated with multiple bending cycles, assembly and re-assembly

FIU

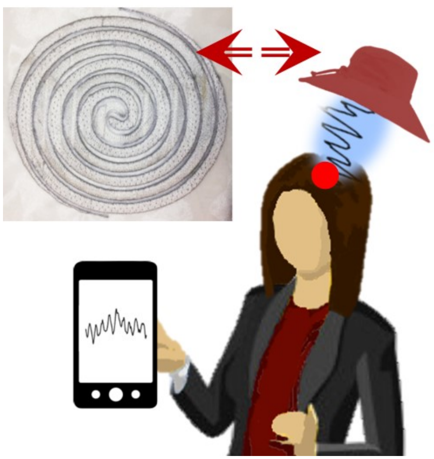
APPLICATIONS

E-Textile Applications

[1] Medical Imaging Sensors



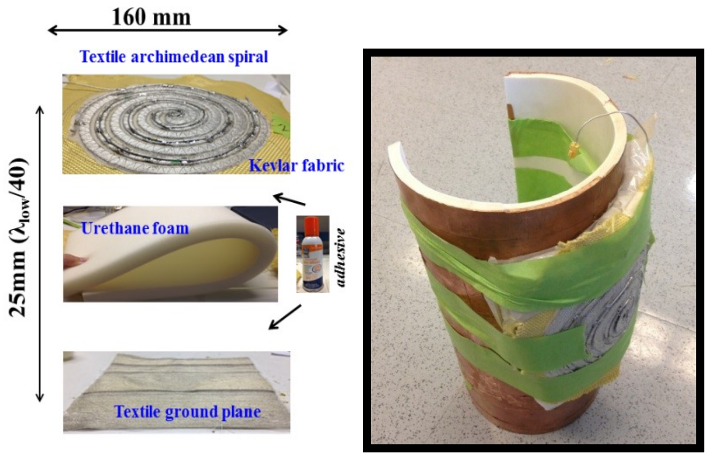
[2] Wireless Brain Implants



[3] Wearable Antennas for Wireless Communications

[4] RFID Tag Antennas

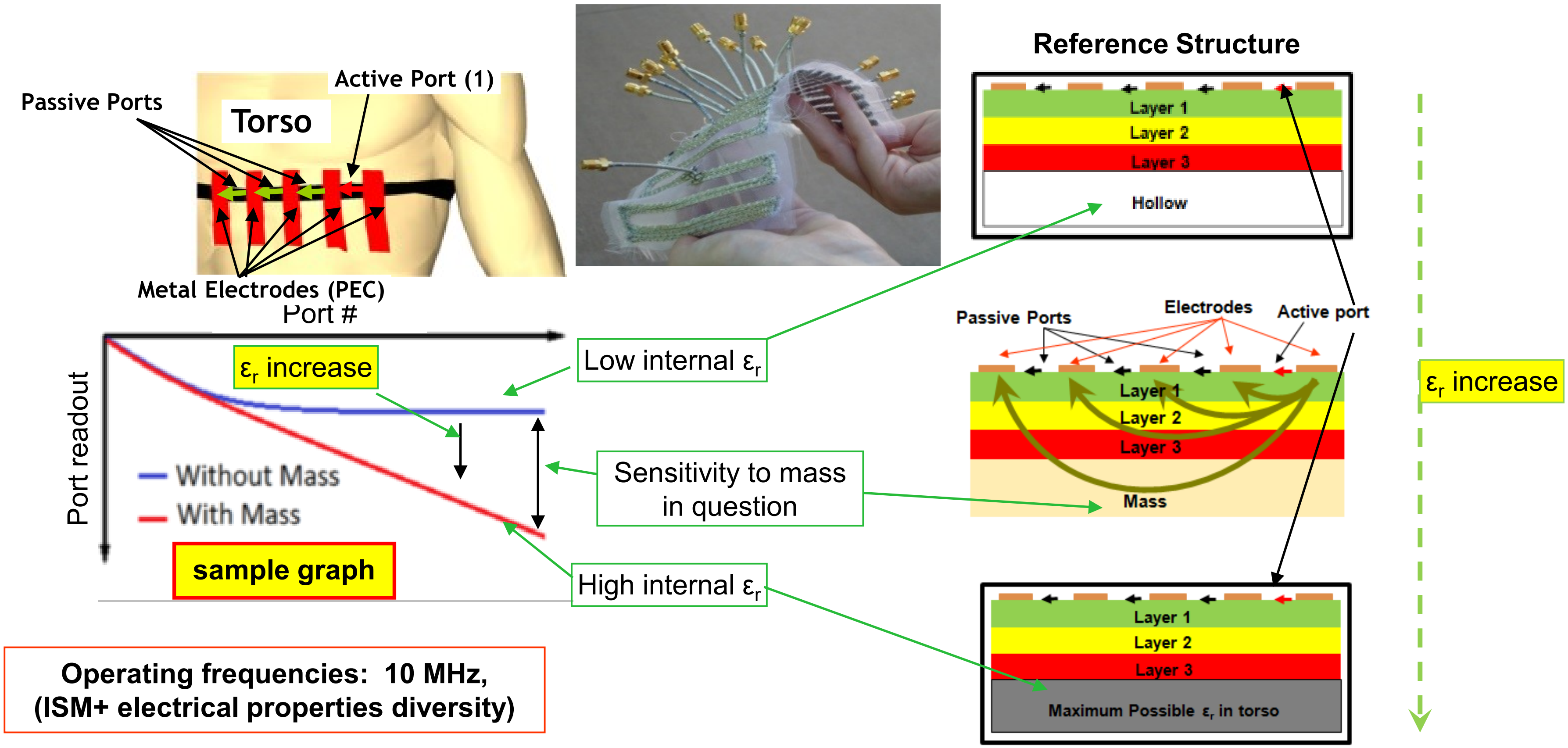
[5] Conformal Antennas



John L. Volakis

[1] Body Conformal Textile Imaging Sensors

- <u>Maximize sensitivity</u> (ability to differentiate between small changes in material ε_r)
- <u>Maximize SNR</u> (signal being the power received at the last element)
- <u>Minimize effect of outer (skin) layers</u>

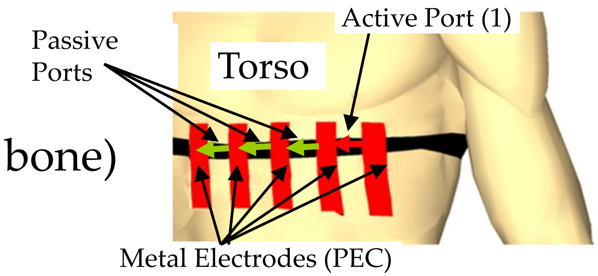


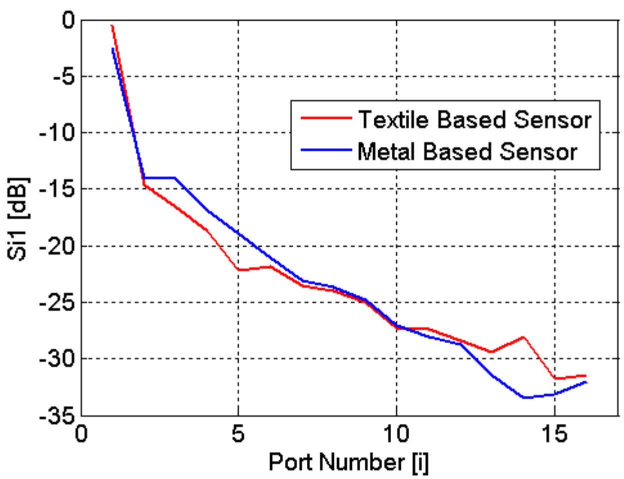
Operating frequencies: 10 MHz,
(ISM+ electrical properties diversity)

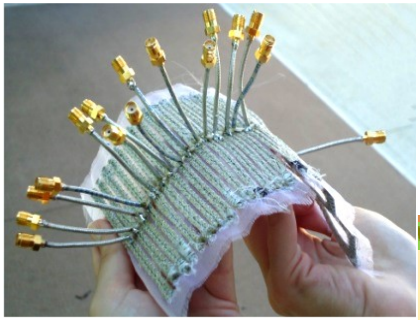
[1] Body-Worn Textile Imaging Sensor

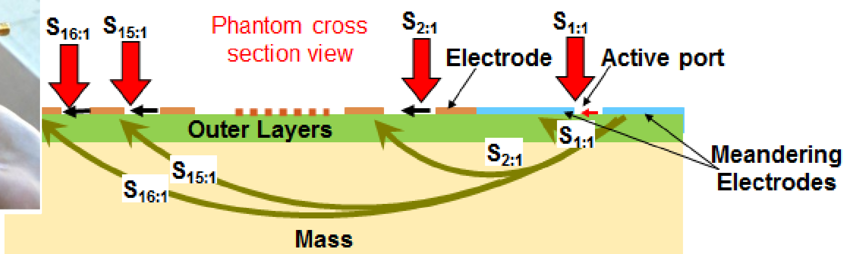
A surgery-free on-body monitoring device to evaluate the dielectric properties of internal body organs (lung, liver, heart) and effectively determine irregularities in real-time ---several weeks before there is serious medical concern.

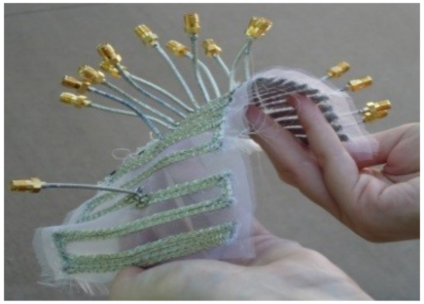
- Operates at **40 MHz (HBC)**
- Deep detection: >**10 cm**
- **Suppresses interference** from outer layers (skin, fat, muscle, bone)

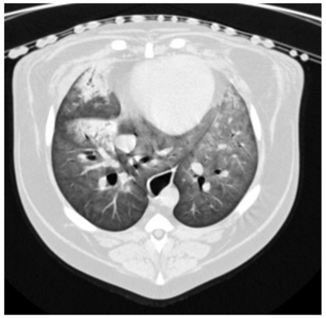








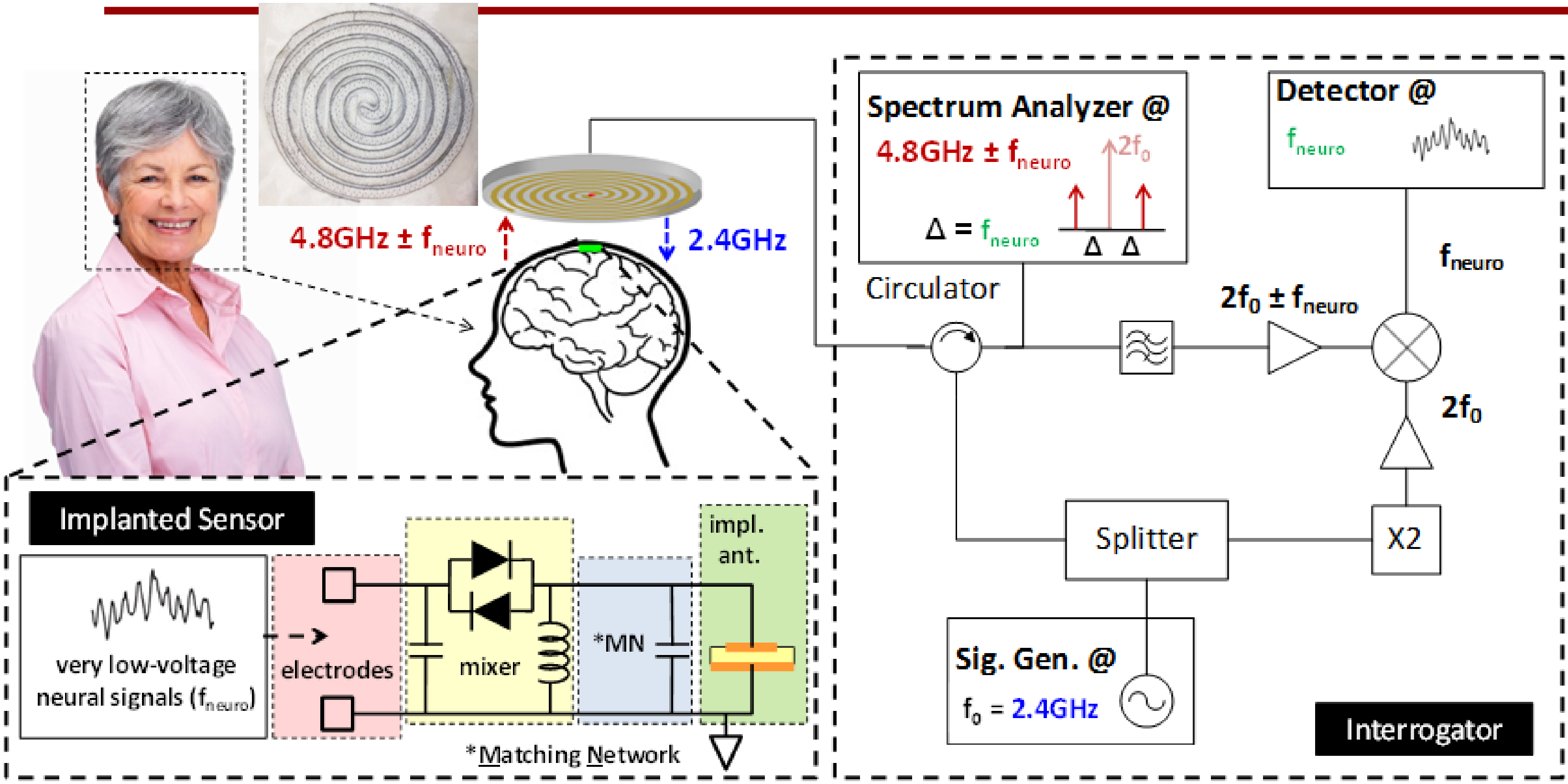


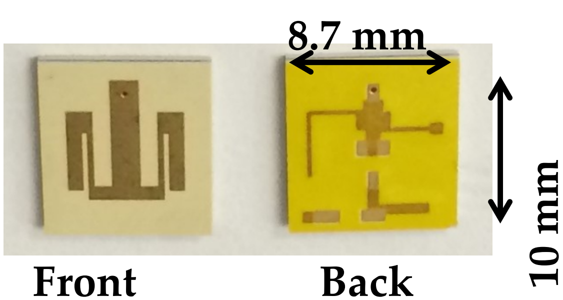


- 17 electrodes + 16 ports
- One excited port, the rest are passive for readouts
- Non-uniform to improve impedance matching

L. Zhang, Z. Wang, and J.L. Volakis, “Textile Antennas and Sensors for Body-Worn Applications,” IEEE AWPL, 2012

[2] Wireless Brain Implants



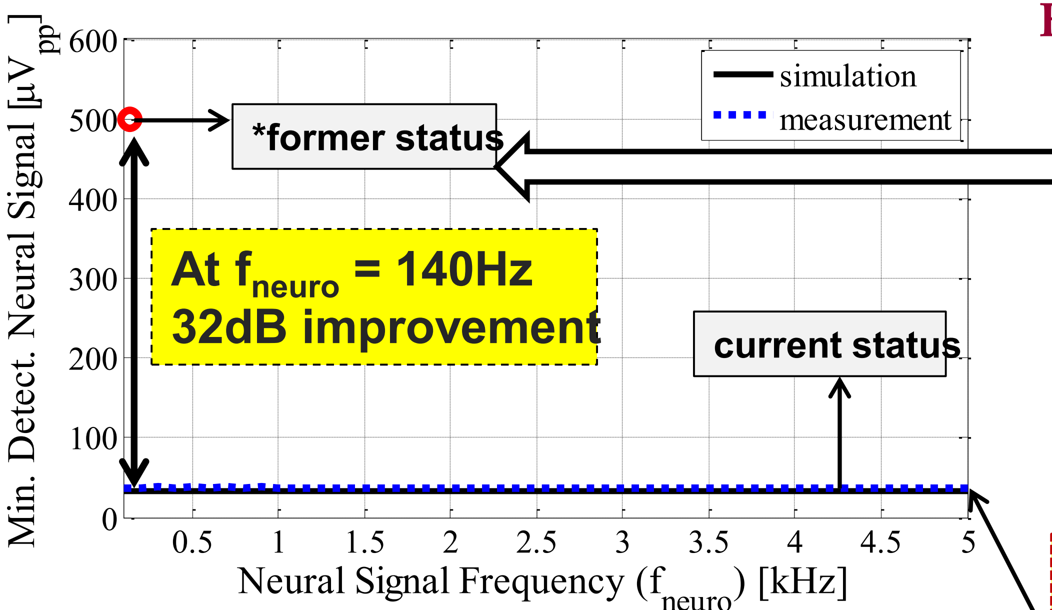


- **Fully-passive and wireless neurosensors** to acquire brain signals inconspicuously.
- Integration of **extremely simple electronics** in a **tiny footprint** to minimize trauma.
- Acquisition of **extremely low signals**, down to 20μV_{pp}. This implies reading of most signals generated by the human brain.

C. Lee, A. Kiourti, J. Chae, J.L. Volakis, “A High-Sensitivity Passive Neurosensing System for Wireless Brain Signal Monitoring,” IEEE T-MTT, 2015.

Time-Domain Measurement Results: Neuropotentials down to $20\mu V_{pp}$ can be detected

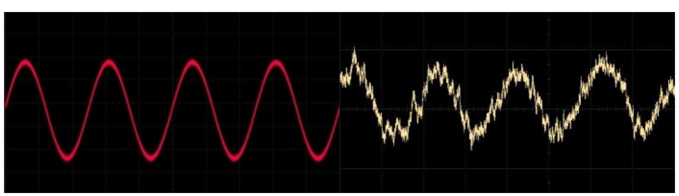
New set-up reduces Minimum Detectable Signal (MDS), allowing reading of neuropotentials down to $20\mu V_{pp}$. Therefore, most human physiological neuropotentials can be recorded wirelessly.



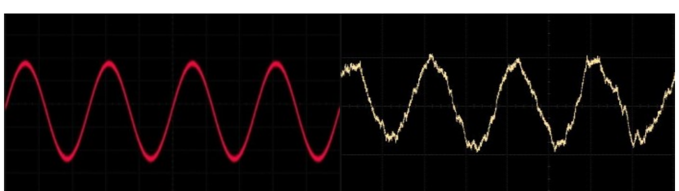
Historical data for minimum detectable signal. Our new implant and interrogator demonstrates a 32dB improvement.

New set-up allows reading of neuropotentials down to $20\mu V_{pp}$ based on MDS = -120dBm across f_{neuro}

MDS_{neuro} = 30 µVpp (-86 dBm)
At 1 kHz



MDS_{neuro} = 30 µVpp (-86 dBm)
At 5 kHz



A. Kiourti, C. Lee, J. Chae, and J.L. Volakis, “A Wireless Fully-Passive Neural Recording Device for Unobtrusive Neuropotential Monitroing,” *IEEE Transactions on Biomedical Engineering*, 2015.

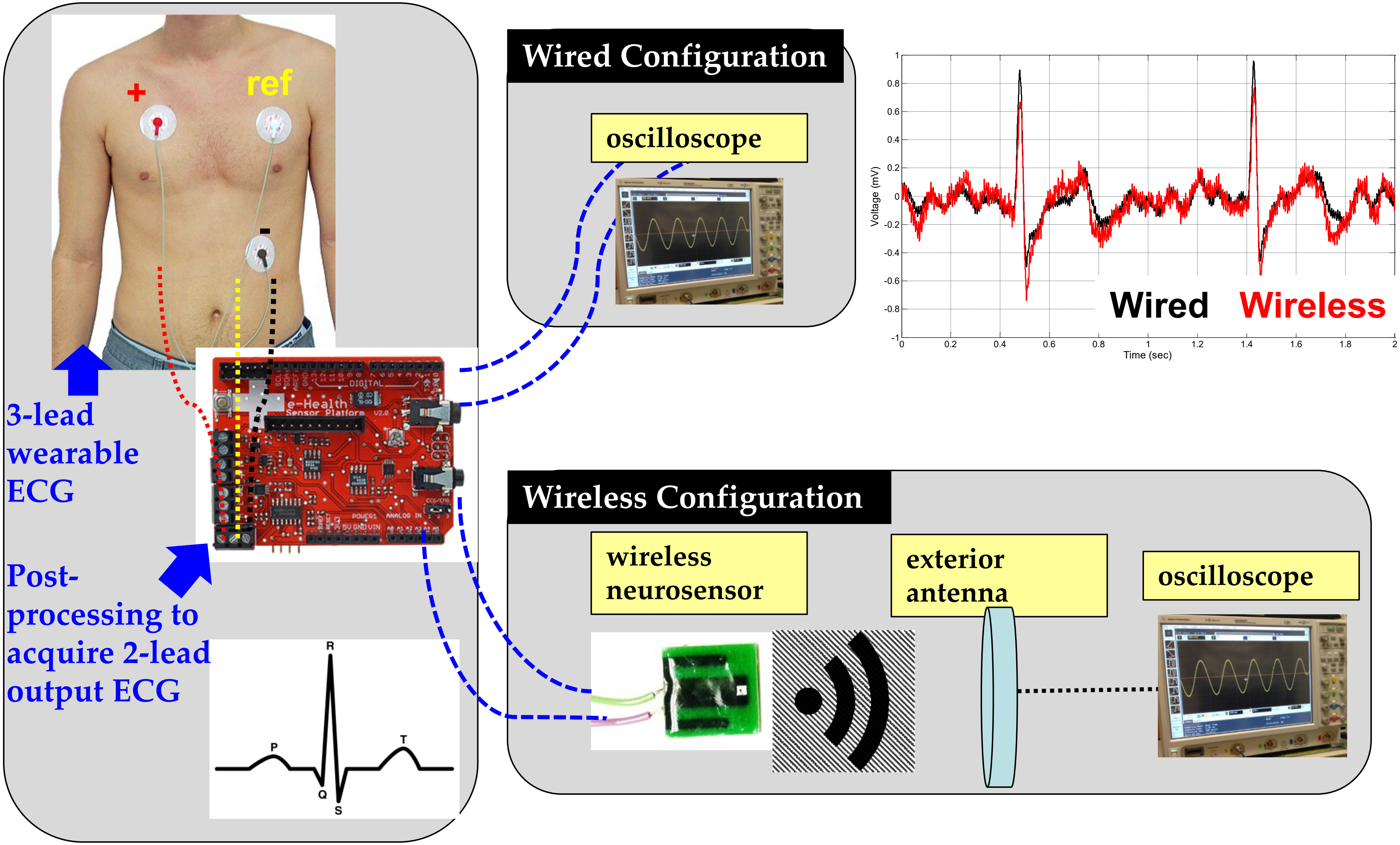
Comparison of Proposed vs. Previously Reported Wireless Brain Implants

Ref.	Type	Footprint	Power consumption	Transmission technology	Operation distance	Min. detectable signal
Yin, 2014	Exterior	52 x 44 mm^2	17 mA from a 1.2 Ah battery to run for 48 hours	3.1 - 5 GHz OOK	< 5 m	N/A
Szuts, 2011	Exterior	N/A	645 mW	2.38 GHz FM	< 60 m	10.2 μV_{pp} (rat)
Rizk, 2007	Exterior	50 x 40 mm^2	100 mW	916.5 MHz ASK	2 m	N/A
Miranda, 2010	Exterior	38 x 38 mm^2	142 mW	3.9 GHz FSK	< 20 m	14.2 μV_{pp} (non-human primate)
Yin, 2010	Exterior	N/A	5.6 mW	898/926 MHz FSK	1 m	13.9 μV_{pp} (rat)
Sodagar, 2009	Exterior	14 x 16 mm^2	14.4 mW	70/200 MHz OOK	1 cm	25.2 μV_{pp} (guinea)
Borton, 2013	Implanted	56 x 42 mm^2	90.6 mW	3.2/3.8 GHz FSK	1-3 m	24.3 μV_{pp} (non-human primate)
Rizk, 2009	Implanted	50 x 40 mm^2	2000 mW	916.5 MHz ASK	< 2.2 m	20 μV_{pp} (sheep)
Sodagar, 2007	Implanted	14 x 15.5 mm^2	14.4 mW	70-200 MHz FSK	N/A	23 μV_{pp} (guinea)
Moradi, 2014	Implanted	N/A	N/A, yet >0 mW	N/A	2 cm	N/A
Schwerdt, 2012	Implanted	12 x 4 mm^2	0 mW	Fully-passive backscattering	< 1.5 cm	6000 μV_{pp} (in-vitro) 500 μV_{pp} (frog)
Lee, 2015	Implanted	39 x 15 mm^2	0 mW	Fully-passive backscattering	8 mm	50 μV_{pp} (in-vitro)
Kiourti/Volakis, 2015	**Implanted**	**10 x 8.7 mm^2**	**0 mW**	**Fully-passive backscattering**	**~ 1.5 cm (on-body portable receiver envisioned)**	**20 μV_{pp} (in-vitro)**

our work

A. Kiourti, C. Lee, J. Chae, and J.L. Volakis, "A Wireless Fully-Passive Neural Recording Device for Unobtrusive Neuropotential Monitroing," *IEEE Transactions on Biomedical Engineering*, 2015.

Preliminary In-Vivo Validation:
Wireless Acquisition of Human ECG

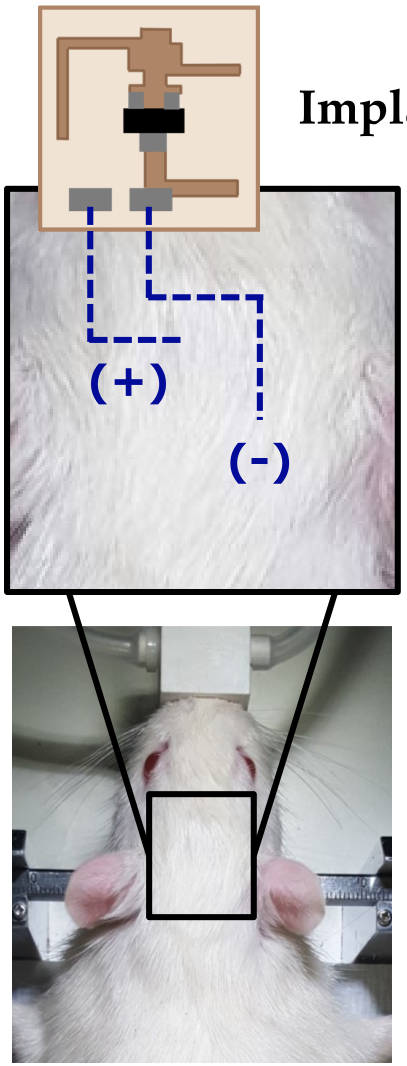


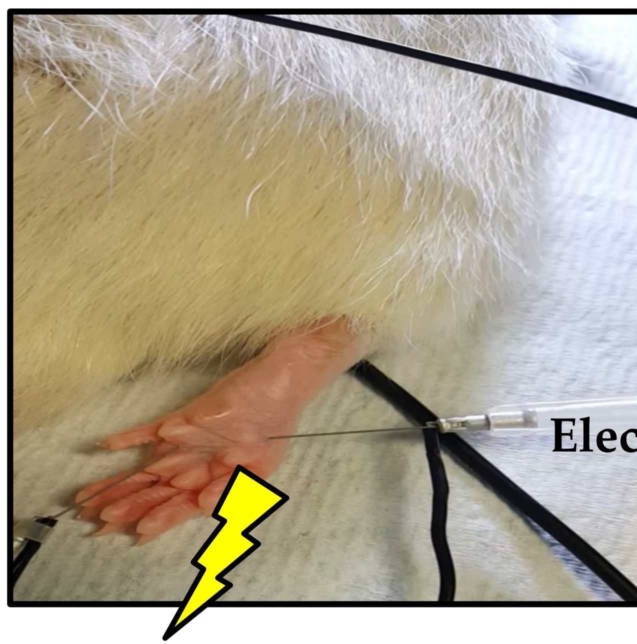
In Vivo Experiment (Rat Implant)

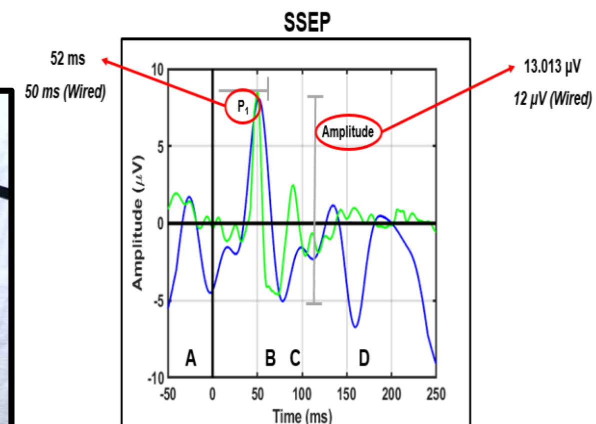
Somatosensory Evoked Potential (SSEP) – Hindlimb Stimulation

- **System validation** with a neural recording
- Signal was recorded with a **wired system for comparison**
- **Challenge –** small region of interest

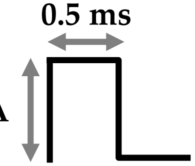
Implant





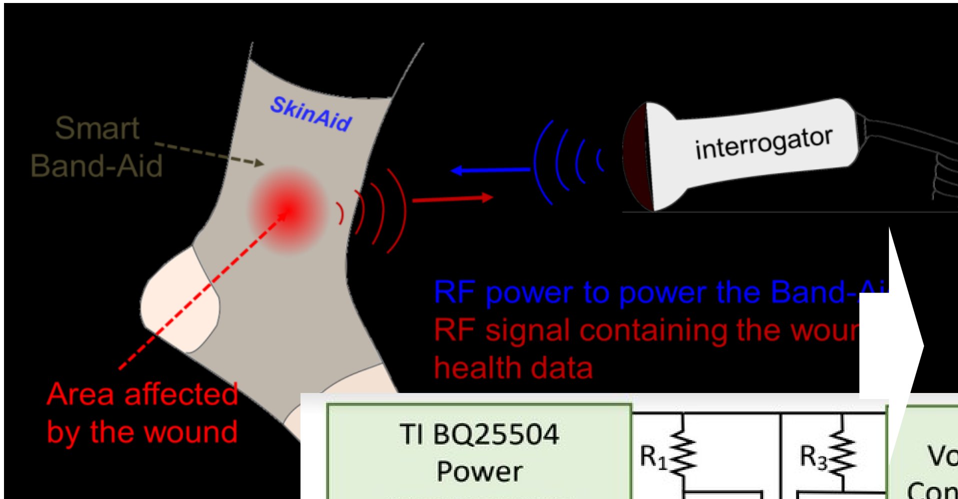


Electrical Pulse Parameters



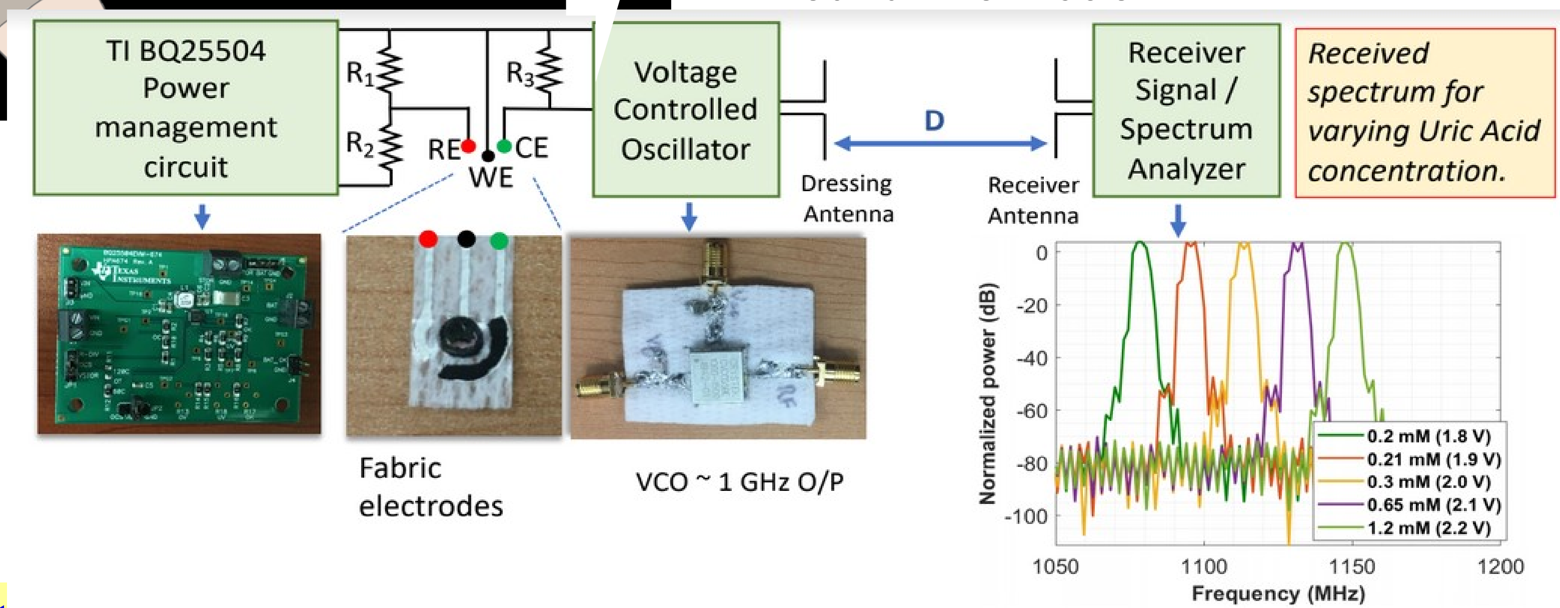
Moncion, Carolina, et al. "Fully-Passive Wireless Implant for Neuropotential Acquisition: An In Vivo Validation." *IEEE Journal of Electromagnetics, RF and Microwaves in Medicine and Biology* (2019).

Smart Bandaid for Wound Monitoring



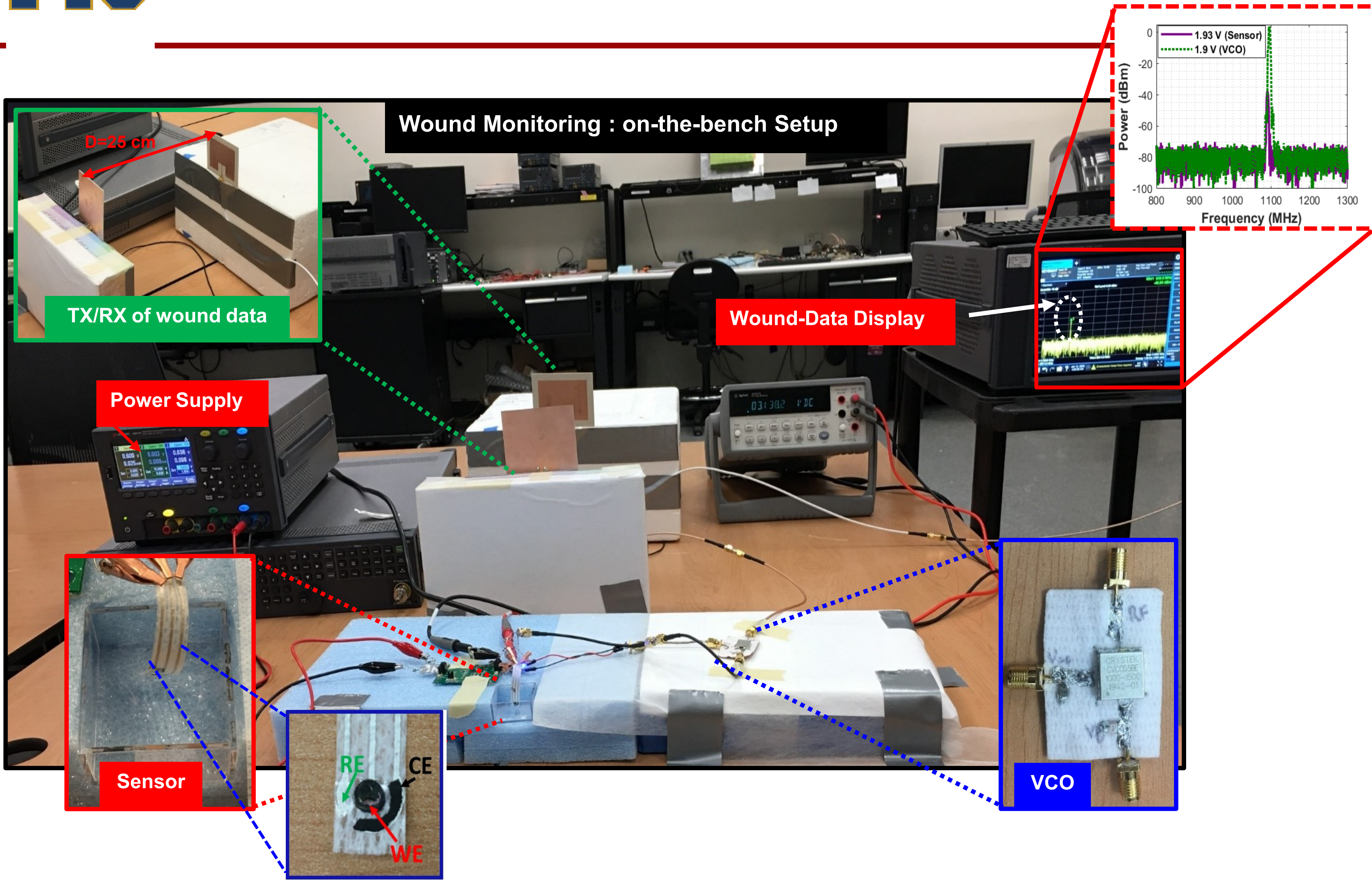
Issues with existing smart bandages

- ❑ Use of Lithium battery to power the bandage
- ❑ Complex circuits with power-hungry microcontroller
- ❑ post-processing required to obtain wound information



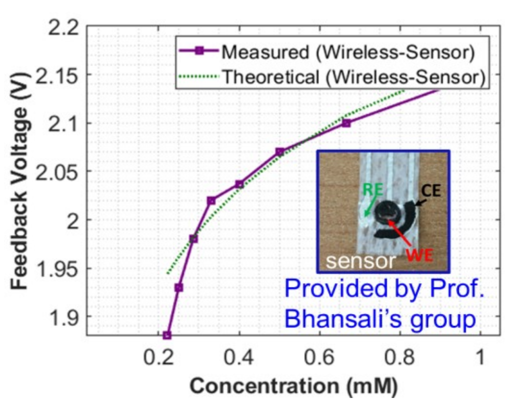
- ❑ Bandaid to be fabric-implemented to assess wound-health status
- ❑ Uric acid to be used as biomarker in the assessment
- ❑ Integration of above components into fabric for wound assessment

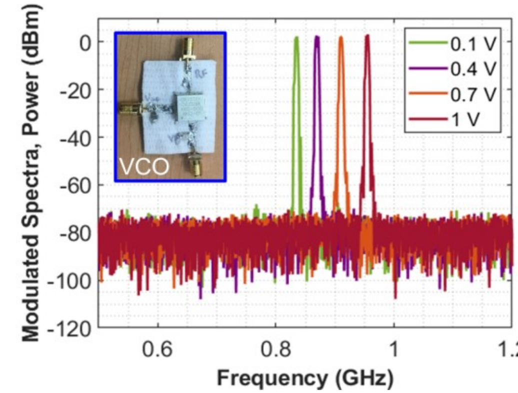
Measurement Setup

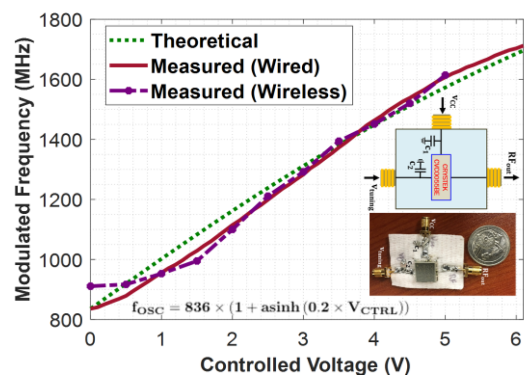


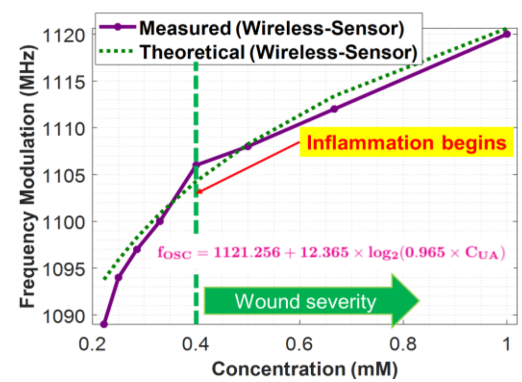
Electronic Wound Data Modulation

- ❑ Change in uric acid concentration yields change in (tuning) voltage
- ❑ Frequency modulation demonstrated for tuning voltage
- ❑ Textile-based enzymatic sensor to sense uric acid from wound
- ❑ Textile PMC + VCO to be developed to enable frequency modulation







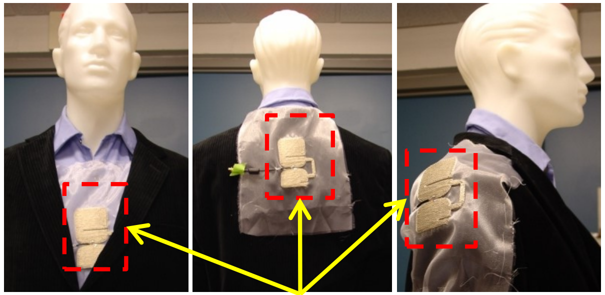


Vital, Dieff, Volakis, John L., Bhansali, Shekhar, Bhardwaj, Shubhendu "Electronic Wound Monitoring Using Fabric-Integrated Data Modulation," Antennas and Propagation & USNC/URSI National Radio Science Meeting, 2020 IEEE International Symposium on (*Accepted*)

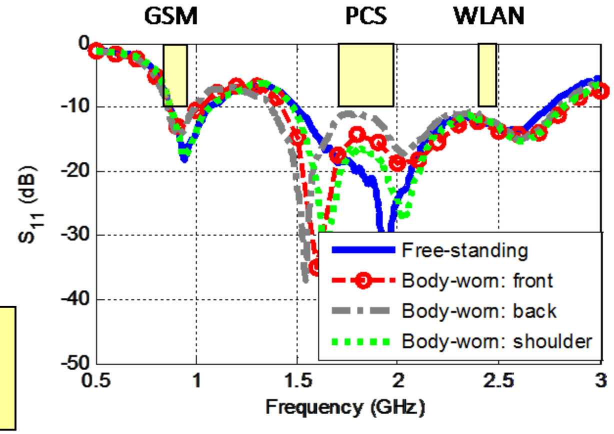
- ❑ **Frequency modulation (FM) to be used for wound assessment**
- ❑ **FM demonstrated using variable uric acid concentration**
- ❑ **Quick assessment can be made from theoretical model**

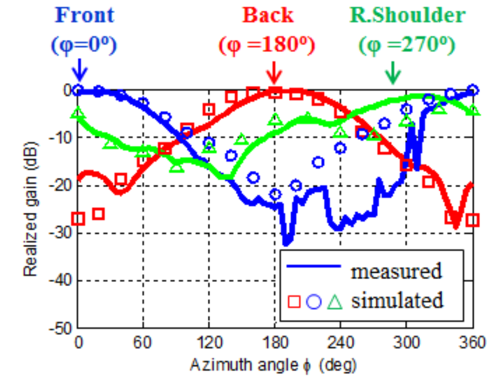
[3] Antennas for Body-Worn Communication

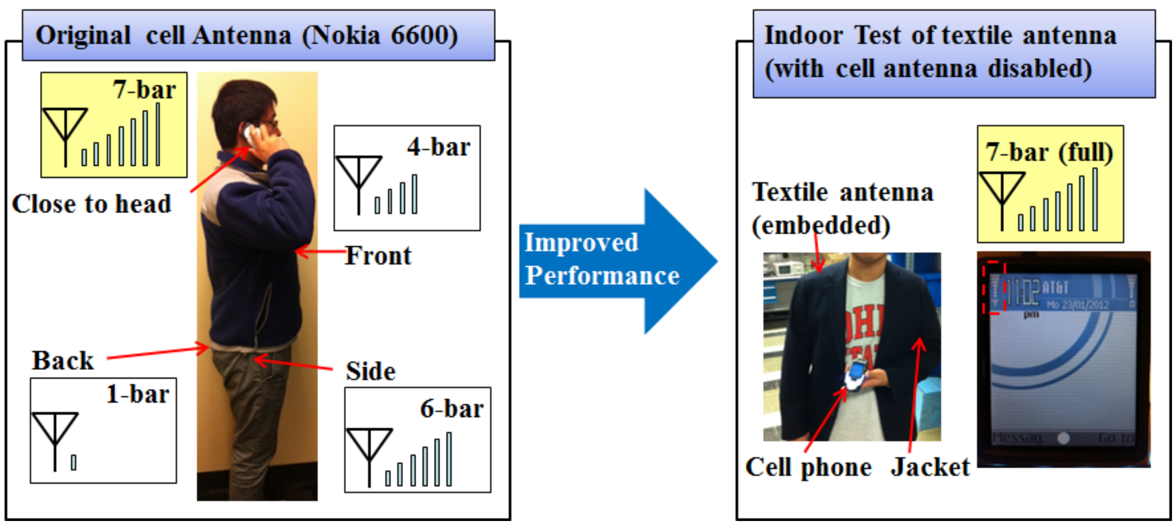
Multiband Dipole for GSM/PCS/WLAN Bands



- 2dB realized gain at all three bands
- Omnidirectional patterns in all bands







Textile antenna is as good as the ordinary cell antenna with the best location

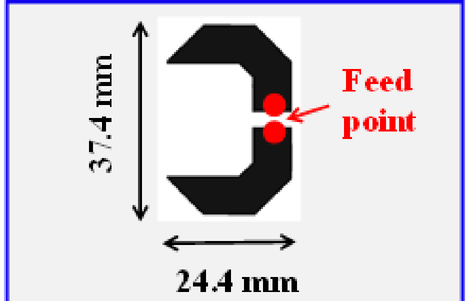
- Textile antenna is low-profile, unobtrusive, and comfortable to wear.

Note: "1-bar": -100 to -95dBm, "4-bar": -85 to -80dBm, "6-bar": -75 to -70dBm, "7-bar": >-70dBm

Z. Wang, L. Lee, D. Psychoudakis, and J.L. Volakis, "Embroidered multiband body-worn antenna for GSM/PCS/WLAN communications," IEEE Trans. Antennas Propag., 2014.

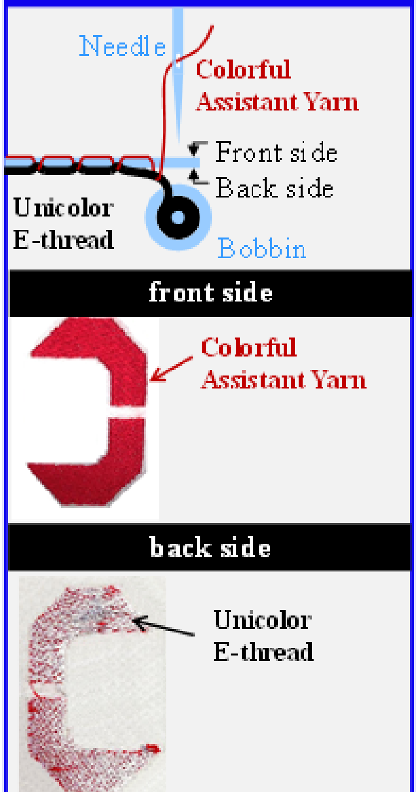
Colorful Textile Antennas

STEP 1: Antenna Design

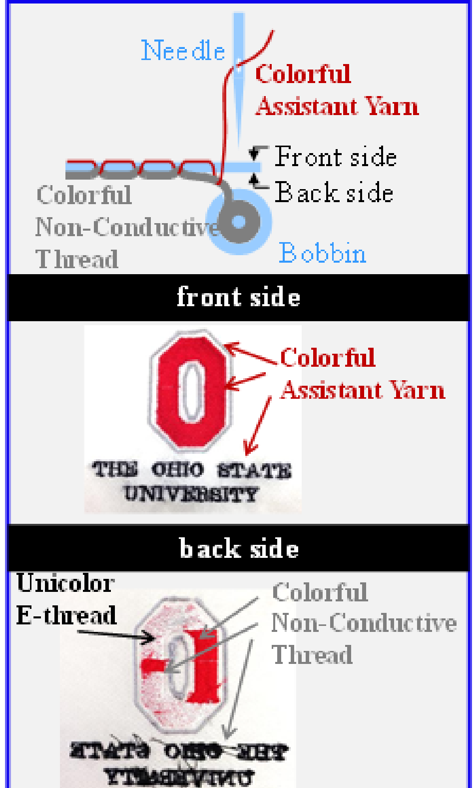


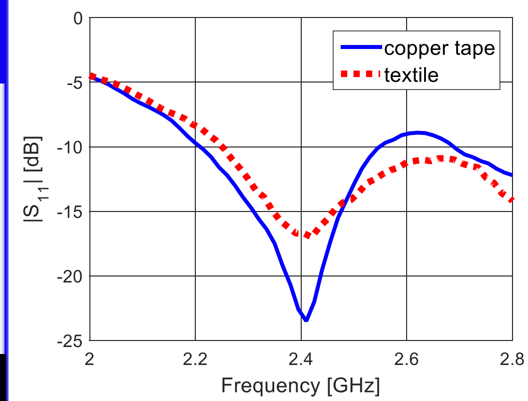
STEP 2: Digitization

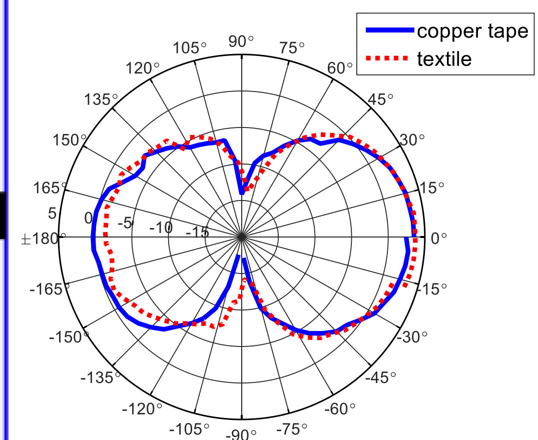
STEP 3: Embroidery of Conductive Portion



STEP 4: Embroidery of Non-Conductive Portion







The colorful textile antenna prototype achieves excellent performance as compared to its copper counterpart. Concurrently, it is flexible, lightweight, and mechanically robust.

A. Kiourti and J.L. Volakis, "Colorful Textile Antennas Integrated into Embroidered Logos," *MDPI Journal of Sensor and Actuator Networks*, 2015.

[4] RFID Tag Antennas

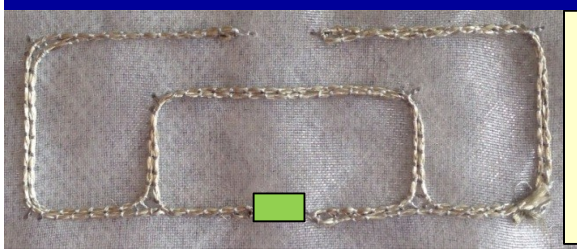
On-Tire Threshold Power Testing:

ELML E-fiber RFID tag antenna embedded in polymer

5 ft On Tire Threshold Power Test

- ❑ Textile: 22 dBm
- ❑ Copper foil: 20 dBm

Simple Folded-Dipole Tag



On-Tire Threshold Power Test

- ❑ Textile: 24 dBm
- ❑ Wire: 24 dBm

ELML Dipole Tag with Circular Loops

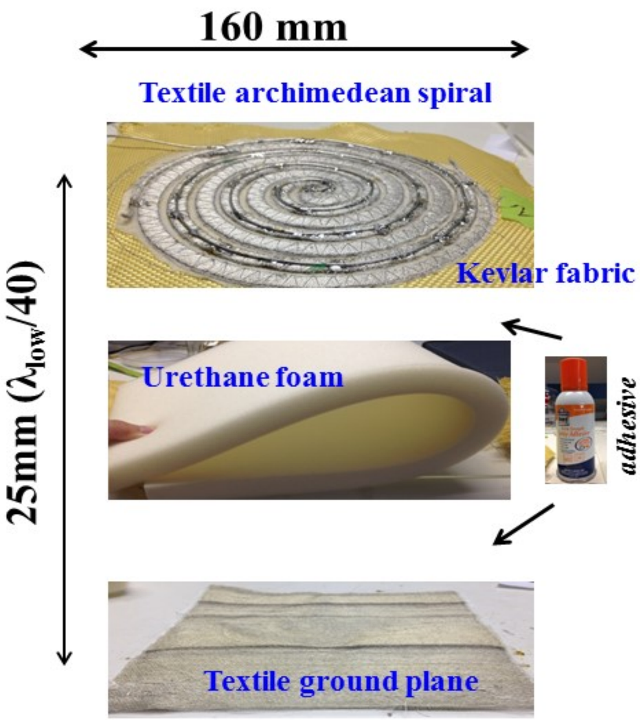
On Tire Threshold Power Test

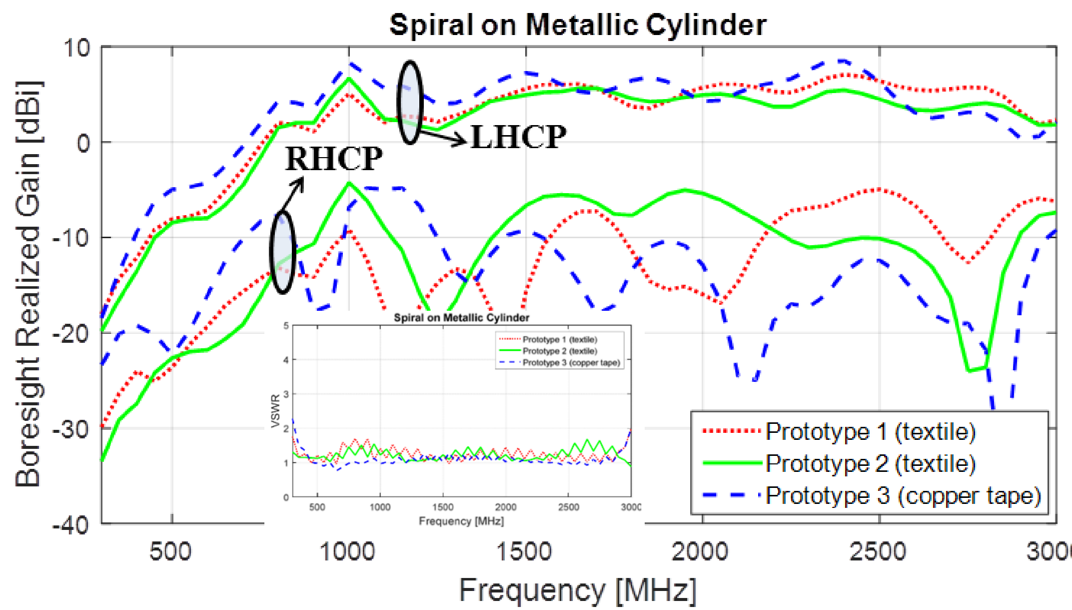
- ❑ Textile: 20 dBm
- ❑ Copper foil: 21 dBm

- Stretchable (up to 10-15%)
- Flexible
- Polymer preserves integrity of E-fiber antenna and protects it against corrosion / Easy integration within tire sidewall (bonding during tire curing)
- Comparable performance to its copper wire counterpart

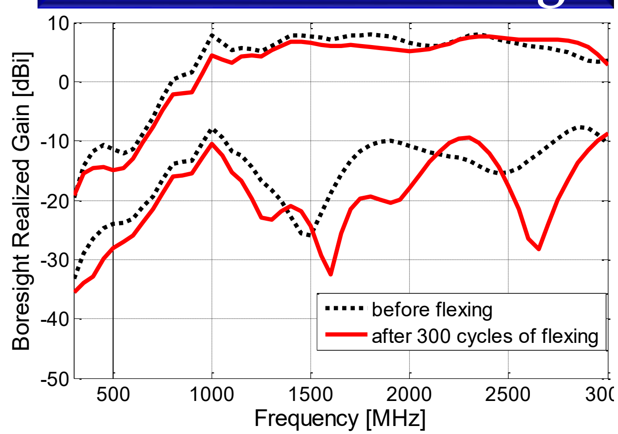
S. Shao, A. Kiourti, R. Burkholder and J.L. Volakis, "Broadband, Textile-Based Passive UHF RFID Tag Antenna for Elastic Material," AWPL 2015

[5] Conformal Antennas for Airborne and Wearable Applications

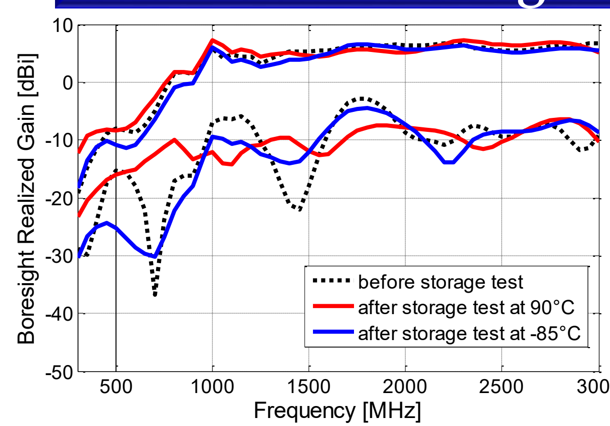




Mechanical Testing



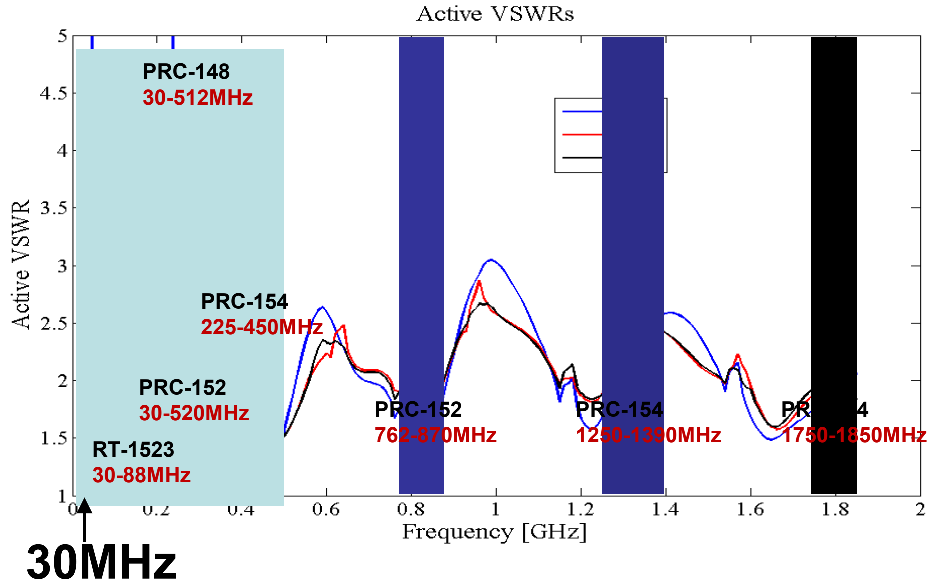
Thermal Testing

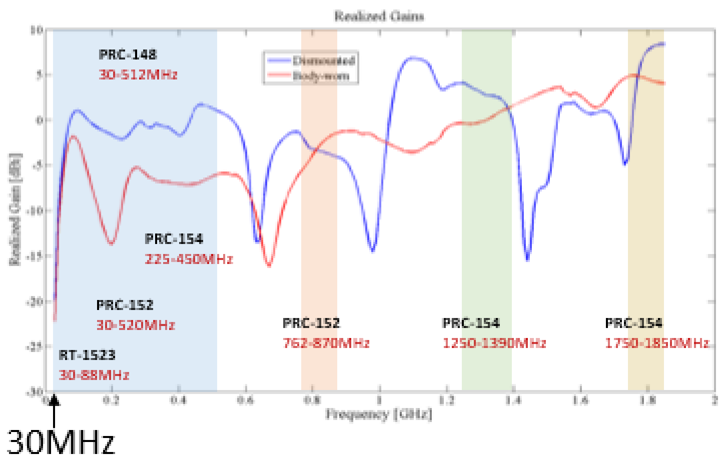


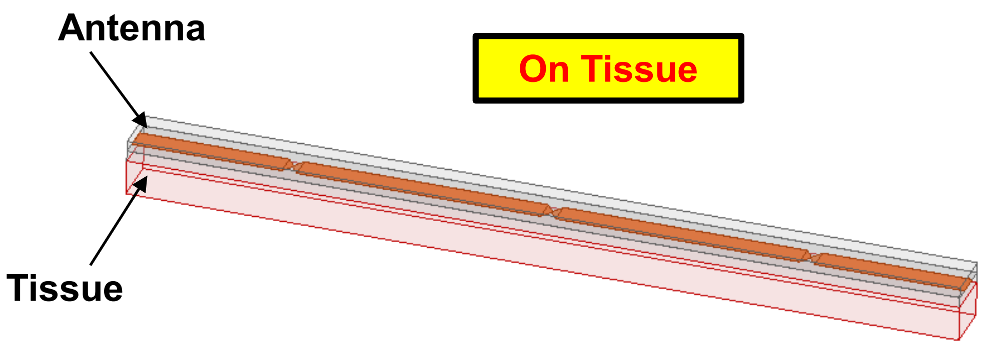
J. Zhong, A. Kiourti, and J.L. Volakis, "Conformal, Lightweight Textile Spiral Antenna on Kevlar Fabrics," AP-S 2015.

[6] Body Wearable Antennas Must Operate at Low Frequencies

Antenna on-Body







On Tissue

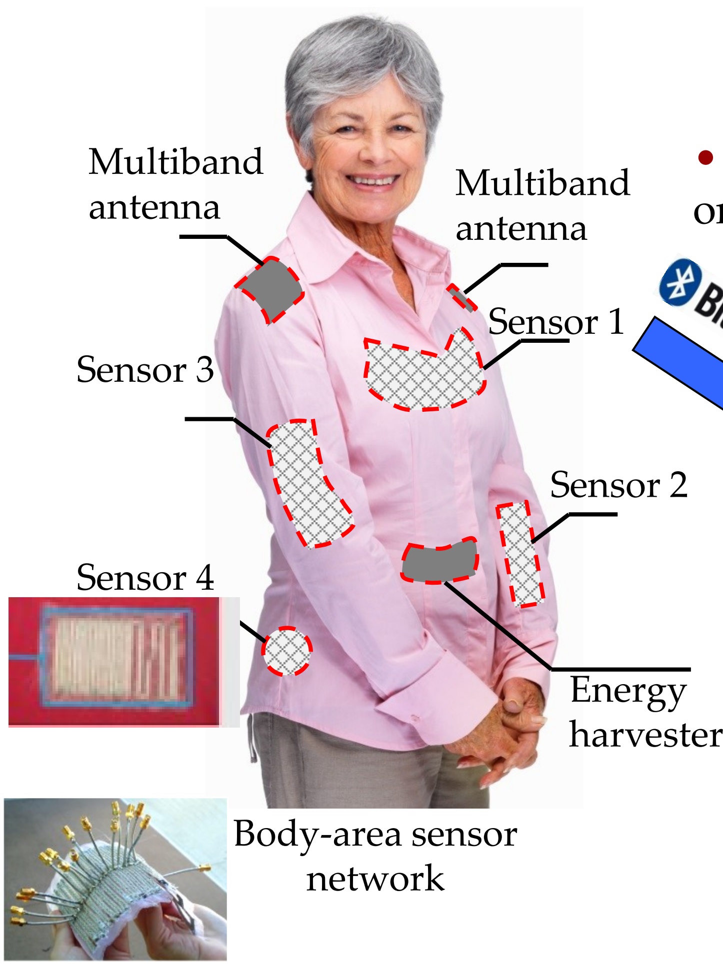
Continuous 30MHz to 2000MHz (67:1 bandwidth)

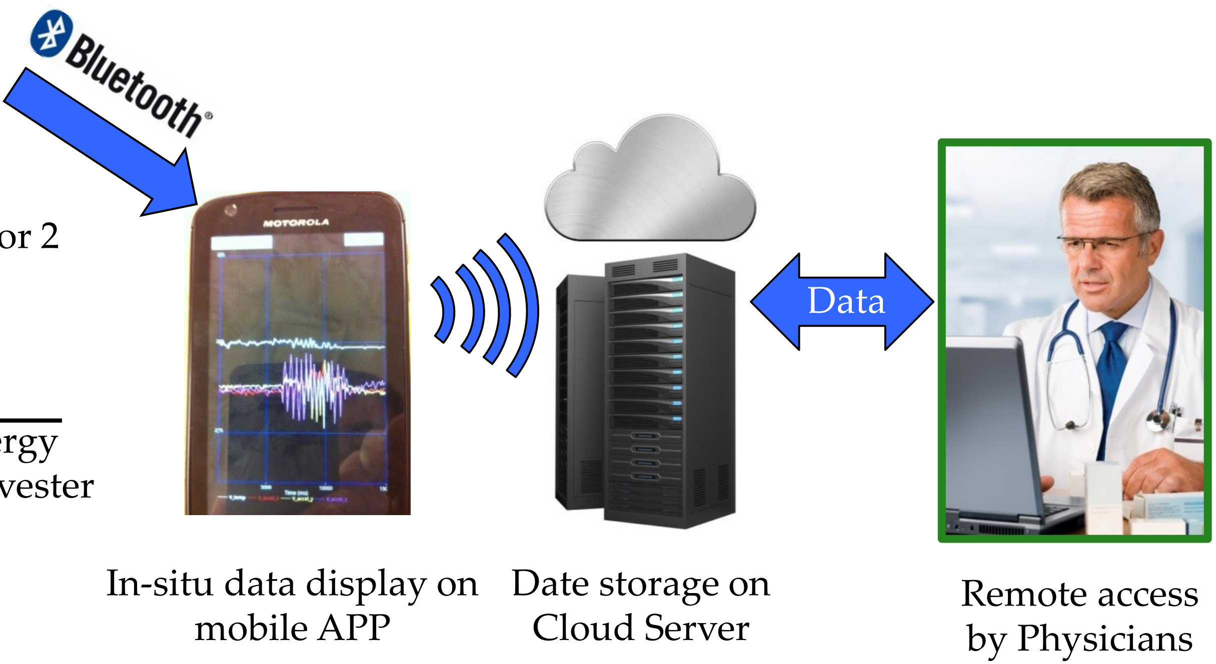
[7] Body-Area Network for Sensing (MS-BAN)

Wireless body-area network for medical sensing (MS-BAN)

Features

- Body-worn multifunctional apertures on RF functionalized garment:
  - Textile based RF sensors for in-situ medical sensing.
  - Multiband textile antenna for high-speed communication.
- Continuous data transfer through BAN for in-situ monitoring on mobile APP.

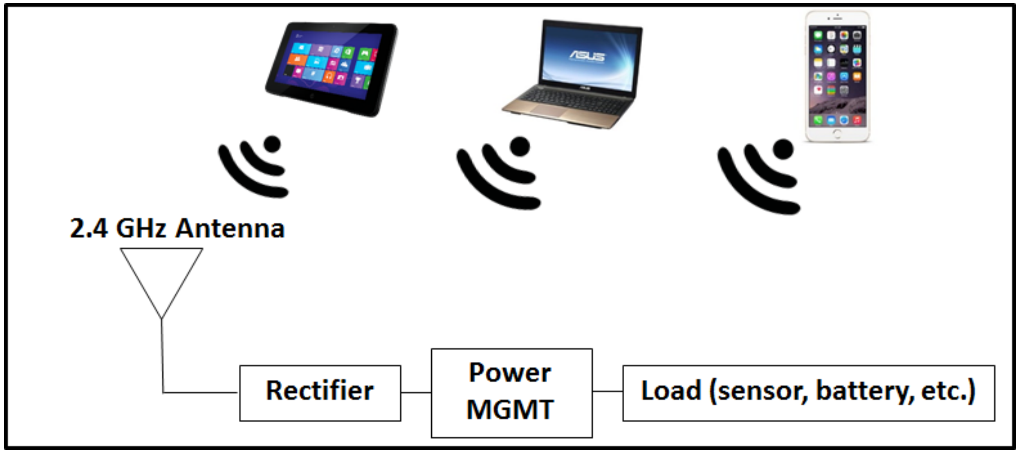




Salman, Wang, Colebeck, Kiourti, Topsakal, Volakis, "Pulmonary edema monitoring sensor with integrated body-area network for remote medical sensing," IEEE TAP, 62(5):2787-2794, 2014

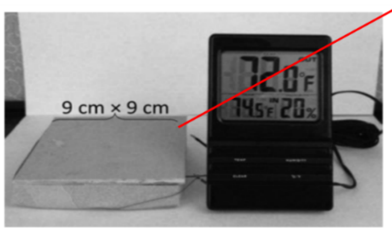
[7] RF Energy Harvesting

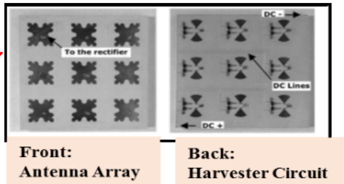
Create an RF power harvesting system that wirelessly powers medical devices (e.g., wearable or implantable sensors).



Ambient WiFi energy harvesting system.

Past Power Harvester Array:

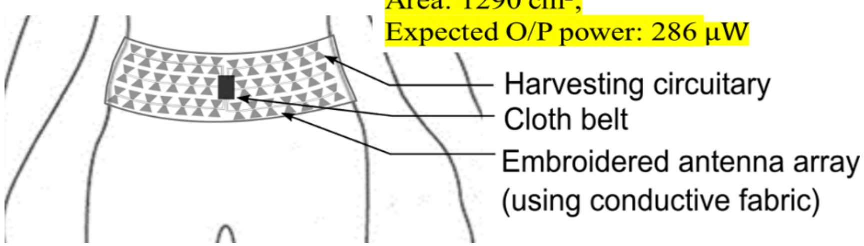


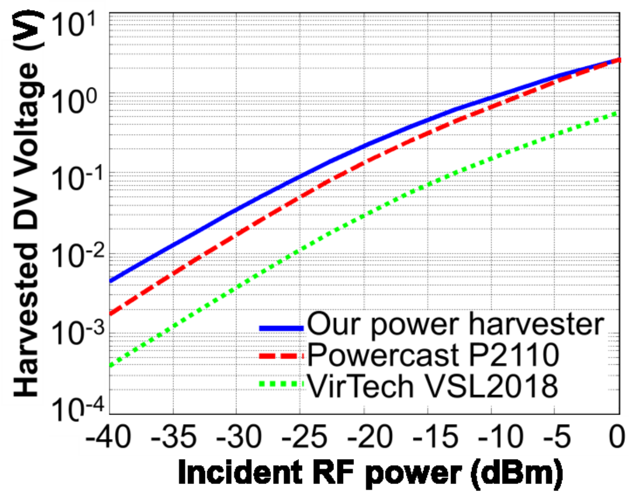


Area: 81 cm^2
Measured O/P power: 18 µW

Power Harvester Belt:

Area: 1290 cm^2,
Expected O/P power: 286 µW





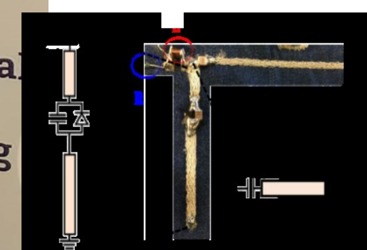
high-efficiency (>80%), better than commercially available harvesters

Olgun, Chen, Volakis, Design of an efficient ambient WiFi energy harvesting system, IET Microw. Ant. & Propag., 6(11): 1200-1206, 2012.

Rectifier Implementation into Clothing

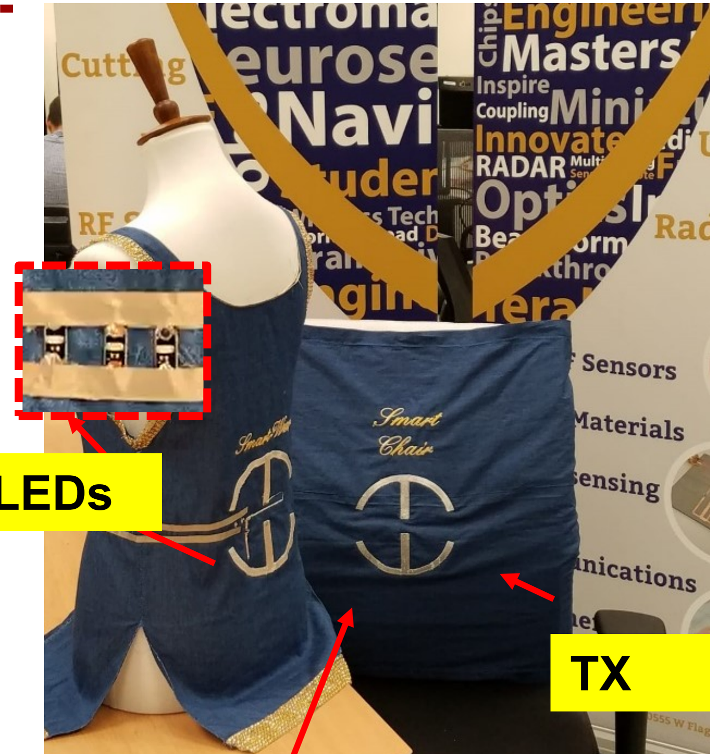
- Integration of smart-wear and smart upholstery
- Use of on-textile power storage unit

Power transfer and harvesting to be performed



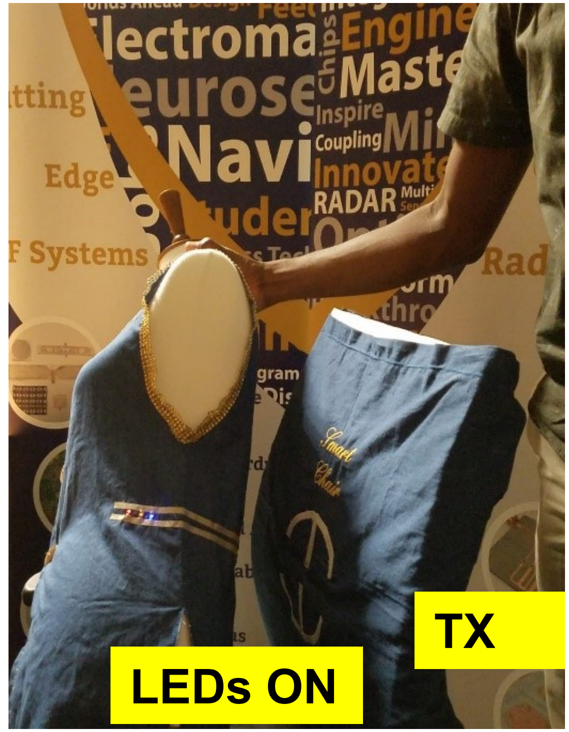
Rectifier

Apparatus for Testing of Smart Clothing



Integration into clothing
and upholstery (Chair)

Rectifier +Anchor-shaped
RX Antenna



Angular Misalignment Test

Lateral Misalignment Test

Input power: 1W (within FCC requirement)
Misalignment: Within 10 cm

FIU

Live Demo

- Resilience to misalignment shown for developed topology

- Harvested (1 - 2 mW) enough power to light up three LEDS in parallel at a distance of ~20 cm

Video credit: Carolina Moncion

Sub-GHz Smart System demonstrates excellent RF performance even under misaligned cases

E-Textile Challenges

Technology Challenges

Precision achieved in embroidery

Powering

Security

Protection against corrosion

Textile-electronics integration
(sensors, feeding, etc.)

Process Challenges

Applications?

Commercialization

Mass Production

Weaving Process

Thank you!

Questions: jvolakis@fiu.edu