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"Conductive Textiles for Wearable Electronic Applications"

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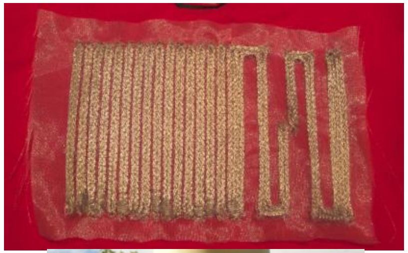
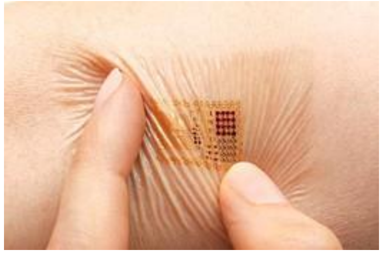


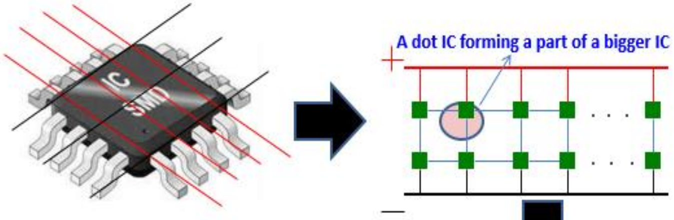


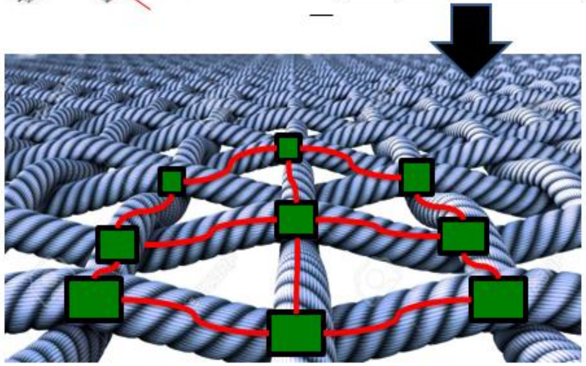
Collaborator:

- **Prof. Asimina Kiourti, The Ohio State Univ.**

Ensuing Concept

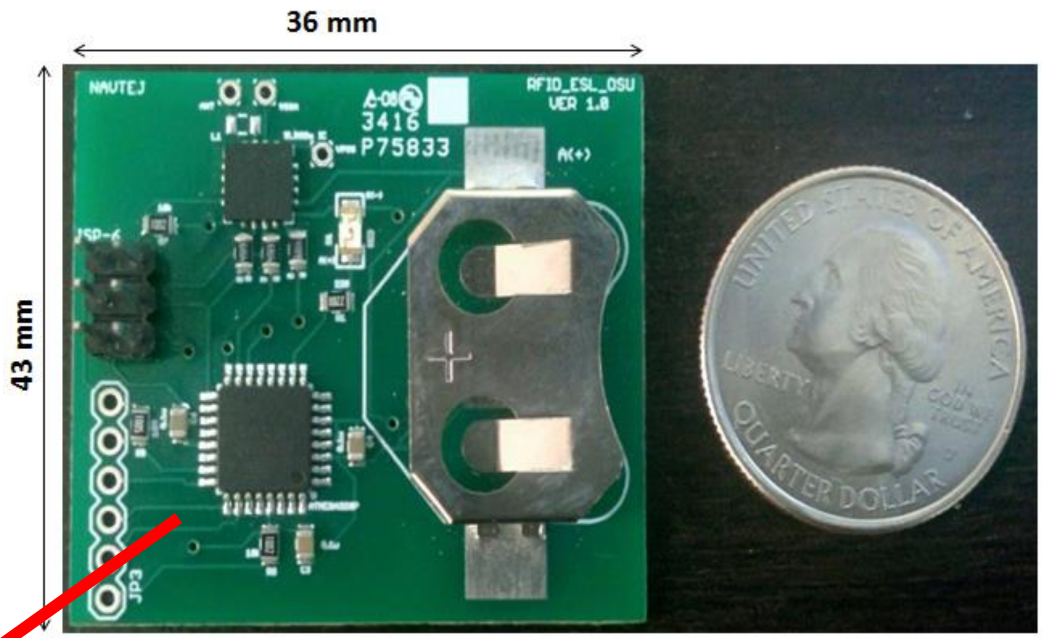
- Create textile-based electronics for integration into clothing or fabrics. Goal is to enable communications, IoT and sensing without using handhelds or discrete accessories.
  - Current Wearables are lumped accessories
- Can we create electronic surfaces that include circuits and IC components and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





Multi-Sensor and 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



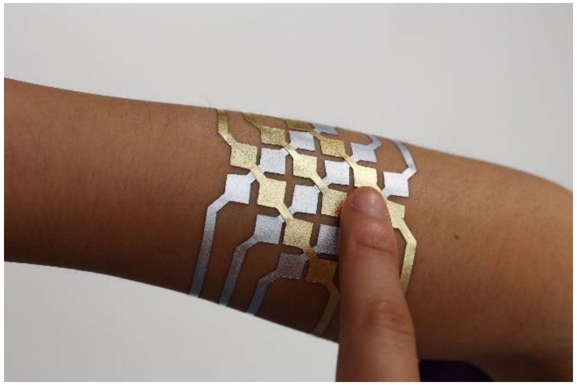
UHF RFID reprogrammable tag circuit board

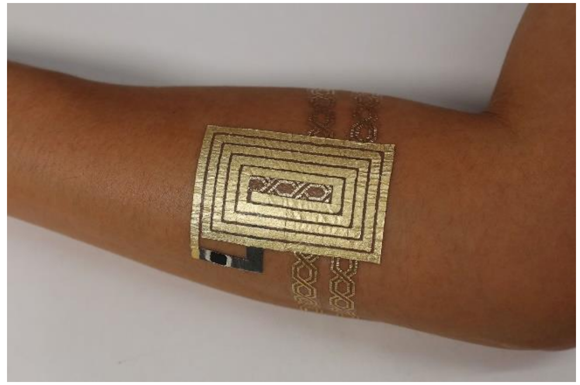
Entire chip & Board is printed on textile surface

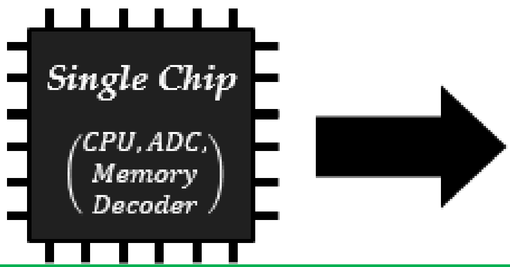
Board Features

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

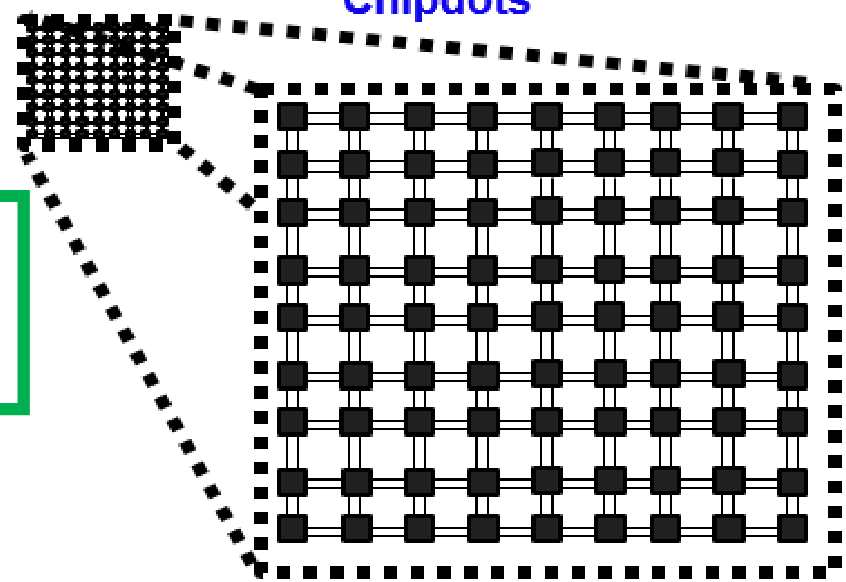
Future Electronics will be Wearable







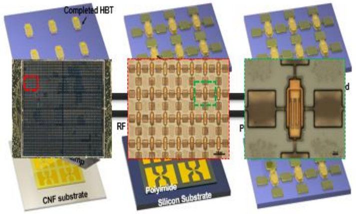
Textile Embedded Chipdots



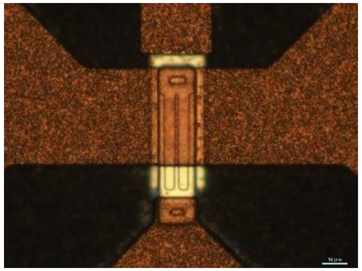
Wearables:
- **37% annual growth**
- **300 million devices to ship**

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

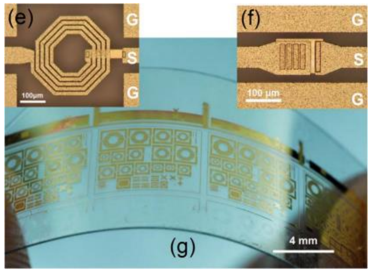
Flexible Electronics are at their Infancy



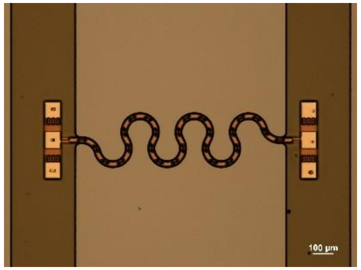
(similar to transistors before microprocessor chips)



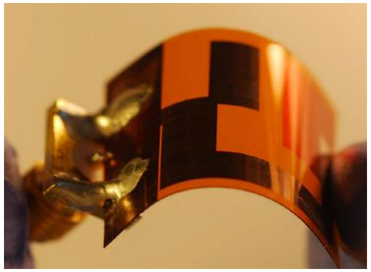
RF transistor



Inductors & Capacitors



Transmission Line

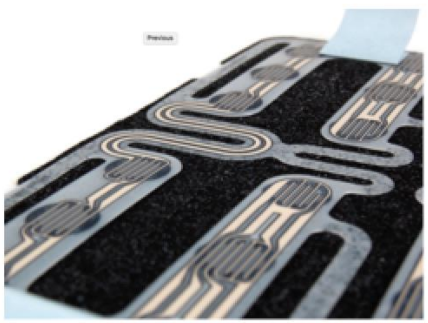


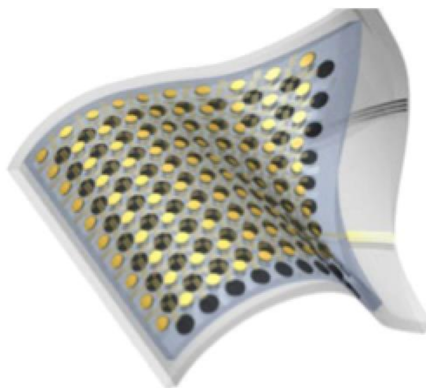
Antenna

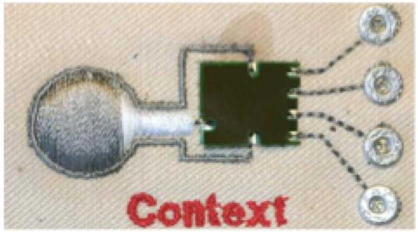
Slide from
Prof. Jack Ma (Wisconsin)

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.





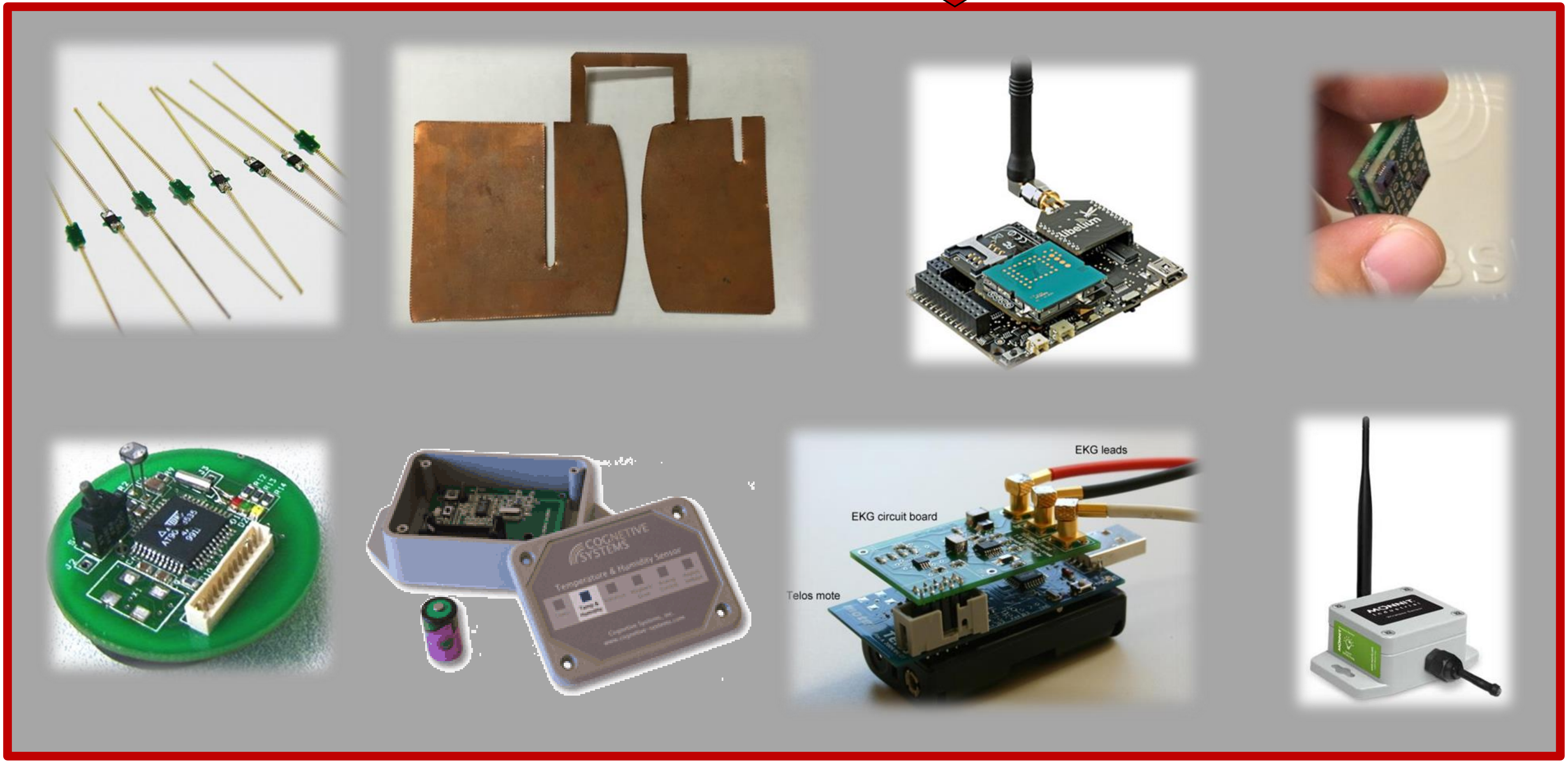


Current state of art- Medtronic ECVUE, all electronics are external, limiting use to clinic

Will be Challenging

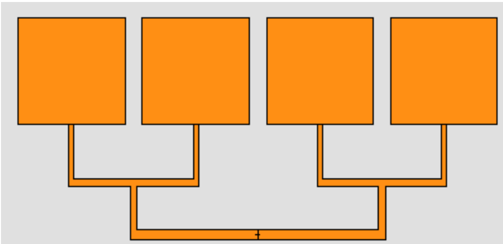
Traditional Sensors and Electronics

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



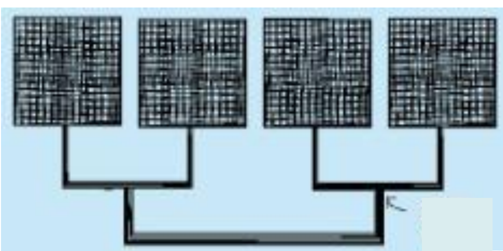
Our Embroidery Technology

HFSS model

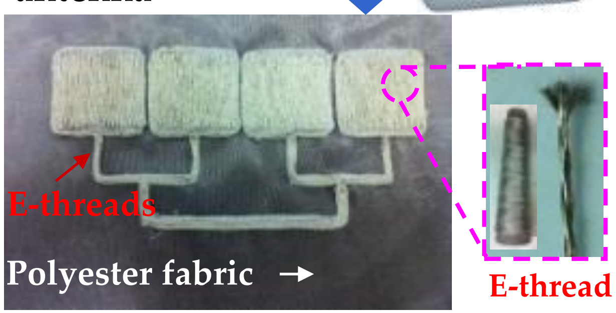


Export to specific computer program

Digitization



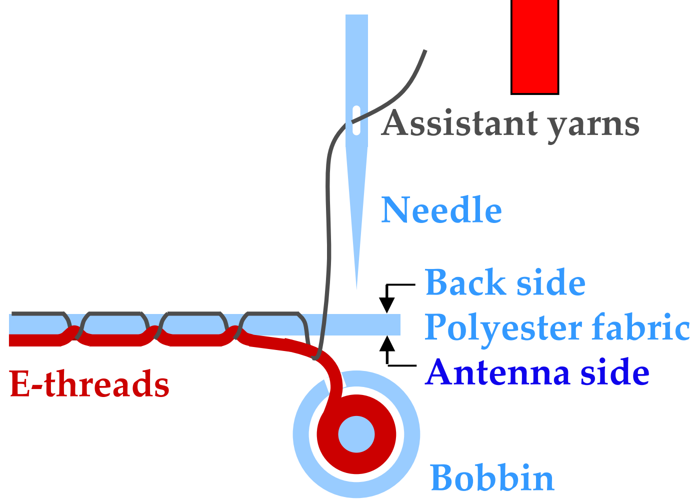
Embroidered antenna



Threads Used for Antenna Embroidery

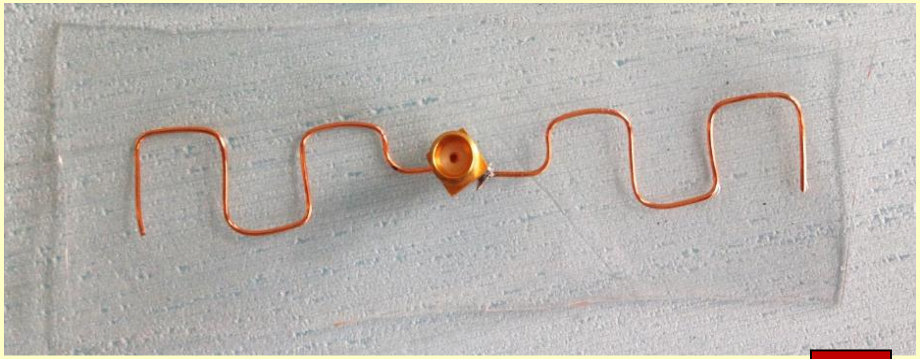
Assistant Yarn: Regular non-conductive thread.

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

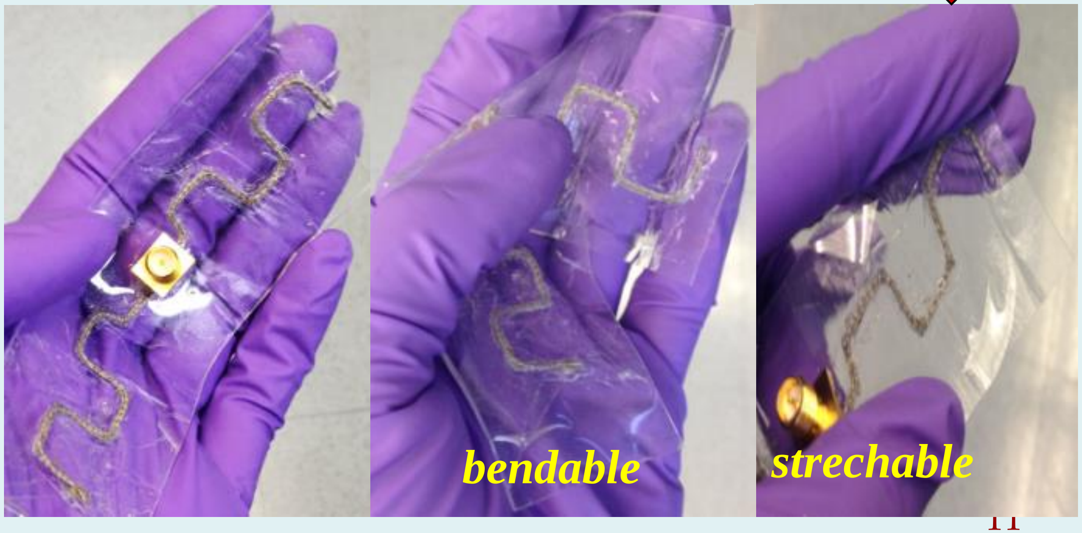


E-Textile Electronics in Our Group

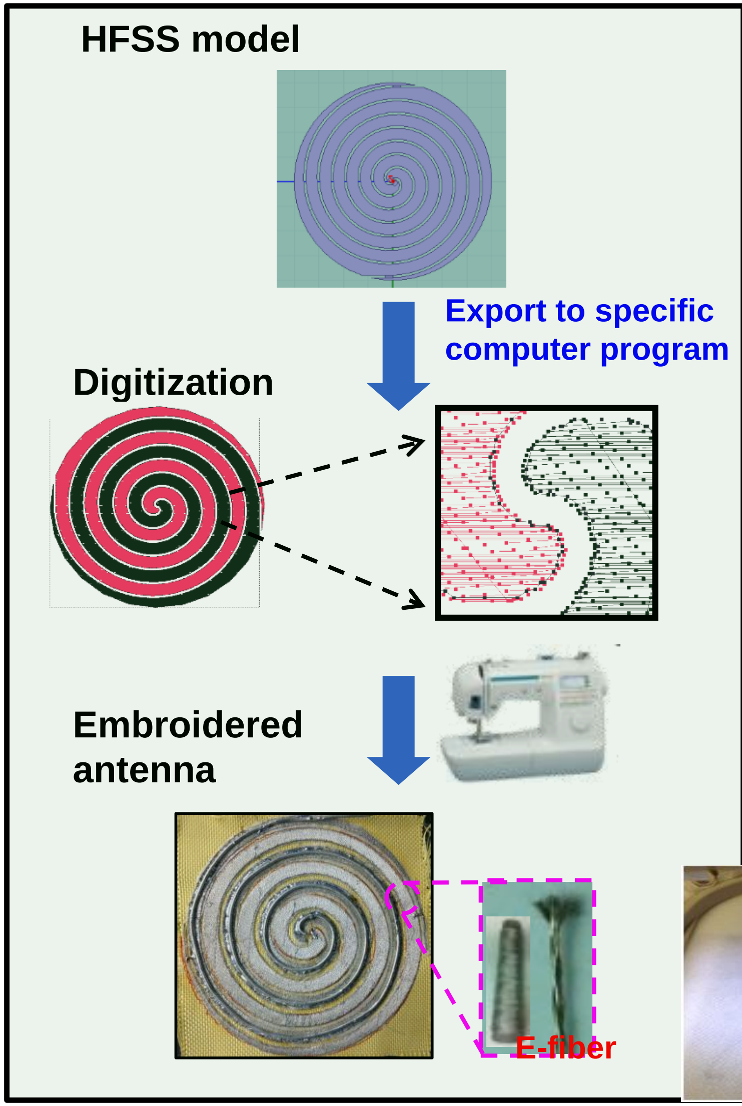
Rigid copper prototypes



Flexible E-textile prototypes

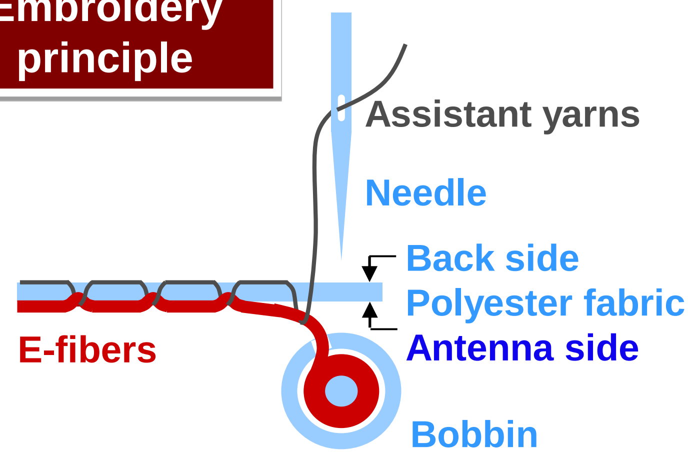


Automated Embroidery of Textile E-threads



- 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

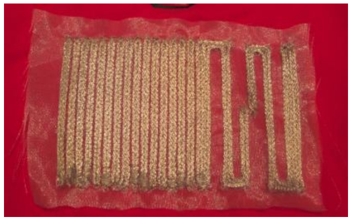


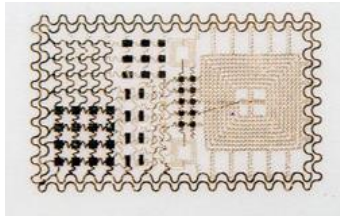
0.1 mm – Precision Achieved in Embroidery

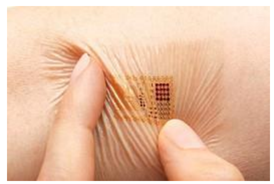
	Former Technology (2013)	Latest Technology (2016)
Provider	SYSCOM, USA	ELEKTRISOLA, Switzerland
# of filaments	664	7
Diameter	0.5mm	~0.1mm
Embroidery accuracy	0.5mm 	**~0.1mm**  
Embroidery density	2 threads/mm	7 threads/mm

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

“Printed” on any Fabric

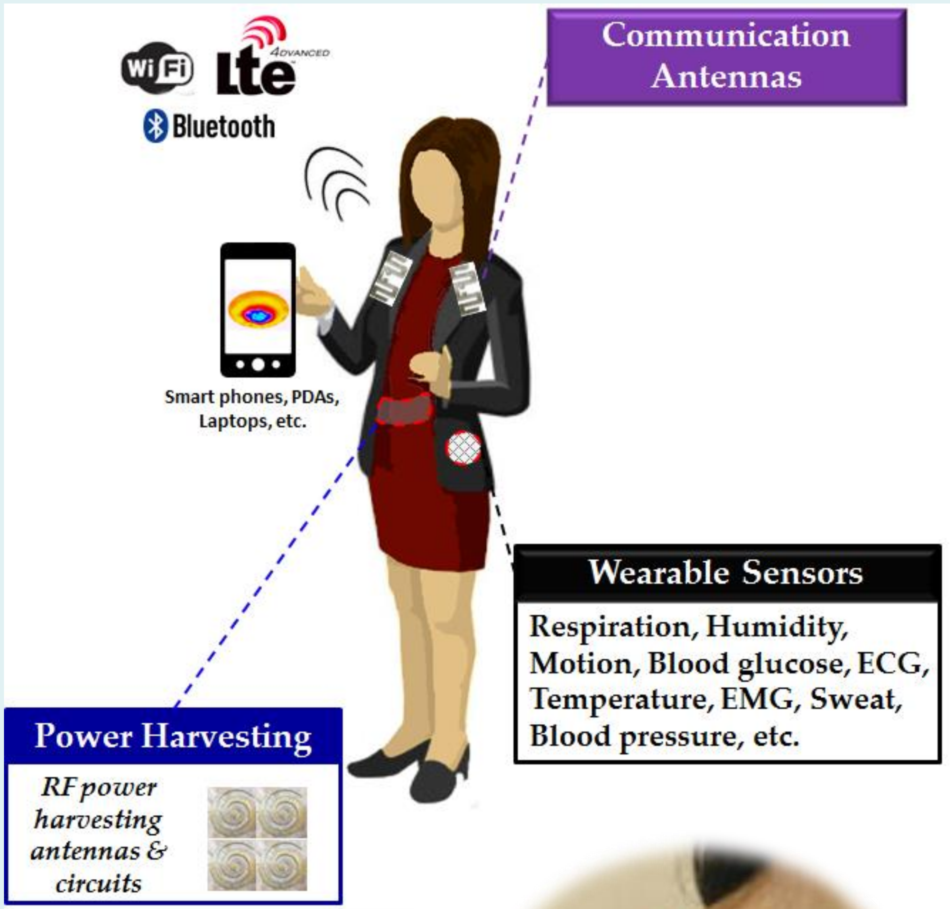






E-Textiles vs. Wearables

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

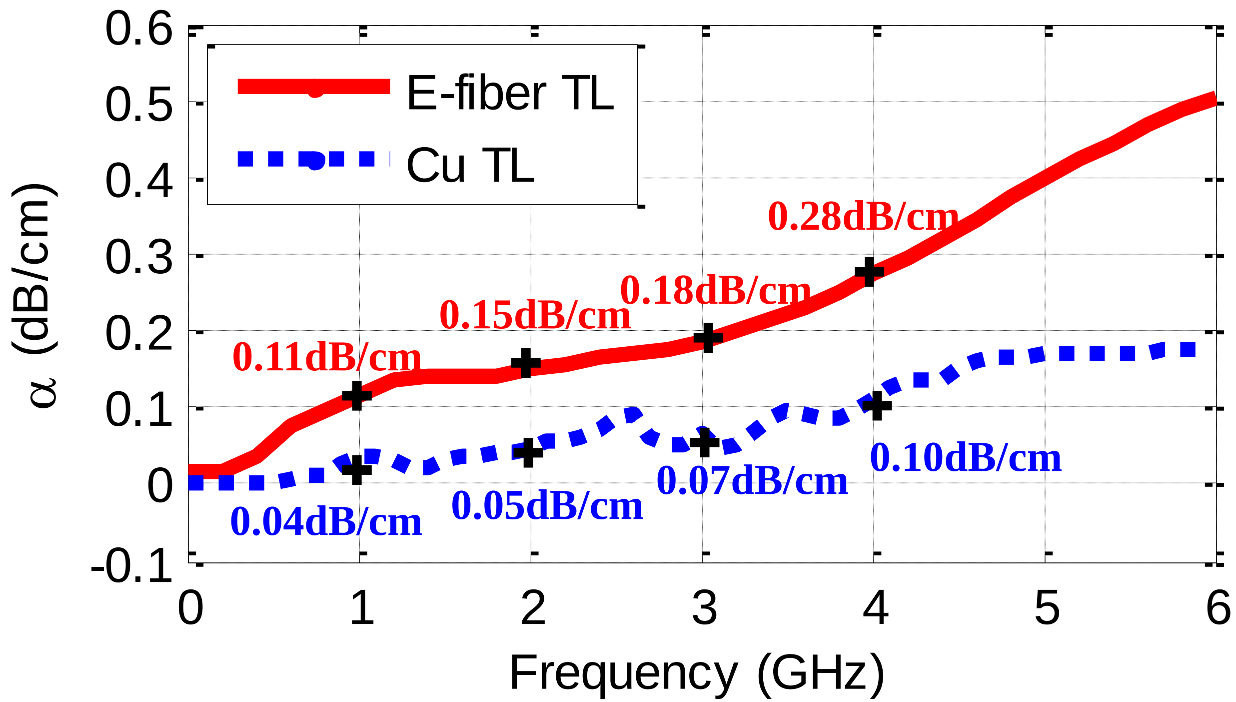
$200

http://www.sensoriafitness.com/

E-Textile Properties

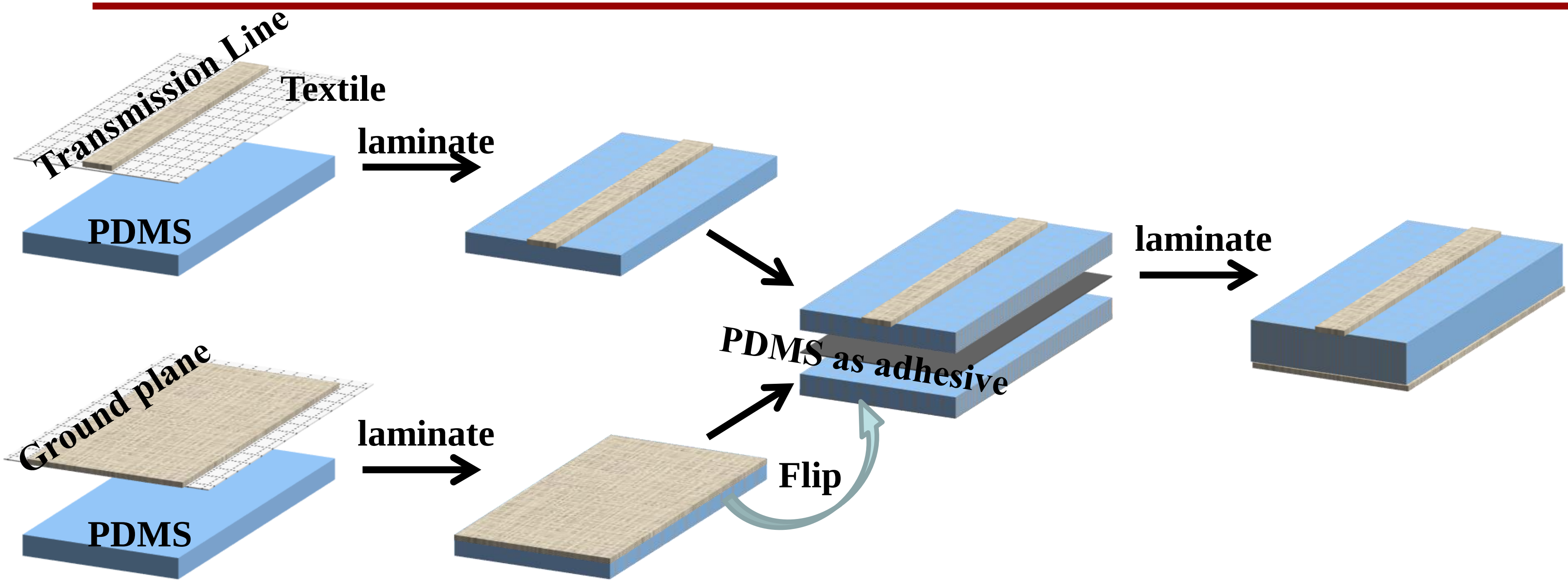
Attenuation Comparison of E-textile and Copper TL

E-fiber textiles are efficient conductive media for RF applications

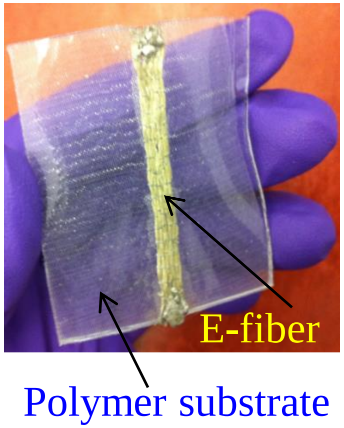


- Overall attenuations of E-fibers are small, making it an efficient conductive media for RF designs.
- Increased attenuation losses at higher frequencies are due to surface roughness and imperfect metallization of the E-fibers.

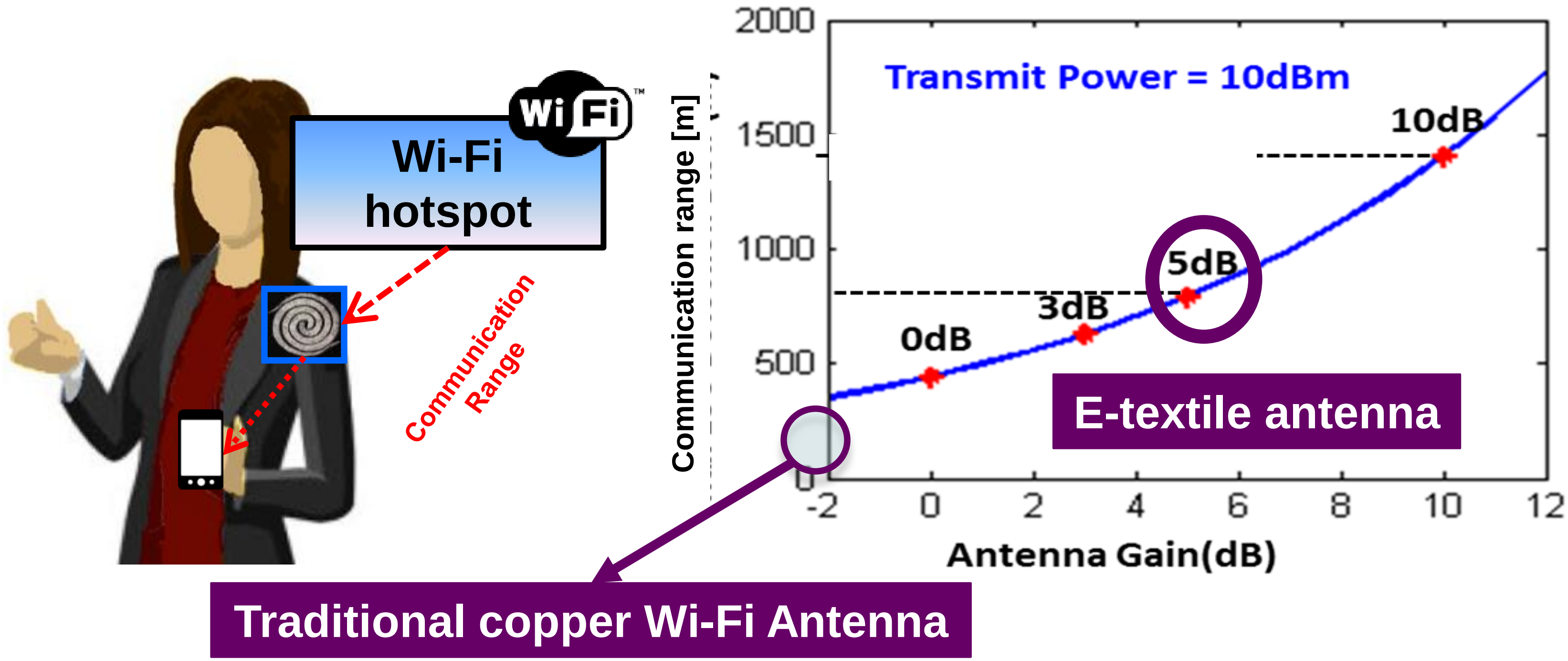
Textile Circuit Assembly on PDMS Substrate



- 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

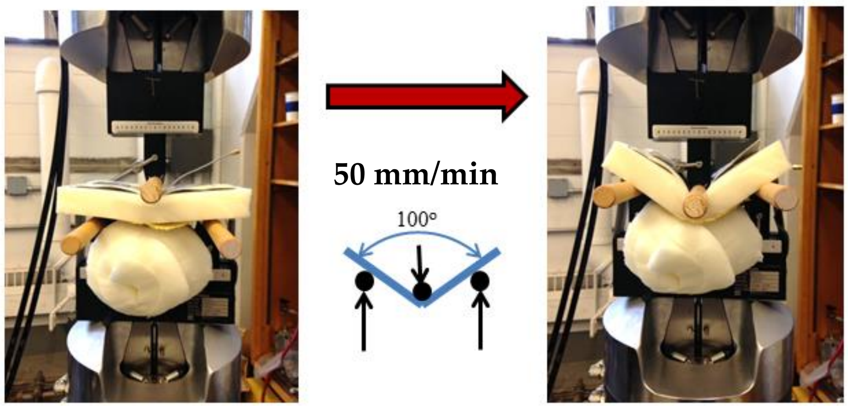


Higher gain E-textile antennas increase max. communication distance (sensitivity).

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

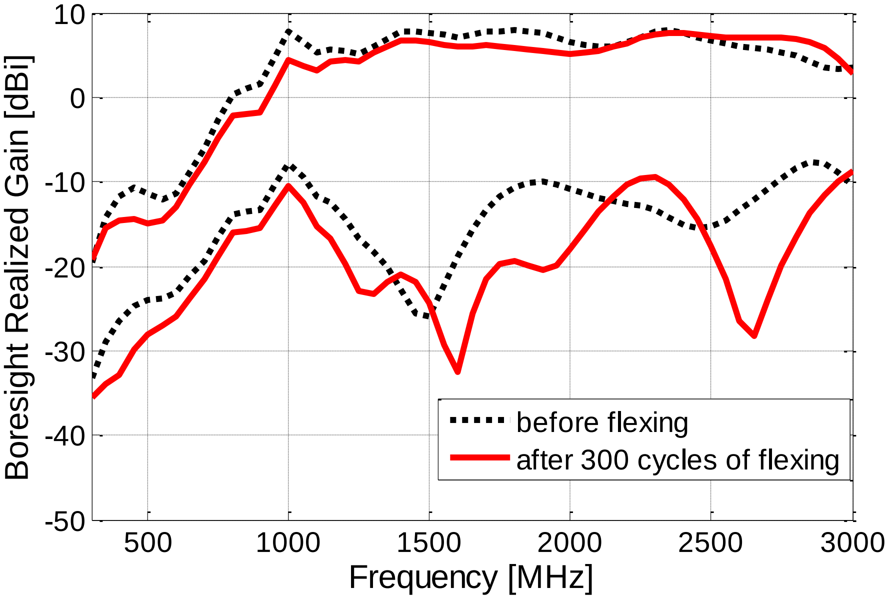
Extreme Mechanical and Thermal Tolerance

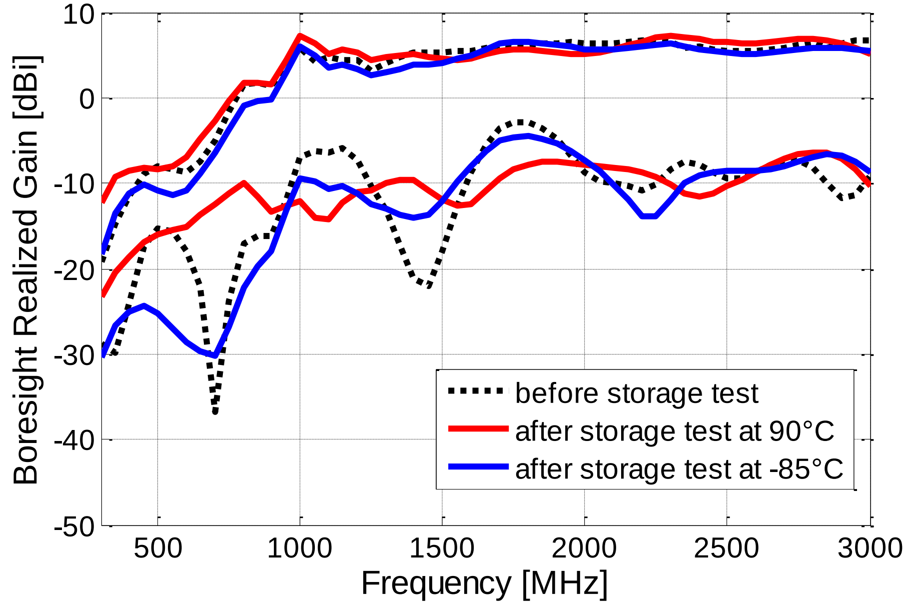
Mechanical Testing



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.



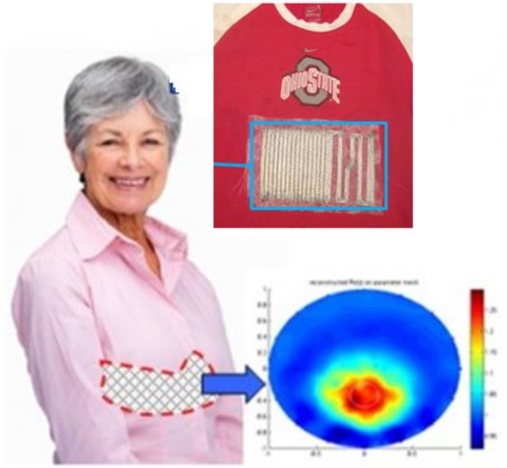


J. Zhong, A. Kiourti, T. Sebastian, Y. Bayram, and J.L. Volakis, "Conformal Load-Bearing Spiral Antenna on Conductive Textile Threads," *IEEE Antennas and Wireless Propagation Letters*, 2016.

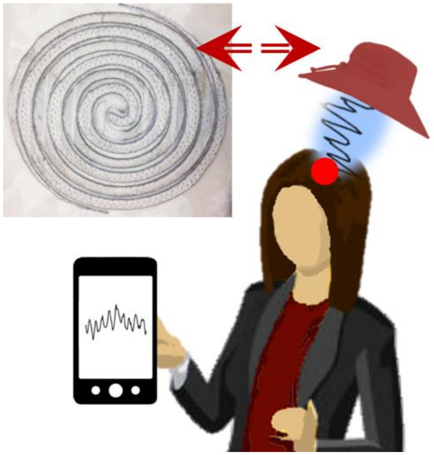
APPLICATIONS

E-Textile Applications

[1] Medical Imaging Sensors



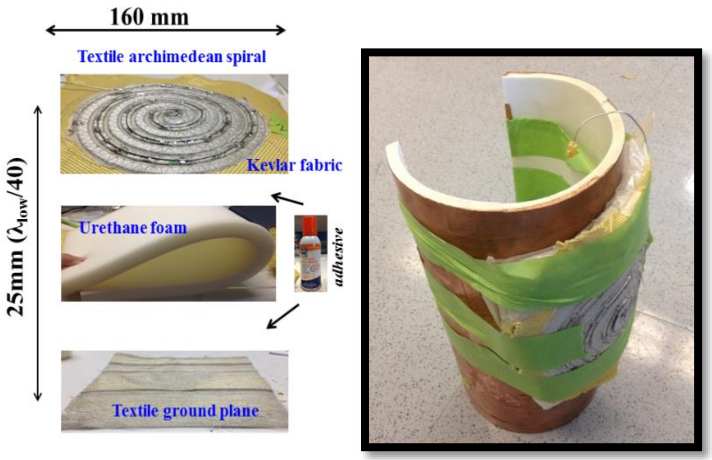
[2] Wireless Brain Implants



[3] Wearable Antennas for Wireless Communications

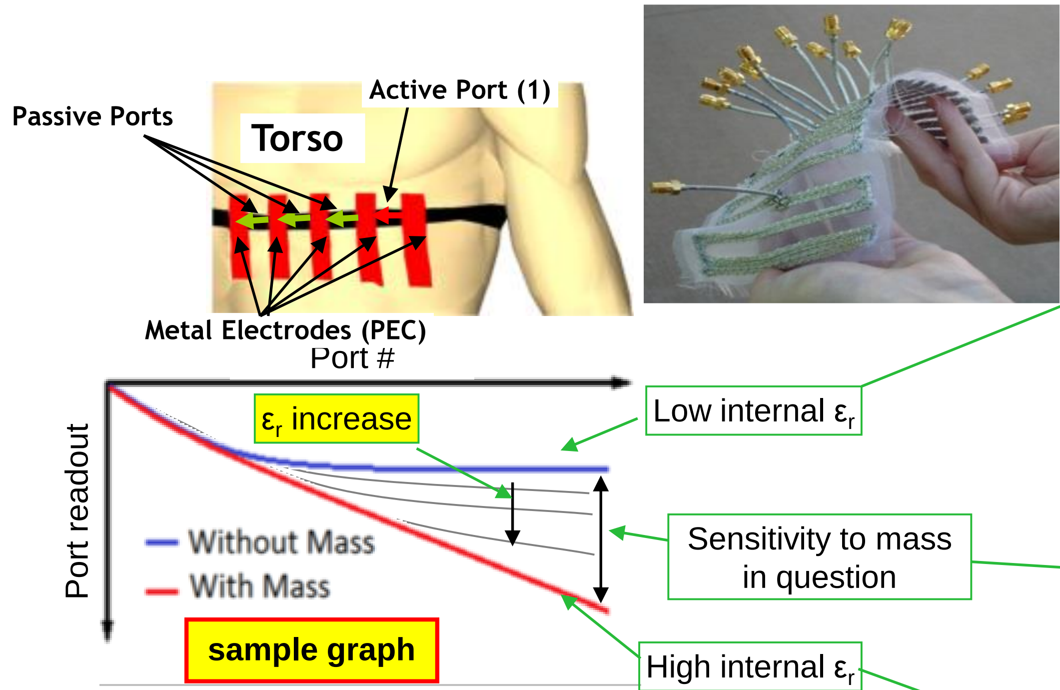
[4] RFID Tag Antennas

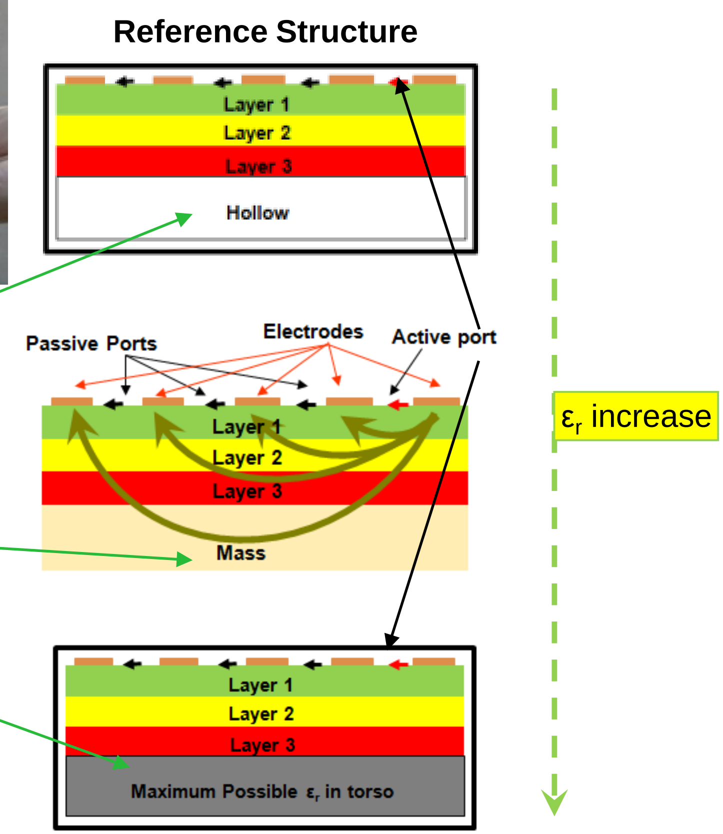
[5] Conformal Antennas



[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>



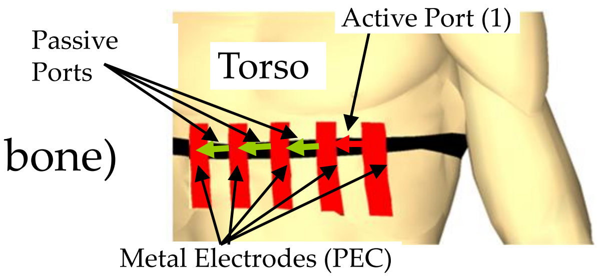


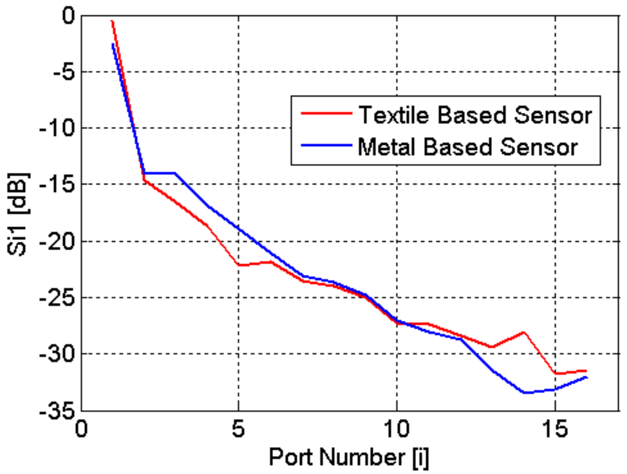
Operating frequencies: 10 MHz,
(ISM+ electrical properties diversity)

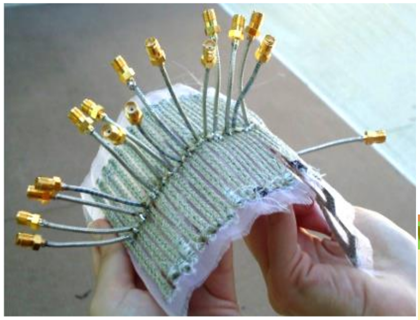
[1] Body-Worn Textile Imaging Sensor

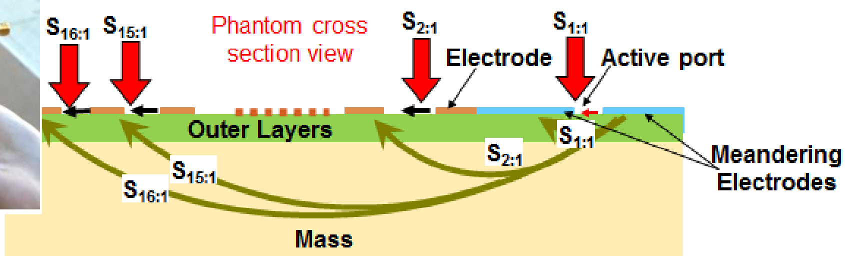
A surgery-free on-body monitoring device to evaluate the dielectric properties of internal body organs (lung, liver, heart) and effectively determine irregularities in real-time ---several weeks before there is serious medical concern.

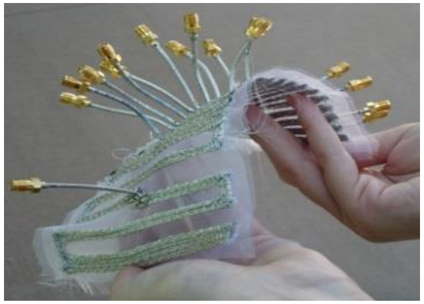
- Operates at **40 MHz (HBC)**
- Deep detection: >**10 cm**
- **Suppresses interference** from outer layers (skin, fat, muscle, bone)

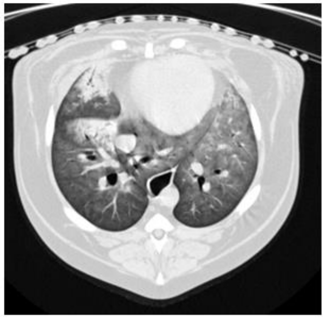








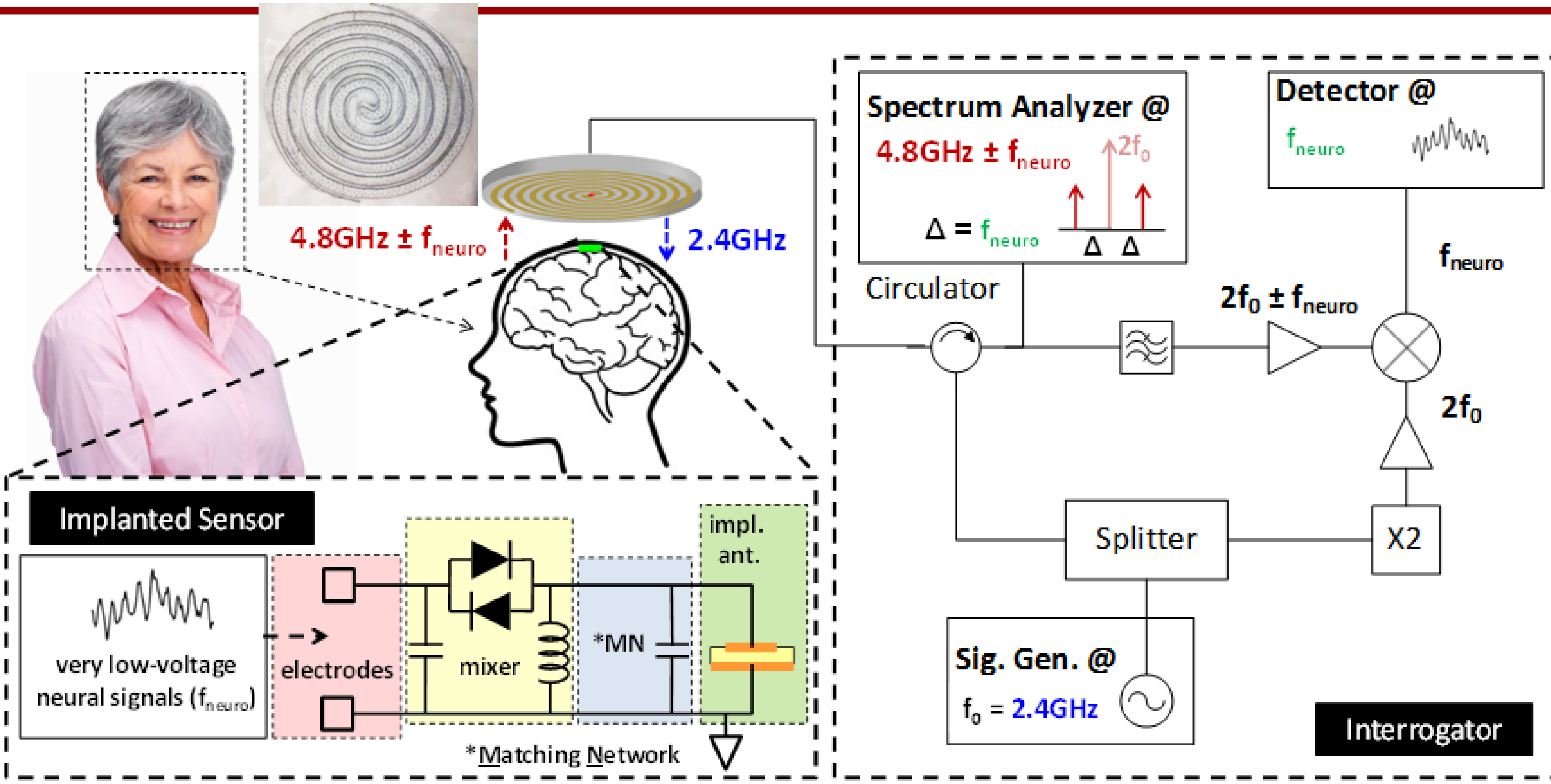


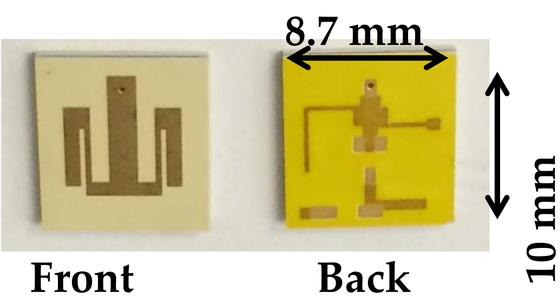


- 17 electrodes + 16 ports
- One excited port, the rest are passive for readouts
- Non-uniform to improve impedance matching

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

[2] Wireless Brain Implants



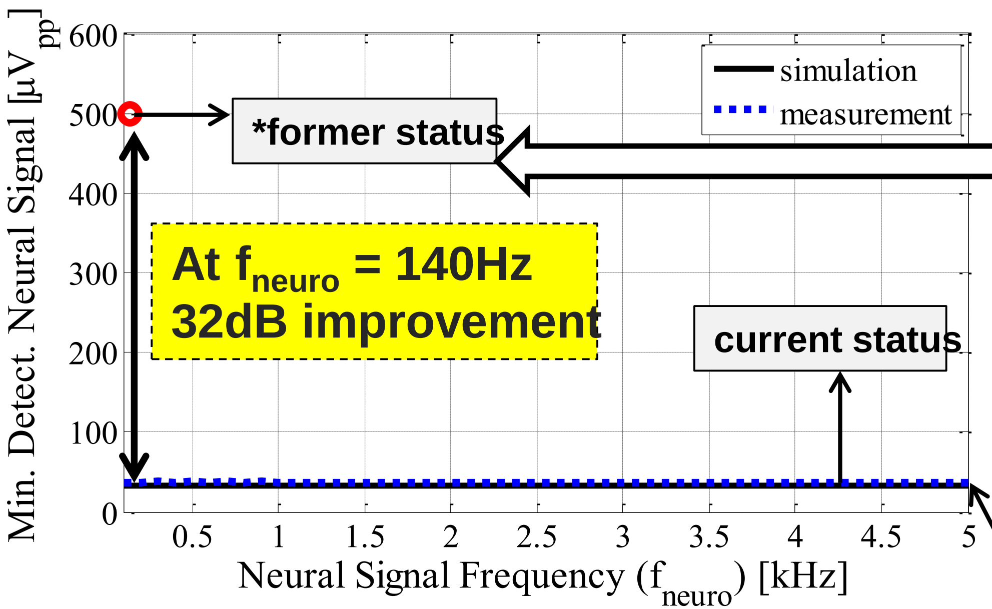


- **Fully-passive and wireless neurosensors** to acquire brain signals inconspicuously.
- Integration of **extremely simple electronics** in a **tiny footprint** to minimize trauma.
- Acquisition of **extremely low signals**, down to $20\mu V_{pp}$. This implies reading of most signals generated by the 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 20μV$_{pp}$ can be detected

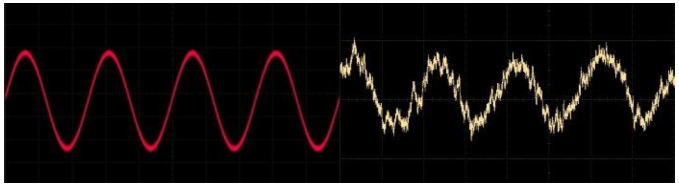
New set-up reduces Minimum Detectable Signal (MDS), allowing reading of neuropotentials down to 20μV$_{pp}$. Therefore, most human physiological neuropotentials can be recorded wirelessly.



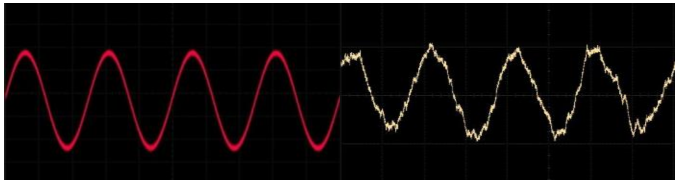
Historical data for minimum detectable signal. Our new implant and interrogator demonstrates a 32dB improvement.

New set-up allows reading of neuropotentials down to 20μV$_{pp}$ 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.

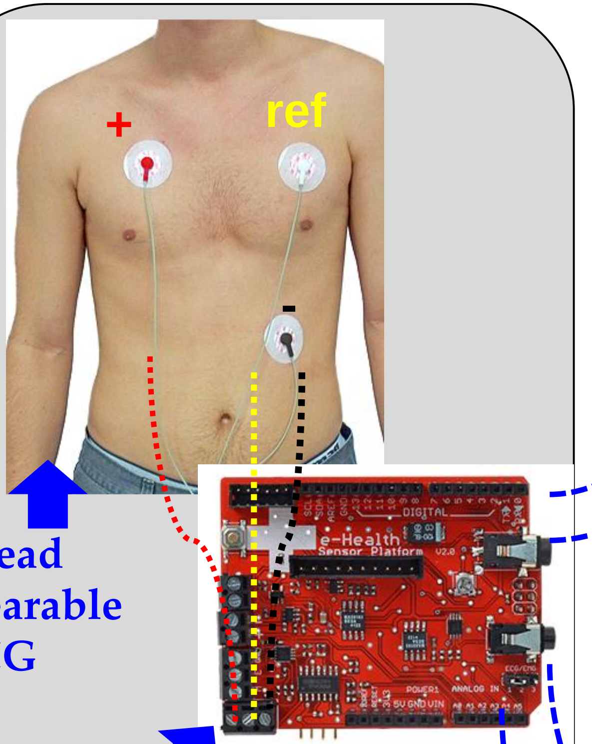
Comparison of Proposed vs. Previously Reported Wireless Brain Implants

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

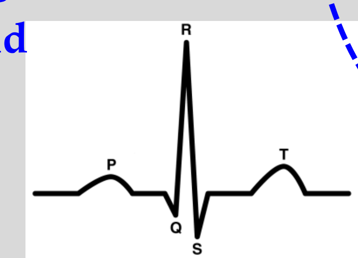
A. Kiourti, C. Lee, J. Chae, and J.L. Volakis, "A Wireless Fully-Passive Neural Recording Device for Unobtrusive Neuropotential Monitroing," *IEEE Transactions on Biomedical Engineering*, 2015.

Preliminary In-Vivo Validation: Wireless Acquisition of Human ECG



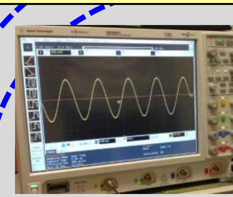
3-lead wearable ECG

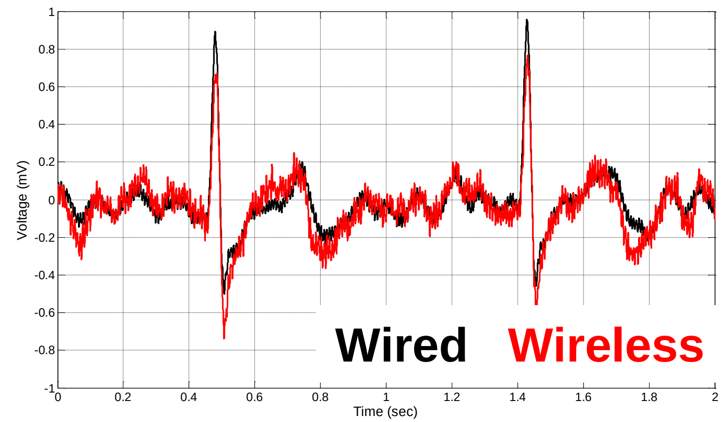
Post-processing to acquire 2-lead output ECG



Wired Configuration

oscilloscope



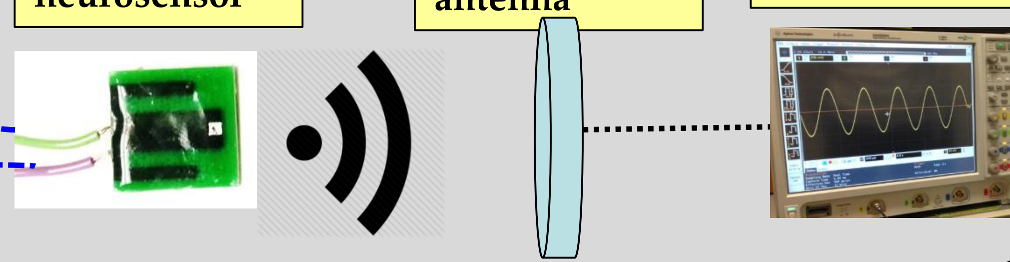


Wireless Configuration

wireless neurosensor

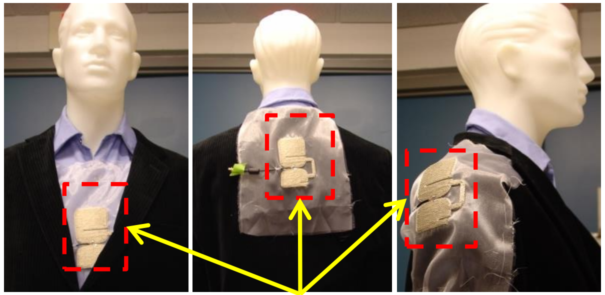
exterior antenna

oscilloscope

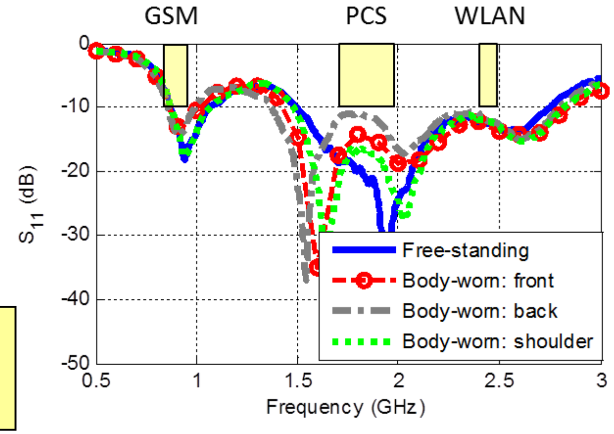


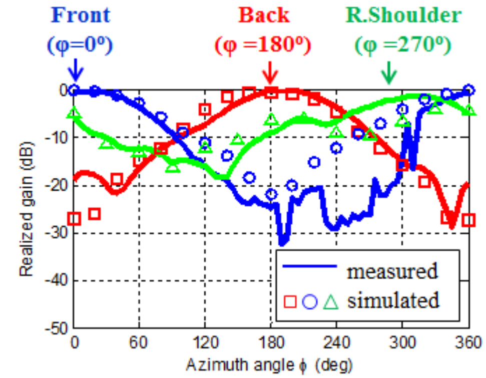
[3] Antennas for Body-Worn Communication

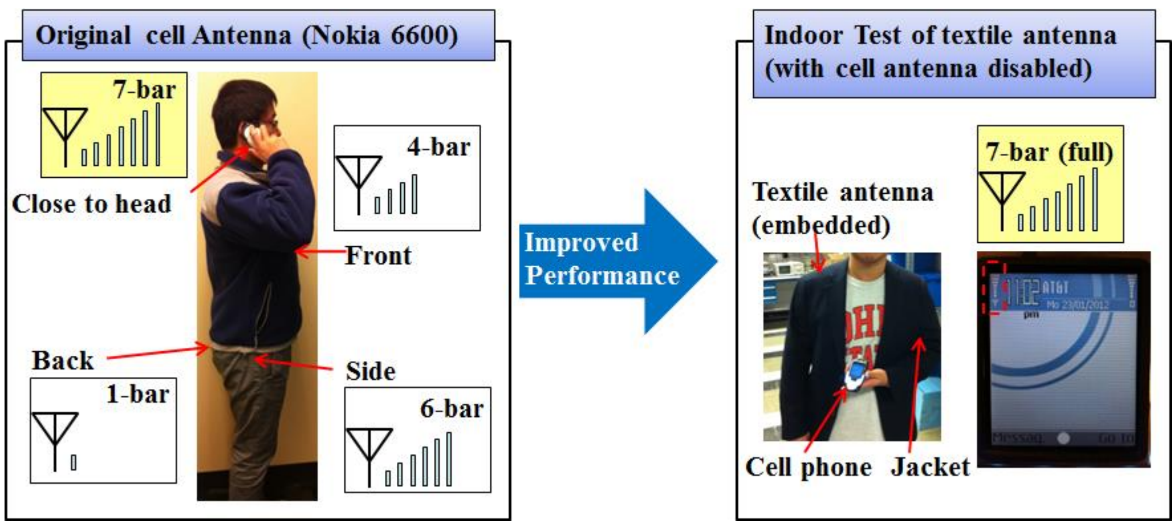
Multiband Dipole for GSM/PCS/WLAN Bands



- 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

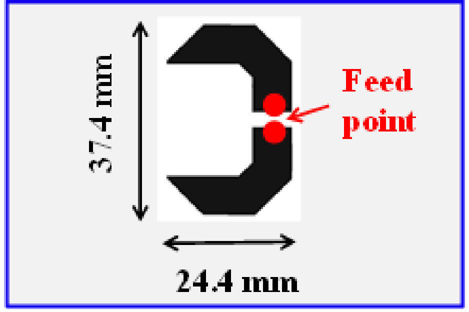
- Textile antenna is low-profile, unobtrusive, and comfortable to wear.

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

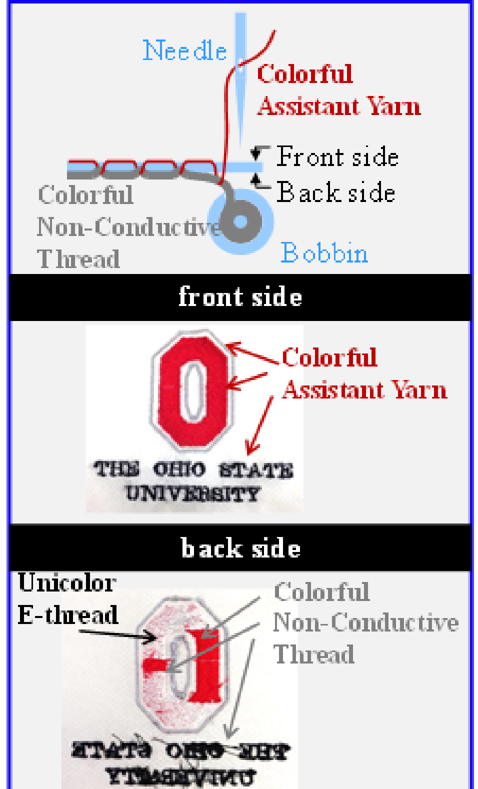
STEP 1: Antenna Design

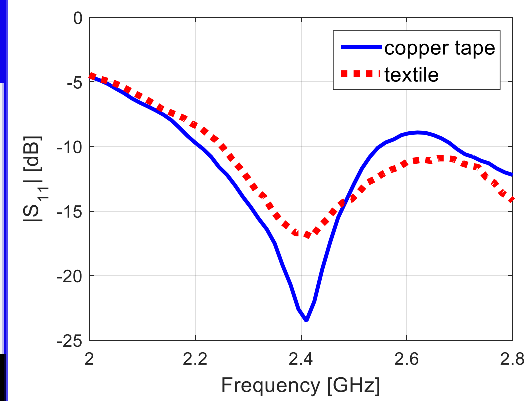


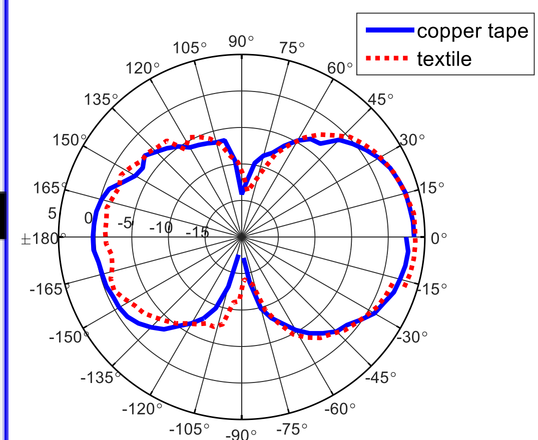
STEP 2: Digitization

STEP 3: Embroidery of Conductive Portion

STEP 4: Embroidery of Non-Conductive Portion







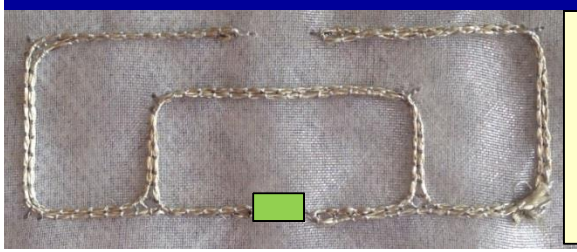
The colorful textile antenna prototype achieves excellent performance as compared to its copper counterpart. Concurrently, it is flexible, lightweight, and mechanically robust.

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:

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

ELML E-fiber RFID tag antenna embedded in polymer

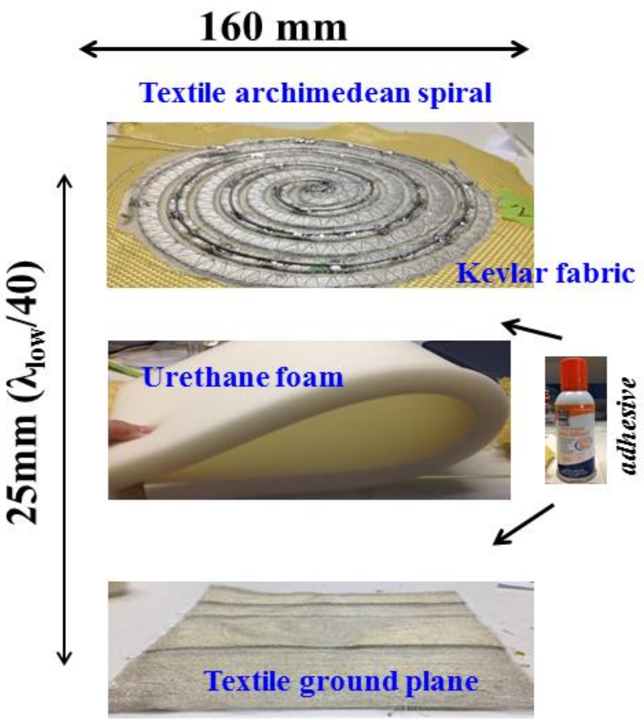
5 ft On Tire Threshold Power Test

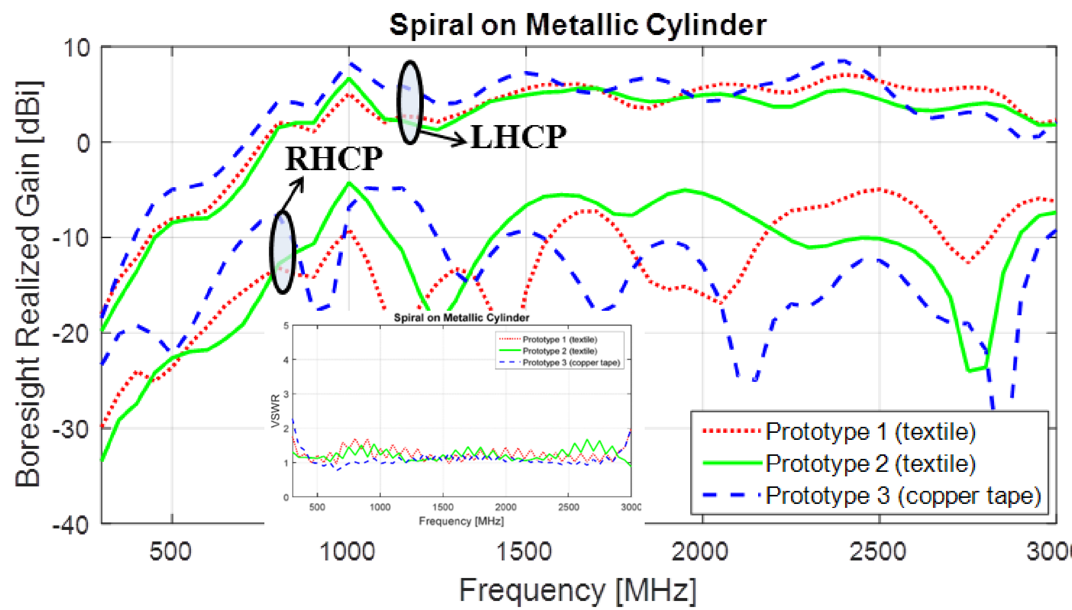
- ❑ Textile: 22 dBm
- ❑ Copper foil: 20 dBm

- 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

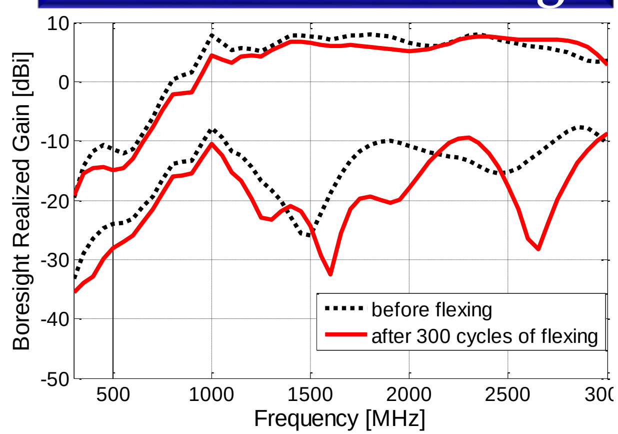
S. Shao, A. Kiourti, R. Burkholder and J.L. Volakis, "Broadband, Textile-Based Passive UHF RFID Tag Antenna for Elastic Material," AWPL 2015

[5] Conformal Antennas for Airborne and Wearable Applications

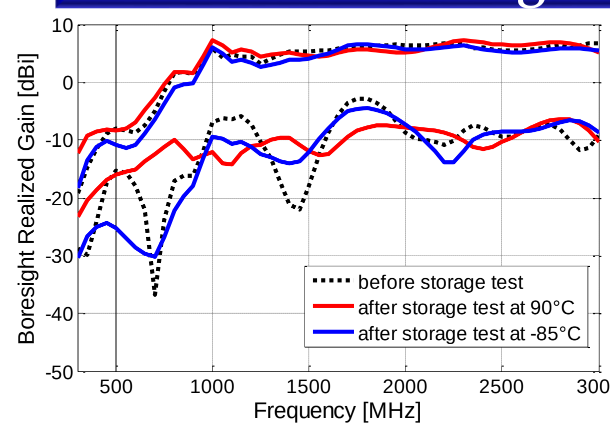




Mechanical Testing



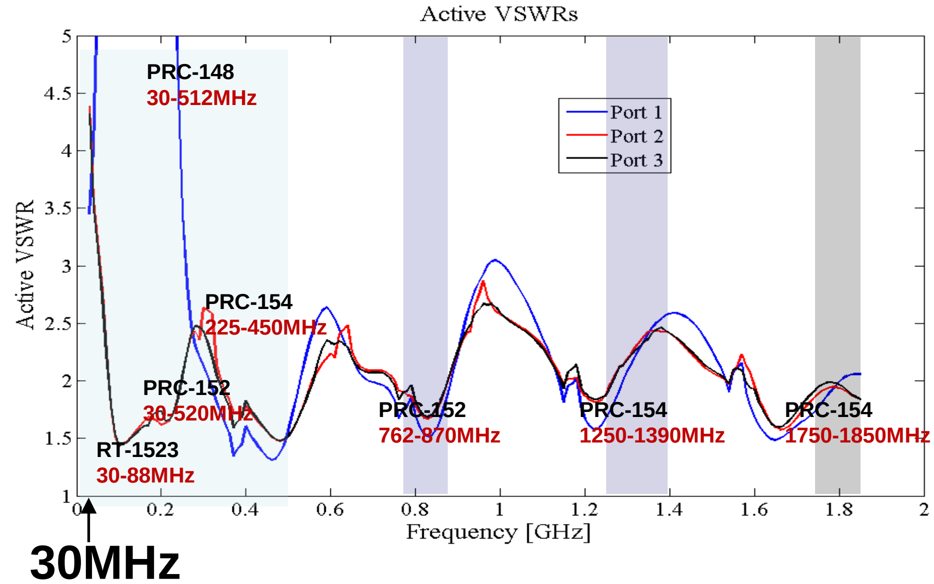
Thermal Testing

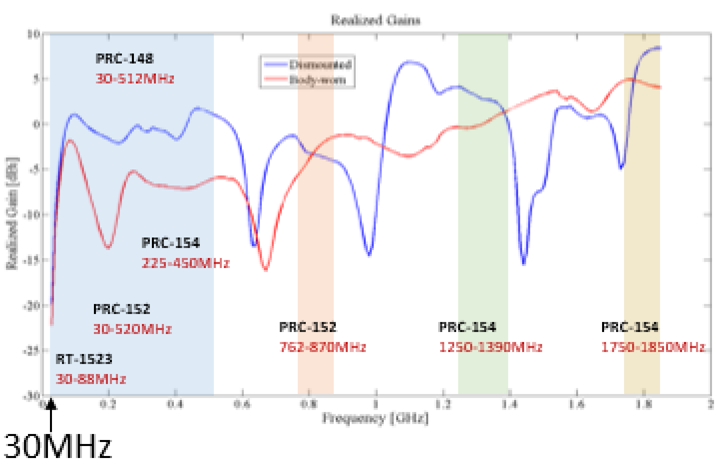


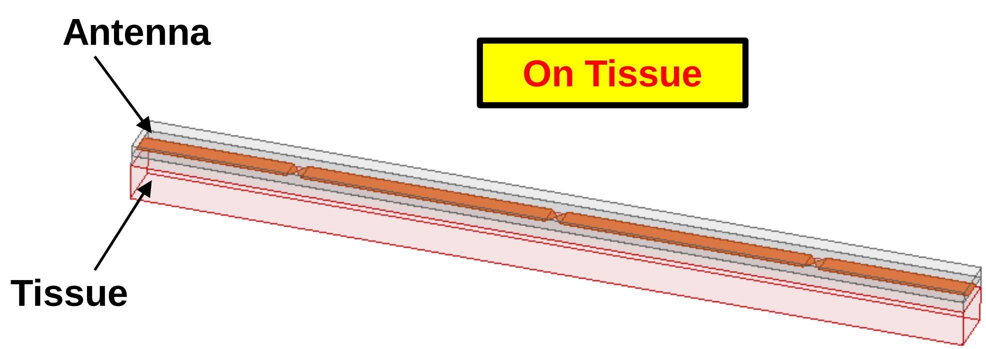
J. Zhong, A. Kiourti, and J.L. Volakis, “Conformal, Lightweight Textile Spiral Antenna on Kevlar Fabrics,” AP-S 2015.

[6] Body Wearable Antennas Must Operate at Low Frequencies

Antenna on-Body



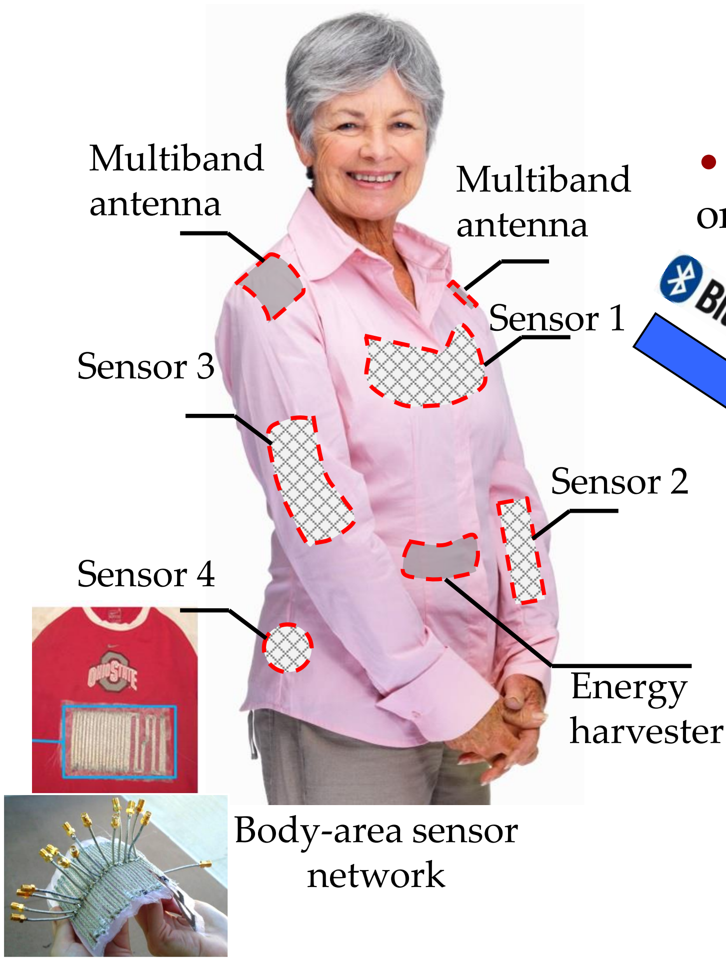




Continuous 30MHz to 2000MHz (67:1 bandwidth)

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

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



Body-area sensor network

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.

In-situ data display on mobile APP

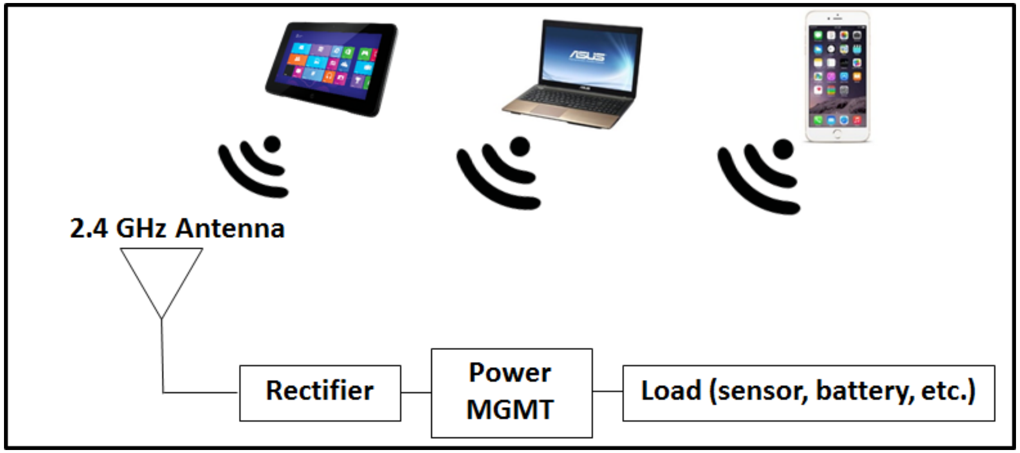
Date storage on Cloud Server

Remote access by Physicians

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

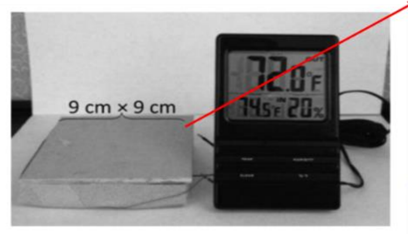
[7] RF Energy Harvesting

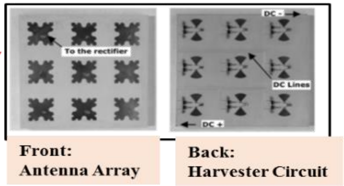
Create an RF power harvesting system that wirelessly powers medical devices (e.g., wearable or implantable sensors).



Ambient WiFi energy harvesting system.

Past Power Harvester Array:

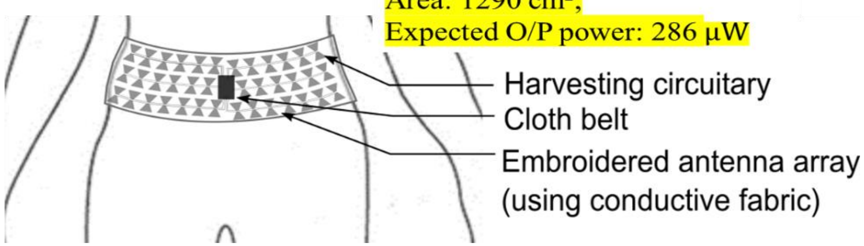


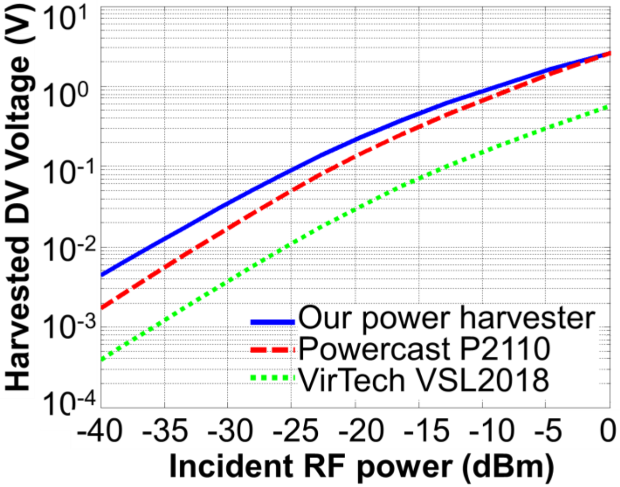


Area: 81 cm^2
Measured O/P power: 18 μW

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.

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

Thank you!

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